NISTIR 6194

Proceedings of the
Second NIST Workshop
on

THE DEVELOPMENT OF MACHINE TOOL PERFORMANCE MODELS AND DATA REPOSITORY

February 18-19, 1997
New Orleans, Louisiana

Edited by:
M. Alkan Donmez
Automated Production Technology Division
Manufacturing Engineering Laboratory

NIST
National Institute of Standards and Technology
Technology Administration
U.S. Department of Commerce

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U.S. DEPARTMENT OF COMMERCE
William M. Daley, Secretary
TECHNOLOGY ADMINISTRATION
Dr. Cheryl L. Shavers, Under Secretary
of Commerce for Technology
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Raymond G. Kammer, Director

INTRODUCTION

This document is a transcription of an audio recording of presentations and discussions from the Second NIST Workshop on the Development of Machine Tool Performance Models and Data Repository. This workshop is the follow up of the first workshop, which was held on September 17, 1996 to identify the needs of the U.S. industry in this area and prioritize the tasks necessary to accomplish the goals of this project. The purpose of the second workshop is to review the progress taken place since the first workshop and identify any modifications to the plans based on the industrial partners' input. There are series of presentations by NIST staff as well as by industrial and academic collaborators describing the work being done to develop and use machine tool performance models and data repositories. The discussions that took place during the workshop were also transcribed in detail in this document to provide accurate information about the decisions taken and their justifications. A summary of the presentations and discussions was also provided at the end of the proceedings.

DISCLAIMER

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DISCUSSIONS

WELCOME AND INTRODUCTION

MR. BLOMQUIST: I'd like to welcome you to the Machine Tool Performance Models and Data Repository Workshop. This project is a collaboration between us and industry. Therefore, we do appreciate you coming. What we'd like to do is to have an actual working workshop, and get as much industrial input as much as possible. We, therefore, have presentations by Boeing, Livermore, Caterpillar, Automated Precision, Inc., Independent Quality Laboratories and others. Furthermore, we'd like to have an exchange of ideas and information.

MACHINE TOOL PERFORMANCE and MACHINE DATA REPOSITORY
PROJECT SUMMARY
A. Donmez

We at NIST are trying to develop machine tool performance models and a machine data repository. This is a part of our National Advanced Manufacturing Testbed (NAMT) Program at Manufacturing Engineering Laboratory (MEL) at NIST. The NAMT Program at MEL is an effort to develop new tools and to find new solutions to the standards and metrology issues raised by the information-based manufacturing.

The NAMT program started last year with four projects. The first one is the project that we're working on and we're going to be talking about today and tomorrow. It is the development of machine tool performance models and machine data repositories. The other three projects within this program are:

Characterization, simulation and remote access of parallel structured machine tools,
Frameworks for discrete part manufacturing, and finally,
Development and manufacture of atom-based standards.

In the very near future, there will be other projects initiated within the NAMT Program.

If distributed manufacturing is going to be the major thrust in the future, we have to have better coordination and resources for information-based manufacturing. In addition, prototyping and evaluation of the manufacturing capabilities are becoming major issues, therefore we must have some tools that are ready for the implementation of distributed manufacturing and reducing the time to market in prototyping efforts.

The problem with the current state-of-the-art in new product introductions and prototyping is that it is basically an iterative one. You start with a new part design, and then from that you start testing some of the processes and some of the machines in your plant in order to find out if you can make that part. If you cannot, then you go back and change your plans and change your machines until you find a satisfactory part that you can make with available resources that you have. Then you go through the inspection of this part and find out whether you can really inspect this part for the capability. You go through this iterative process until you fine tune your production and then start doing the actual parts. In general, this whole process takes somewhere between 2-3 years. We talked with major manufactures, like Boeing, Caterpillar (where we have representatives here) and their basic claim is that it's too expensive to go through this iterative process. We're looking for ways to decrease this time and decrease this cost, by taking some of this physical activity into the computer domain so that instead of cutting the part, we start with cutting bits, and then analyze all this information before we actually start the cutting.

In order to be able to do this type of activity, we need a lot of resources to enable us to carry out this whole prototyping effort in the computer domain. These resources include predictive machine and process models, reliable machine capability data, and accurate environmental and material specifications. How can we make sure that, when we simulate the operation in our computer models, we can get realistic parts out of that simulation? How can we represent the performance of the machine in a realistic form in our computers so that we can get that information out of that model? And how can we really incorporate the environmental information on our machine tools, our equipment, located in our factory environment, and how can we incorporate that information into our models and therefore into other parts? These are basic ideas that we are trying to get ourselves prepared to handle in our computer models. A big step, of course, in achieving this type of prototyping is going to be the repository that we will talk about today and tomorrow.

Last September we prepared a very limited demonstration, to see what we could do and what we would need in order to accomplish this virtual prototyping effort. We started with a Computer Aided Design (CAD) and a computer model of one of our machines. Based on the CAD design, we generated the realistic description of part geometry by calculating the actual tool path using the machine model. At the same time, we used our machine to make the actual parts and compare these parts with the calculated part geometry. One is the real part, the other is the virtual part. We also tried to identify what problems are associated with this type of implementation.

We used a commercial solid modeling package to describe the virtual part. However, we had to manipulate some functions of the package in order to show the actual shape of the part. Whiskers are plotted on top of the nominal geometry. We have the same thing corresponding to actual measurements, which are again superimposed on the nominal part geometry. Now, if you were to show a more realistic part, then we would have to have a lot of data points around this nominal geometry. That is becoming a problem because, to be able to even show this, we had to play a lot of tricks about defining new features for each of these whiskers. Likewise, to be able to show the positive and negative errors, we had to go through a lot of trouble. We would like the software developers to give us the tools to be able to represent these parts more realistically, not only the nominal parts, but the actual parts that would be coming out of the simulation like this.

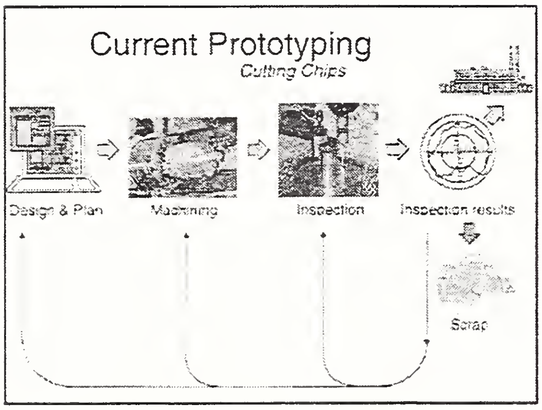
We have identified our challenges in order to be able to do this virtual prototyping effort. We definitely need virtual machining and inspection modules that can be implemented in existing CAD packages or new CAD packages. We need to have information models representing, comparing, and computing all this machine-related data. We also need distributed repositories allowing many people to access to this information for different purposes. We are now going to be concentrating on the repository and the information models. Eventually, we'll move onto these virtual machining and inspection modules in our project.

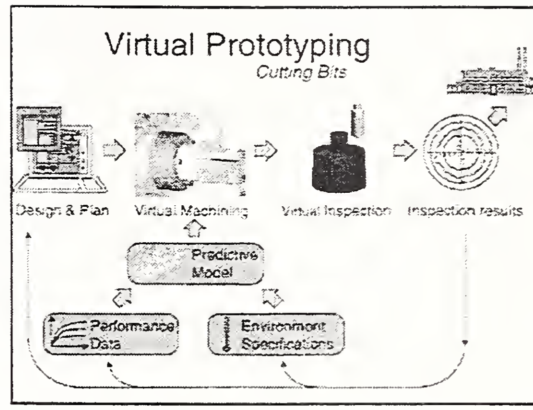
QUESTION: You mentioned the software package for solid modeling. Which package was that?

MR. DONMEZ: The machine model is implemented in ADAMS to do the kinematics of the machine, but the solid model itself is generated in Pro-E and transferred over to ADAMS. The parts themselves are all in Pro-E. The company that owns ADAMS is called Mechanical Dynamics and the company that owns Pro-E is called Parametric Technologies. These are just samples of software packages that you can use.

QUESTION: The last chart that you showed, before we asked the questions, you'd mentioned modules. Is each of these software packages related?

MR. DONMEZ: Yes. We're thinking about these as software packages that you could incorporate into existing CAD packages, for example. What we've done in this concept demonstration is to take ADAMS and we put some of the modeling that we used to do on these machines into this ADAMS model, but it was a very crude way of incorporating the models into these existing models. We want to have more capability, generic capability, to be able to put machine models, process models, into these CAD systems.


Current Prototyping
Cutting Chips
Design & Plan
Machining
Inspection
Inspection results
Scrap


Virtual Prototyping
Cutting Bits
Design & Plan
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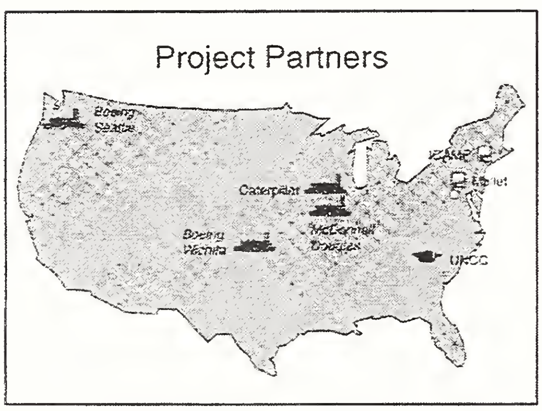
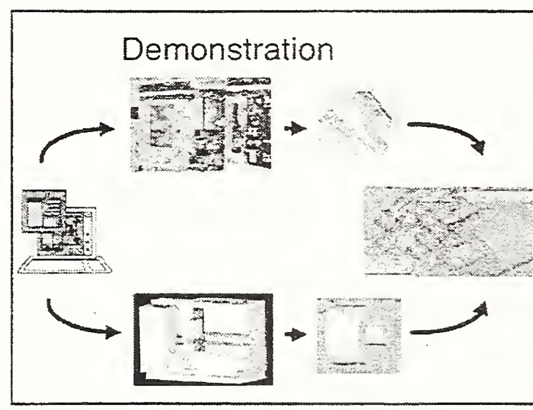
Predictive Model
Performance Data
Environment Specifications


Project Partners
Boeing Seattle
Caterpillar
Boeing Wichita
McDonnell Douglas
UNCC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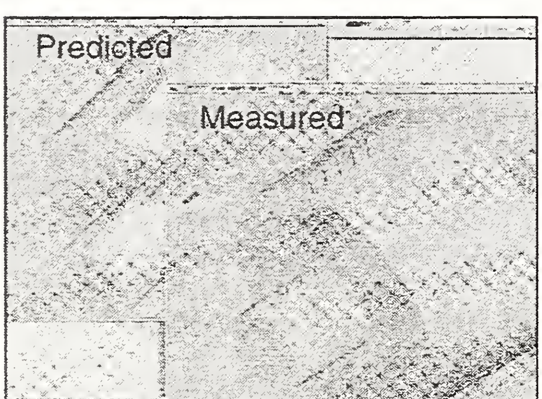
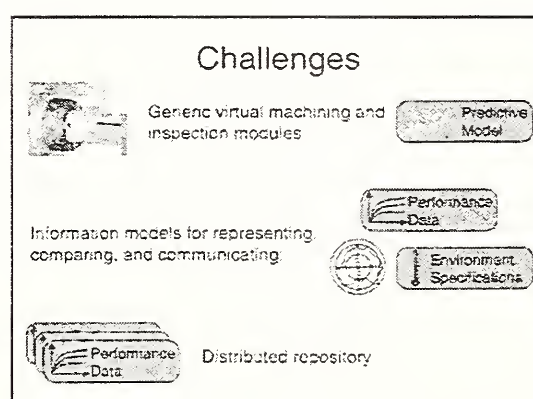

Predicted
Measured


Challenges
Generic virtual machining and inspection modules
Predictive Model
Performance Data
Information models for representing, comparing, and communicating
Environment Specifications
Performance Data
Distributed repository

REVIEW OF LAST WORKSHOP
A. Donmez

We had the first workshop in September 17, 1996, in Gaithersburg, MD. Its purpose was to identify what are the industry's needs and what we are expected to do. We wanted to establish if it would be necessary to get involved in these types of activities.

We had presentations by industry and academia. Industrial needs on machine selection capability, suppliers' capability, make-by decision tools, simulation tools, capacity planning and maintenance planning were all reiterated in that workshop.

We also look at academia as a partner in this type of program, and their needs. They want to have some collaboration tools in research and development of machine tools and manufacturing processes. They need tools to handle and share between multiple researchers, as well as large amounts of data on machine tools to generate and test machine tool models. By the introduction of the ANSI/ASME B5.54 and B5.57 standards, more and more people are measuring their machines and this data is becoming available. There are new measurement systems that are inexpensive to collect data on machine tools and, with that kind of environment, we need to have structured tools to be able to collect and analyze and identify some of the machine performance characteristics. In addition, of course, they want to have apples-to-apples kind of comparison between the different types of data-sets.

The consensus among and a basic conclusion made by the people who participated in that workshop based on one full day of discussions in September, was that NIST should be leading the effort to develop both structure and contents of a database to be eventually spun off to private enterprise. We were planning to work on these problems, but we want to be sure that we have the industry's support. With that kind of result, we felt much more comfortable to continue the work that we were planning to do.

Listed here are several comments from that workshop. One of them says, "Whatever the repository is, it should have some hierarchical nature." [In other words, some people will need a small amount of data, and some people will need more detailed data, more detailed models, so it has to be hierarchical or a layered structure.] If you want a few numbers just to represent your machine, you should not go into too much detail in this structure. The hierarchical nature will allow you to be able to pick the level of complexity of your data structures.

Participants of the workshop also stated that it should have a graphical representation capability along with the numerical information.

Another point was that we should use commercially available relational databases as much as possible, and that's also our philosophy in any development we do.

One other item of real concern was that there is a mechanism needed to weed out bad data. So many people are collecting a lot of data and, if we put all the data in the same repository, there has to be some way of finding out the bad data and to weed it out. That's a difficult issue and we need to discuss that later on today.

Further comments were made on the overall direction of the project. One of them was the indication that we need an industrial consensus about basic components--standards, simulation tools, software models--

and I think that's an important issue. Another related item is the need for cross-sectional representation by industry, which are automotive, machine tool builders, small shops. We were lacking representation of these industries. We have done some work in order to generate some interest in the part of the industry, but this is still an ongoing effort on our part.

Another issue that was emphasized is that private industry should develop the third party software tools. We have some software developers among us today to discuss that with us.

There were some further comments. There is a need to write a specification, devise prototypes, test prototypes and franchise our whole operation in real life. In order to accomplish these, we've been working since September to write some specifications, some data formats. We also worked on some prototypes that we'll show you along with the testing on them. Hopefully, we'll get some idea where we are going in the prototyping issue.

We should start coordinating with national and international standards. Our original schedule was that we would finish all the development and then go for standardization processes. But, a suggestion was to start thinking about standards early on so that they will be ready when we complete this stage of our work. Therefore, we started heading in that direction. And as you'll see in Simon Frechette's presentation on the EXPRESS models to be able to incorporate this type of activity within the STEP standard's framework.

Another item was to completely digitize the description of parts without drawings, and we are going to have some discussion on that. We need standardized simplistic models to produce data to characterize machines.
Those were some important comments that we heard at the last workshop, and we're going to try to address some of those comments today and tomorrow morning.

Industrial needs were reiterated:

- machine selection capability
- evaluate suppliers' capabilities
- make/buy decision tools
- simulation tools
- capacity planning
- maintenance planning

NIST APTD

Academic needs were reiterated:

- Tools for collaboration in research
- Tools to handle and share between multiple researchers lots of data on machine tools to generate and test basic models
- Enable "apples-to-apples" kind of comparison

NIST APTD

Consensus was

NIST should be leading to develop both structure and contents of database to be eventually spun off to private enterprise

NIST APTD

Comments on Repository

- Should be in hierarchical nature
- Should have graphical representation capability
- Should use commercially available relational databases as much as possible
- Need a mechanism to weed out bad data

NIST APTD

Further comments on project

- Need industrial consensus about basic components - standards, simulation tools, software models
- Need cross-sectional representation by industry - automotive, machine tool builders, small shops (NTMA)
- Private industry should develop third party software tools

NIST APTD

Comments (continued)

- Need to write a specification, devise prototypes, test prototypes and franchise the whole operation in real life
- Should start coordinating with National and International Standards early on
- Need completely digitized description of parts (without drawing)
- Standardize simplistic models, produce data to characterize machines

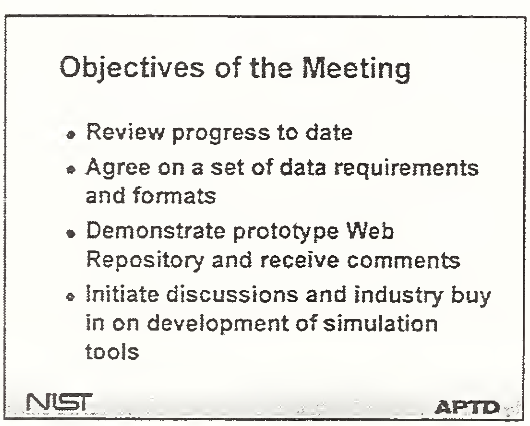
NIST APTD

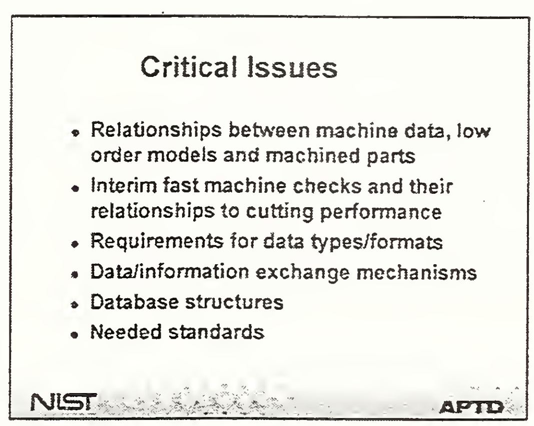
OBJECTIVES OF THIS MEETING
A. Donmez

Based on all this input that we had from our first workshop, we've worked on the definition of the data requirements and data formats among ourselves at NIST. We developed some documents that we will be going over. Also, we're going to show you the experimental Web repository that we developed based on these types of data formats. We'll show you what the problems are and what we can do with these types of Web repositories. In this meeting, we hope to come to some conclusion and agreement on the set of data requirements and formats [demonstrate the repository]. We hope to receive your comments on any modifications that may make it more useful, and we'd like to initiate some discussion on the simulation tools. I'm sure we're not going to be able to conclude the discussion on the simulation tools, but at least we should have some idea where we are going and what type of industrial development we need in order to satisfy our goals.

I'd like to also remind everybody the critical issues that we're trying to answer in this project. Eventually we need this relationship between the machine data and the machined parts. There is a lot of machine data available, and a lot of data on machined parts, but the correlation between the machine data and the machined parts is a significant problem that we need to resolve. We also need to resolve the issue of the interim fast machine checks and their relationship to cutting performance. We also have to allow our repositories to have information in it such as requirements, data types, and formats. I think that the main goal for this meeting is to address the critical issues of information exchange mechanisms, structures and standards.

Now, we're going to hear some industrial presentations to set the stage for the discussions in the afternoon. We have a presentation by Loyd Bishop from Boeing. He is going to talk about his efforts in machine characterization and Boeing's ideas of how to use these types of data. Debbie Krulewich, from Lawrence Livermore National Laboratory (LLNL), will talk about their efforts in machine modeling. Professor Steve Patterson, of the University of North Carolina at Charlotte (UNCC), is going to give us a little bit of his insight on what we need in these types of data repositories. Vivek Chandrasekharan, from Caterpillar, will talk about Caterpillar's activities. Quan Ma, from Automated Precision, Incorporated (API), will talk about a new instrumentation that they tried on machine tool metrology. Buzz Callaghan, from Independent Quality Labs (IQL), is going to talk about an overview of what we need for this type of repository.





INDUSTRY PRESENTATIONS

BOEING COMMERCIAL AIRPLANE GROUP
WICHITA DIVISION

L. Bishop

I have a lot of documented data on machines that I've been measuring since 1992. What you have in front of you is a sample of some of the work that I do on machine characterization. The machine we're looking at is one that I tested in January. It's an off-the-shelf machine which costs about $100,000. It's a very good machine, which we got with the intent of using its off-the-shelf controller first. Then, eventually, we are going to evaluate the new Hewlett-Packard open architecture controller on this machine as well as the Renishaw black box.

As we move into the world of increased production schedules and part acceptance of machine tools, I also know that the machine tools we buy today are much more accurate than they were 20 to 30 years ago. And most of them come with some type of probing system. So I've been working with Bruce Borchardt and Dr. Steve Phillips at NIST on some ways of doing some in-process metrology. Not only do I characterize the machine tool initially, but we would like to go out and do some in-process measurement. These evaluate the machining center as a measuring tool, so we don't have to take the part off and let it go into its relief state. I'd like us to focus on evaluating our machining centers as measuring devices also. I think we need to work on that a little bit.

The first test I performed on this machine was measuring diagonal displacements by laser interferometer. I like measuring diagonal displacements because they look at all the sources of error at one time. This is a 3-axis machine. The tolerances we use for tooling is ± 250 micrometers(10-thousandths) and for production parts, though it depends on the part, is usually ± 750 micrometers(30-thousandths).

I document everything. You'll see a sample of how I document everything in slide 6. As Jim Bryan and Jeff Portas pointed out several years ago, random results are the consequence of random procedures. I can duplicate these tests tomorrow, next year, and five years from now and hopefully, if I'm in a nice controlled environment, I'll get the same results. I put a mark on the first graph in slide 2 because I like to know how the errors propagate in the diagonals and how I can look at what's causing those errors. If you look at the other graphs, you're going to see the linear displacement errors along X axis are doing almost the same thing [slide 5.]

The next test I did was a drift test while I went home [slide 4.] Even though this isn't a production machine, I like to do drift tests. The average outside temperature on that morning when I came in was 15 degrees, so it was rather cold. The reason that I've got a shift in the data (around 6,000 seconds) is because, a few hours after I started this drift test, the power failed. The hydraulics went down with it causing the machine to settle down. So, I would assume that if the power had not gone down, it probably would have stayed and been rather sinusoidal within about 5 micrometers(2 ten-thousandths) for the duration of that drift test.

The data show on slide 8 is from an X axis incremental test and it's a drift test. I asked the machine to move the smallest increments that the controller is capable of moving. I asked the machine to go a total distance of one-thousandth of an inch and then return. So, those are one ten-thousandth steps. The machine has very little backlash seen as it discontinuates in the data as the direction of motion changes . What you see for a backlash in the X axis is right up at the top of it when it completely changes direction.

Slide 9 shows the X pitch test. If I put a mark on it, it will fall in line with the diagonals and the X axis error. So in some cases you see, I think pitch is coming into play as well as the X axis error on the machine.

Slide 11 shows the X axis yaw. All of the graphs are labeled down in the bottom right-hand corners. A lot of the noise in the data was due to vibration. The spikes right at the end, are due to the inertia when the machine is first starting up. Even though we weren't moving the machine fast, when it comes from no movement to some movement you can see a few spikes at the end. So, I would say I don't really see a problem with this machine when the bandwidth is 4 arc-seconds. Yet, you're mainly looking at about 1 or 2 arc-seconds in that machine for angular error.

Slide 13 shows the Z axis linear displacement errors. Slide 14 shows Z incremental tests results. You can note the same backlash that you see for the linear in Z apparent in this smallest increment test. For the Z Incremental Test, I asked the machine to do a one thousandth of an inch move out and back with one ten thousandth steps.

The Z axis yaw was rather minimal as shown in slide 16-- a bandwidth of 1 arc-second.

Slide 17 shows the Y axis linear displacement errors. They look rather nice, with the average reversal error being less than 2 ten-thousandths of an inch.

The Y axis incremental test [Slide 20] also looks very nice. These are out and back three times, telling the machine to move one ten-thousandths of an inch up to one thousandths back.

Slide 21 shows the Y axis pitch data and it's a very small number also--2 arc-seconds.

Slide 23 shows the Y axis yaw data, which is a small number, and I also see the same kinds of trends like I saw in my diagonal displacement data.

MR. DONMEZ: We need to look at the types of data that Loyd is presenting, as well as the types of plots and types of information that go along with the data. Those are the things that we need to discuss in the afternoon. Also, I'd like to emphasize that the unambiguous documentation of this data is very important.

MR. PATTERSON: A number of the plots you have displayed non-repeatability in the data. That non-repeatability can come either from the machine tool itself or from the measuring system. Two questions. Do you have an idea of which? And how do you document your understanding of that so that the spread is attributed to the right source?

MR. BISHOP: No, and no. I don't know where the error comes in, whether it's in my measuring system or whether the non-repeatability is in the machine. Since my tolerances are much larger than the spread of the data, I don't really care.

MR. CALLAGHAN: In your X axis yaw plot, you have that area where you have the data circled there.

When you present this information to somebody how do you explain that curve? Do you just hand them the graph and there is no question of the fact that we have that spike in there?

MR. BISHOP: The spike looks somewhat repeatable to me, and probably because of the initial move of the machine. That's what I try to explain to them. I would say, "Don't worry about that; that's a very nice machine."

MR. CALLAGHAN: The question really isn't raised then when somebody looks at that data set?

MR. BISHOP: Probably not, because that's a very good machine. If you look at that bandwidth, the number is actually exaggerated because you're looking at the most positive and the most negative extremes there.

MR. DONMEZ: If the machine was actually bad--let's assume your scale to be 10 times worse--how would you put information into your data to explain these things from the point of view of repositories?

MR. BISHOP: If my machine were 10 times that bad I'd call the mechanics in there and tell them to straighten it out. I mean, if it's angular error because that's going to creep into the picture everywhere. I don't know. I don't have a good answer.

MR. CALLAGHAN: One of the reasons why I'm raising this question is that the frequency content of this data is incredibly important. If you look at the frequency of that particular spike and say, "Okay, that frequency is associated with setup errors, and not necessarily the machine's," we could then, if you were going to put it in the repository or extract it say, "This is not important." This is what we do currently. We'll go in there, but before we present the data to somebody, the unwashed, we'll actually modify the data. We remove that spike, make a comment and say we have removed the setup errors from start and finish. Then we'll present the data but eliminate that question. Maybe we can discuss it later this afternoon because it was one of the issues I had with this data.

MR. BISHOP: I'd also like to point out that the people that are with me here, Jim Covington and Sue McMillan, they have a lot of data also. Jim goes out and runs periodic ballbars on a lot of our machines in Wichita to ensure that they haven't changed or that they haven't crashed the machine. So, if any of you are interested in how he does that, just talk to Jim.

MR. HEMMERLE: When you look at your data, you take an evaluation of a machine, are you comparing differences between evaluations? Say an evaluation in June, an evaluation in September. Are you subtracting or doing anything? Are you looking at it saying, "This is what I currently have," and adjust to it?

MR. BISHOP: That's a good question. This machine happens to be in a controlled environment, meaning there's not so much cyclical effect depending upon our four completely varying seasons in Kansas. It's also probably not being affected thermally like a lot of the machines are out in a hostile environment.

MR. HEMMERLE: I'm looking at accuracy deterioration tracking.

MR. BISHOP: It depends on what they're using the machine for. If we're doing a lot of hogging with titanium and then I see a lot of wear on the machine. I'm sure Jim sees deterioration when he runs his ballbar. In that case, that might be a good tool to use to monitor deterioration to raise the red flag and call maintenance in to change the roller packs, or whatever they may need to do.

Slide 1

BOEING COMMERCIAL AIRPLANE GROUP, WICHITA DIVISION

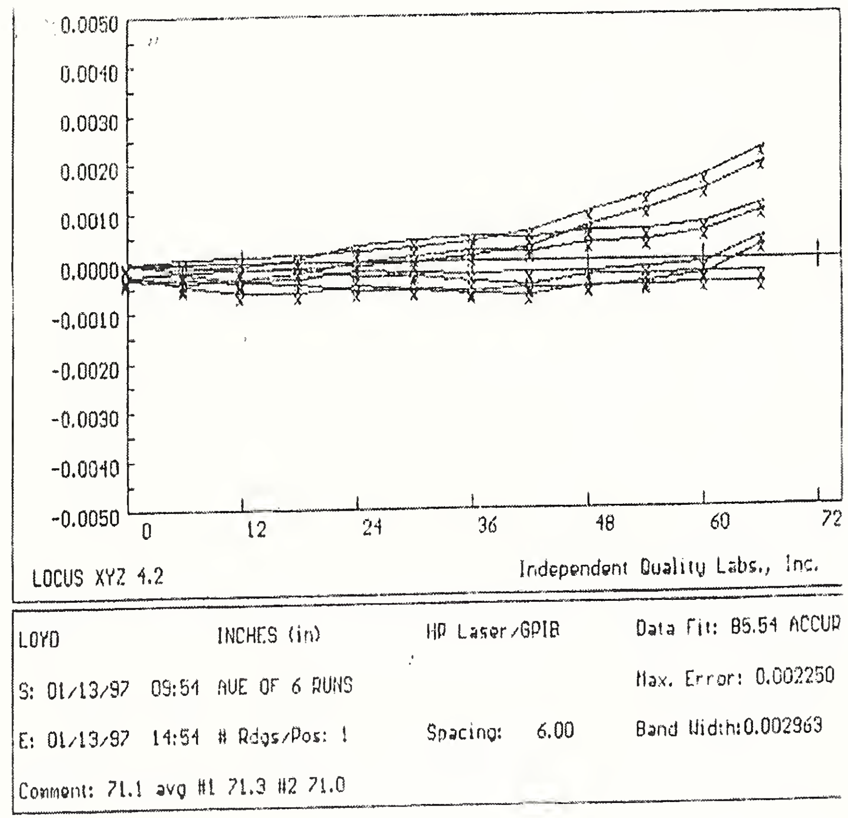
NIST MACHINE TOOL PERFORMANCE MODELS AND DATA REPOSITORY WORKSHOP

PRESENTED BY: LOYD BISHOP

FEBRUARY 18, 1997

NEW ORLEANS, LA

Slide 2



Slide 3

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E: 01/13/97 14:54	# Rdgs/Pos: 1	Spacing: 6.00	Band Width:0.002963

Comment: 71.1 avg #1 71.3 #2 71.0

1:3:1 LASER DIAGONAL xyz

DIRECTION - D1

POS	FWD ERROR	BWD ERROR
0.0	-0.00005	-0.00035
6.0	-0.00013	-0.00042
12.0	-0.00007	-0.00035
18.0	0.00007	-0.00024
24.0	0.00030	-0.00001
30.0	0.00040	0.00009
36.0	0.00049	0.00018
42.0	0.00044	0.00016
48.0	0.00059	0.00034
54.0	0.00059	0.00037
60.0	0.00075	0.00055
66.0	0.00114	0.00097

DIRECTION - D2

POS	FWD ERROR	BWD ERROR
0.0	-0.00004	-0.00030
6.0	-0.00006	-0.00034
12.0	-0.00015	-0.00042
18.0	-0.00016	-0.00046
24.0	-0.00031	-0.00060
30.0	-0.00037	-0.00059
36.0	-0.00042	-0.00068
42.0	-0.00047	-0.00071
48.0	-0.00030	-0.00052
54.0	-0.00031	-0.00053
60.0	-0.00029	-0.00050
66.0	-0.00026	-0.00047

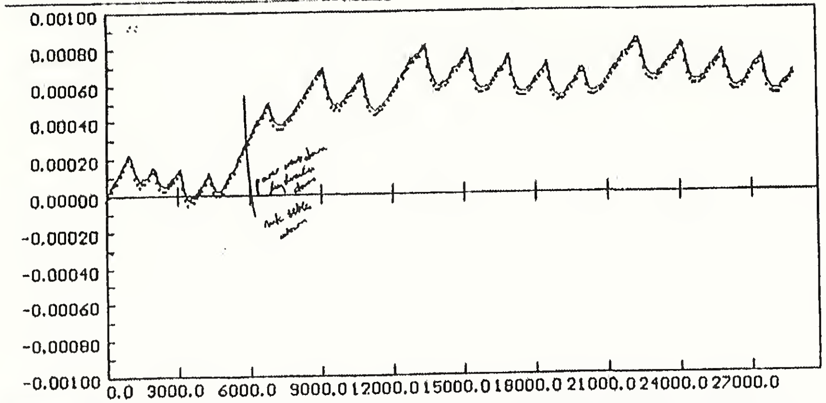
DIRECTION - D3

POS	FWD ERROR	BWD ERROR
0.0	0.00002	-0.00023
6.0	-0.00023	-0.00048
12.0	-0.00037	-0.00062
18.0	-0.00035	-0.00064
24.0	-0.00020	-0.00049
30.0	-0.00025	-0.00056
36.0	-0.00027	-0.00060
42.0	-0.00022	-0.00056
48.0	-0.00022	-0.00054
54.0	-0.00018	-0.00045
60.0	-0.00008	-0.00030
66.0	0.00044	0.00025

DIRECTION - D4

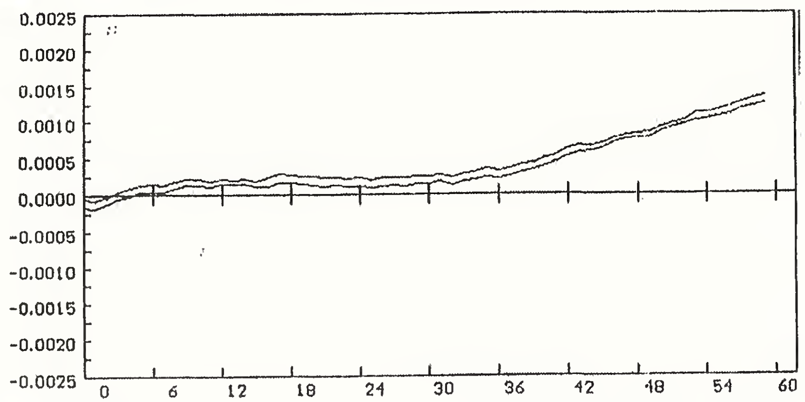
POS	FWD ERROR	BWD ERROR
0.0	-0.00001	-0.00026
6.0	0.00007	-0.00018
12.0	0.00010	-0.00015
18.0	0.00013	-0.00014
24.0	0.00019	-0.00008
30.0	0.00026	-0.00002
36.0	0.00038	0.00008
42.0	0.00058	0.00028
48.0	0.00099	0.00071
54.0	0.00130	0.00102
60.0	0.00170	0.00143
66.0	0.00225	0.00198

Slide 4



LOCUS XYZ 4.2 Independent Quality Labs., Inc.

LOYO	INCHES (in)	HP Laser/GPIB	Data Fit: LINEAR
S: 01/14/97 15:14	RUN # 1 OF 1		Max. Error: 0.000830
E: 01/15/97 07:19	# Rdgs/Pos: 1	Interval: 120.00	Band Width: 0.000860
Comment: 78.6 avg outside 15F			Time Unit: sec



LOCUS XYZ 4.2 Independent Quality Labs., Inc.

LOYO	INCHES (in)	HP Laser/GPIB	Data Fit: B5.54 ACC
S: 01/14/97 10:14	BOTH DIRECTIONS		Accuracy: 0.001533
E: 01/14/97 10:52	# Rdgs/Pos: 1	Spacing: 1.00	Max. R. Err: 0.000130
Comment: 75.2 avg #1 75.6 #2 74.9			Ave R. Err: 0.000094

1:3:1 LINEAR ACCURACY xlin

Slide 5

```
F1 Help                                    F10 CONFIRM  IQL
   1 |  0 | INSTR : LINEAR ACCURACY      xlin

        Laser on east end of machine on tripod.
        Temp probes on NW and SE corners of bed.
        Interferometer in spindle. Data begins
        at x -59.330 y -12.957 z -11.6

                                        01/30/97  11:30
```

```
F1 Help                                    F10 CONFIRM  IQL
   1 |  0 | INSTR : PITCH                xPIT

        Same as x linear: rotate spindle optic
        (interferometer) clockwise facing north
        to go 4.

                                        01/30/97  11:31
```

Slide 7

LOYD   INCHES (in)   HP Laser/GPIB   Data Fit: 85.54 AK

S: 01/14/97 10:14   BOTH DIRECTIONS   Accuracy: 0.00153

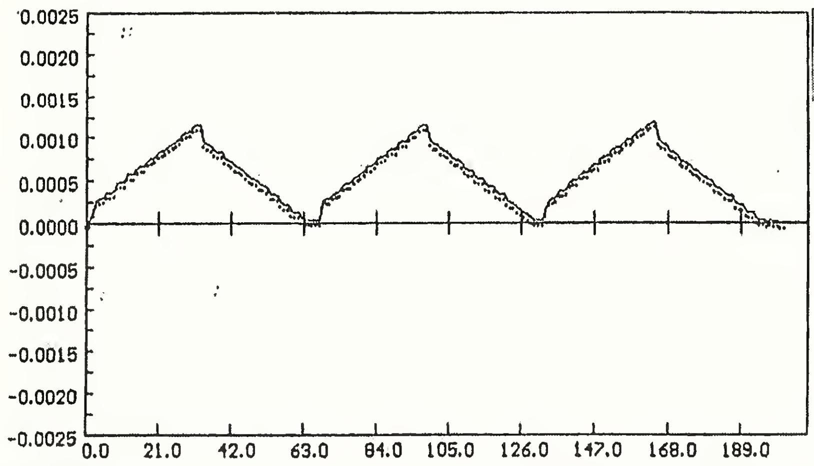
E: 01/14/97 10:52   # Rdgs/Pos: 1   Spacing: 1.00   Max. R. Err: 0.00

Comment: 75.2 avg #1 75.5 #2 74.9   Ave R. Err: 0.000

1:3:1   LINEAR ACCURACY xlin

POS	+A	-A
1	-0.00007	-0.00016
2	-0.00008	-0.00019
3	-0.00004	-0.00014
4	0.00003	-0.00007
5	0.00008	-0.00003
6	0.00012	0.00003
7	0.00013	0.00002
8	0.00012	0.00003
9	0.00017	0.00008
10	0.00020	0.00012
11	0.00020	0.00011
12	0.00017	0.00010
13	0.00020	0.00014
14	0.00019	0.00013
15	0.00020	0.00013
16	0.00017	0.00010
17	0.00023	0.00010
18	0.00028	0.00016
19	0.00026	0.00015
20	0.00024	0.00013
21	0.00024	0.00012
22	0.00022	0.00010
23	0.00023	0.00012
24	0.00021	0.00011
25	0.00022	0.00011
26	0.00020	0.00008
27	0.00023	0.00010
28	0.00025	0.00011
29	0.00027	0.00010
30	0.00025	0.00013
31	0.00024	0.00014
32	0.00026	0.00016
33	0.00023	0.00012
34	0.00028	0.00017
35	0.00030	0.00019
36	0.00035	0.00023
37	0.00032	0.00021
38	0.00035	0.00025
39	0.00040	0.00030
40	0.00042	0.00033
41	0.00050	0.00039
42	0.00053	0.00044
43	0.00062	0.00052
44	0.00065	0.00057
45	0.00066	0.00059
46	0.00069	0.00063
47	0.00076	0.00070
48	0.00080	0.00074
49	0.00082	0.00076
50	0.00084	0.00077
51	0.00091	0.00085
53	0.00101	0.00094
54	0.00110	0.00100
55	0.00110	0.00102
56	0.00114	0.00106
57	0.00119	0.00110
58	0.00125	0.00116
59	0.00130	0.00119
60	0.00135	0.00123

Slide 8



LOCUS XYZ 4.2 Independent Quality Labs., Inc.

.OYO INCHES (in) HP Laser/GPIB Data Fit: LINEAR

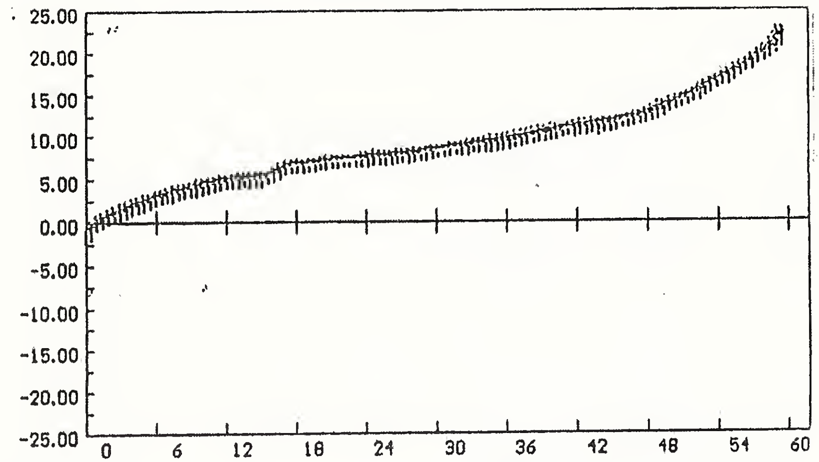
S: 01/14/97 10:59 RUN # 1 OF 1 Max. Error: 0.001170

E: 01/14/97 11:03 # Rdgs/Pos: 1 Interval: 1.00 Band Width: 0.001170

Comment: 75.2 avg nice test! Time Unit: sec

XINCREM 1:3:1 DRIFT TEST x

Slide 9



LOCUS XYZ 4.2 Independent Quality Labs., Inc.

LOYO ARC SEC HP Laser/GPIB Data Fit: ANGULAR

S: 01/14/97 11:33 ALL RUNS & AVG Max. Error: 22.2

E: 01/14/97 11:47 # Rdgs/Pos: 1 Spacing: 0.50 Band Width: 22.8

Comment: good data

1:3:1 PITCH xPIT

Slide 10

"LOYD — ARC SEC — HP Laser/GPIB — Data Fit: ANGULAR

"S: 01/14/97 11:33 — ALL RUNS & AVG — Max. Error: 22.2

"E: 01/14/97 11:47 — # Rdgs/Pos: 1 — Spacing: 0.50 — Band Width: 22.8

"Comment: good data

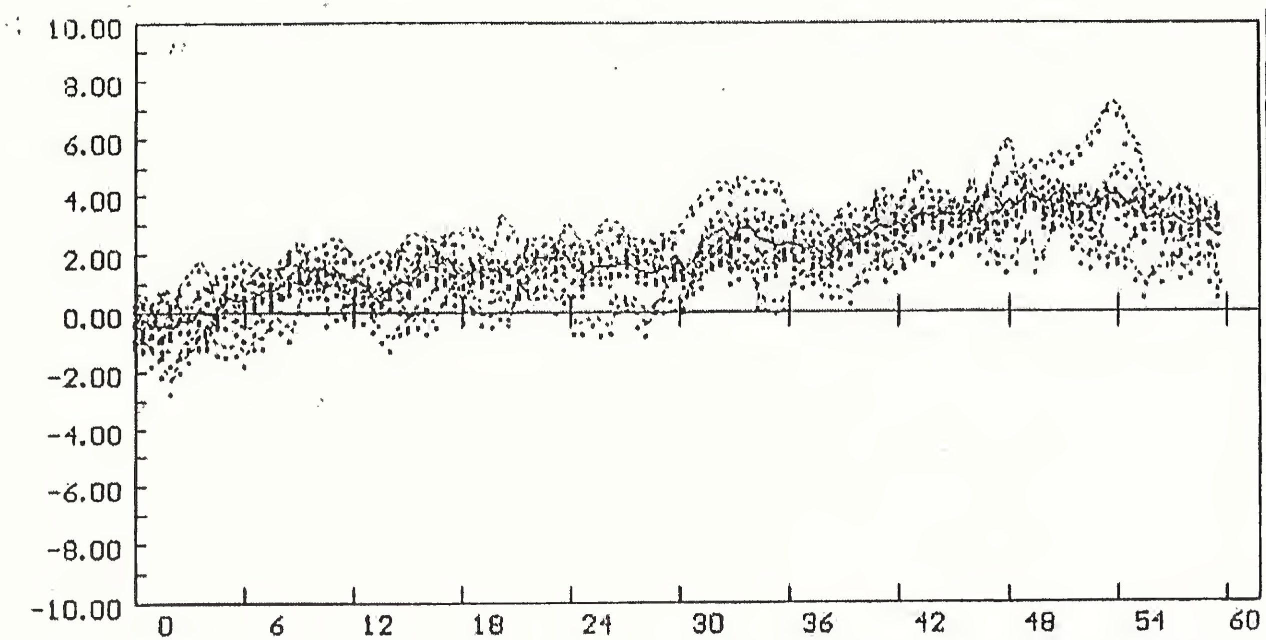
1:3:1 PITCH xPIT

DIRECTION – X"

LINE – 1"

"POS"	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN 6	AVG
1	0.00000	-0.20000	-1.00000	-0.80000	-0.10000	-1.30000	-0.56667
2	0.50000	-0.60000	-0.10000	-0.90000	0.20000	-0.20000	-0.18333
3	0.90000	0.60000	0.30000	0.10000	0.60000	0.30000	0.46667
4	1.20000	0.80000	0.50000	0.50000	0.50000	0.60000	0.68333
5	1.60000	1.20000	0.80000	0.80000	0.80000	1.00000	1.03333
6	2.00000	1.50000	1.10000	1.00000	1.20000	1.30000	1.35000
7	2.10000	1.70000	1.20000	1.50000	1.50000	1.60000	1.60000
8	2.40000	1.90000	1.70000	1.60000	1.80000	1.90000	1.88333
9	2.70000	2.40000	1.90000	1.80000	2.10000	2.10000	2.16667
10	2.90000	2.60000	2.20000	2.10000	2.40000	2.50000	2.45000
11	3.20000	2.70000	2.50000	2.30000	2.70000	2.60000	2.66667
12	3.30000	3.20000	2.70000	2.60000	2.70000	2.90000	2.90000
13	3.50000	3.30000	3.00000	2.90000	3.00000	3.20000	3.15000
14	3.80000	3.60000	3.20000	3.20000	3.30000	3.40000	3.41667
15	4.10000	3.80000	3.40000	3.30000	3.30000	3.50000	3.56667
16	4.20000	4.20000	3.80000	3.40000	3.60000	3.60000	3.80000
17	4.20000	4.20000	3.90000	3.60000	3.70000	3.80000	3.90000
18	4.40000	4.30000	3.90000	3.90000	3.80000	4.10000	4.06667
19	4.70000	4.50000	4.10000	4.40000	4.00000	4.30000	4.33333
20	4.90000	4.70000	4.30000	4.40000	4.10000	4.50000	4.48333
21	5.00000	5.00000	4.60000	4.60000	4.20000	4.70000	4.68333
22	5.20000	5.10000	4.70000	4.80000	4.40000	4.90000	4.85000
23	5.20000	5.30000	4.70000	4.90000	4.60000	4.90000	4.93333
24	5.30000	5.50000	4.90000	5.00000	4.70000	5.10000	5.05000
25	5.40000	5.30000	5.00000	5.00000	4.90000	5.20000	5.13333
26	5.30000	5.60000	5.00000	5.20000	5.00000	5.40000	5.25000
27	5.50000	5.70000	5.20000	5.40000	5.00000	5.50000	5.38333
28	5.40000	5.70000	5.40000	5.20000	5.20000	5.30000	5.36667
29	5.50000	5.70000	5.30000	5.40000	5.00000	5.30000	5.36667
30	5.50000	5.70000	5.30000	5.40000	5.10000	5.40000	5.40000
31	5.40000	5.60000	5.40000	5.50000	5.10000	5.40000	5.40000
32	5.80000	5.60000	5.80000	5.60000	5.40000	5.50000	5.61667
33	6.50000	5.70000	6.40000	5.70000	6.10000	5.80000	6.03333
34	7.00000	6.00000	6.60000	6.10000	6.40000	6.50000	6.43333
35	7.10000	6.70000	6.90000	6.60000	6.60000	6.80000	6.78333
36	7.10000	7.10000	7.00000	6.80000	6.90000	7.00000	6.98333
37	7.20000	7.10000	7.00000	6.70000	6.90000	6.90000	6.96667
38	7.10000	7.20000	7.00000	6.80000	6.90000	7.00000	7.00000
39	7.30000	7.30000	6.90000	6.90000	7.10000	7.00000	7.08333
40	7.40000	7.20000	7.00000	7.20000	7.00000	7.20000	7.16667
41	7.40000	7.30000	7.10000	7.20000	7.10000	7.10000	7.20000
42	7.70000	7.20000	7.30000	7.20000	7.20000	7.10000	7.28333
43	7.60000	7.50000	7.50000	7.30000	7.40000	7.20000	7.41667
44	7.60000	7.60000	7.40000	7.30000	7.30000	7.20000	7.40000
45	7.60000	7.60000	7.40000	7.40000	7.50000	7.40000	7.48333
46	7.70000	7.60000	7.40000	7.40000	7.50000	7.60000	7.53333
47	7.90000	7.70000	7.40000	7.50000	7.60000	7.60000	7.61667
48	8.00000	7.70000	7.50000	7.50000	7.80000	7.60000	7.68333
50	8.30000	7.90000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
51	8.20000	7.90000	7.70000	7.70000	8.10000	7.60000	7.86667
52	8.10000	8.00000	7.80000	7.70000	8.00000	7.60000	7.86667
53	8.30000	8.10000	7.80000	7.80000	8.20000	7.70000	7.98333
54	8.40000	8.20000	7.80000	7.90000	8.20000	7.90000	8.06667
55	8.40000	8.30000	7.80000	7.80000	8.20000	7.90000	8.06667
56	8.50000	8.30000	7.80000	8.00000	8.20000	8.00000	8.13333
57	8.50000	8.30000	8.00000	8.10000	8.40000	8.10000	8.23333
58	8.60000	8.50000	8.10000	8.20000	8.40000	8.10000	8.31667
59	8.80000	8.70000	8.20000	8.30000	8.60000	8.20000	8.46667
60	8.90000	8.70000	8.30000	8.40000	8.50000	8.30000	8.51667
61	8.80000	8.70000	8.50000	8.50000	8.60000	8.50000	8.60000
62	8.90000	8.70000	8.60000	8.60000	8.60000	8.50000	8.65000
63	9.10000	8.80000	8.80000	8.80000	8.80000	8.70000	8.83333
64	9.10000	8.70000	8.80000	8.80000	8.90000	8.80000	8.85000
65	9.30000	8.80000	8.80000	8.80000	9.00000	8.90000	8.93333
66	9.60000	8.80000	9.00000	9.00000	9.20000	9.20000	9.13333
67	9.50000	9.20000	9.00000	9.10000	9.40000	9.10000	9.21667
68	9.70000	9.20000	9.20000	9.10000	9.50000	9.30000	9.33333
69	9.90000	9.40000	9.10000	9.20000	9.60000	9.40000	9.43333
70	10.00000	9.40000	9.10000	9.20000	9.70000	9.50000	9.48333
71	10.00000	9.50000	9.40000	9.20000	9.70000	9.70000	9.58333
72	10.10000	9.60000	9.40000	9.30000	9.80000	9.70000	9.65000
73	10.40000	9.70000	9.50000	9.50000	9.90000	9.80000	9.80000
74	10.50000	9.80000	9.60000	9.60000	10.00000	9.90000	9.90000
75	10.60000	10.00000	9.80000	9.80000	10.10000	10.00000	10.05000
76	10.70000	10.20000	10.00000	10.00000	10.10000	10.30000	10.21667
77	11.00000	10.40000	10.20000	10.10000	10.30000	10.40000	10.40000
78	10.90000	10.50000	10.40000	10.30000	10.40000	10.60000	10.51667
79	11.20000	10.60000	10.60000	10.30000	10.50000	10.70000	10.65000
80	11.20000	10.80000	10.60000	10.50000	10.60000	10.90000	10.76667
81	11.10000	11.00000	10.80000	10.60000	10.80000	11.00000	10.88333
82	11.30000	11.00000	10.90000	10.90000	11.10000	11.00000	11.03333
83	11.40000	11.10000	11.00000	11.00000	11.30000	11.10000	11.15000
84	11.80000	11.10000	10.80000	11.20000	11.30000	11.40000	11.26667
85	11.70000	11.20000	11.00000	11.20000	11.40000	11.30000	11.30000
86	11.90000	11.40000	11.10000	11.50000	11.50000	11.50000	11.48333
87	11.90000	11.50000	11.20000	11.50000	11.60000	11.70000	11.56667
88	11.80000	11.70000	11.10000	11.60000	11.80000	11.80000	11.63333
89	11.80000	12.00000	11.40000	11.50000	11.80000	11.70000	11.70000
90	11.90000	12.00000	11.40000	11.70000	12.00000	12.00000	11.83333
91	12.10000	12.00000	11.60000	11.70000	11.90000	12.10000	11.90000
92	12.10000	12.10000	11.90000	12.00000	12.00000	12.40000	12.08333
93	12.50000	12.40000	12.00000	12.10000	12.20000	12.50000	12.20333
94	12.70000	12.40000	12.20000	12.30000	12.20000	12.60000	12.40000
95	12.90000	12.60000	12.40000	12.30000	12.50000	12.70000	12.56667
96	13.20000	13.00000	12.60000	12.50000	12.80000	13.00000	12.85000
97	13.70000	13.20000	13.00000	12.70000	13.00000	13.30000	13.15000
98	14.00000	13.50000	13.30000	12.90000	13.20000	13.50000	13.40000
99	14.10000	13.70000	13.60000	13.30000	13.60000	13.90000	13.70000
100	14.60000	13.90000	13.80000	13.70000	14.00000	14.20000	14.03333
101	14.70000	14.20000	14.20000	14.10000	14.30000	14.60000	14.35000
102	14.90000	14.70000	14.40000	14.30000	14.50000	14.80000	14.60000
103	15.20000	14.90000	14.60000	14.70000	14.90000	15.10000	14.90000
104	15.60000	15.30000	15.00000	15.10000	15.30000	15.50000	15.30000
105	16.30000	15.70000	15.40000	15.20000	15.70000	15.70000	15.66667
106	16.40000	16.00000	15.80000	15.70000	16.10000	16.20000	16.03333
107	16.80000	16.30000	16.10000	16.40000	16.50000	16.70000	16.46667
108	17.10000	16.80000	16.60000	16.80000	17.10000	16.90000	16.88333
109	17.50000	17.00000	17.00000	17.10000	17.40000	17.20000	17.20000
110	18.00000	17.30000	17.20000	17.30000	17.80000	17.70000	17.55000
111	18.50000	17.60000	17.60000	17.60000	18.10000	18.10000	17.91667
112	18.80000	18.10000	18.00000	18.00000	18.60000	18.60000	18.35000
113	19.20000	18.60000	18.60000	18.60000	19.00000	19.10000	18.85000
114	19.90000	18.80000	18.90000	19.20000	19.40000	19.70000	19.31667
116	20.90000	20.10000	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
117	21.60000	20.30000	20.50000	21.00000	21.00000	21.30000	20.95000
118	23.20000	20.70000	21.70000	21.50000	22.80000	21.90000	21.96667
119	22.40000	22.10000	21.50000	22.90000	22.70000	21.60000	22.20000

Slide 11



LOCUS XYZ 4.2 Independent Quality Labs., Inc.

LOYD		ARC SEC	HP Laser/GPIB		Data Fit: ANGULAR	
S: 01/14/97	12:41	ALL RUNS & AVG			Max. Error:	4.2
E: 01/14/97	12:54	# Rdgs/Pos: 1	Spacing:	0.50	Band Width:	4.7

Comment: good data, with some vibration

1:3:1 YAW xYAW

Slide 12

S: 01/14/97 12:41 ALL RUNS & AVG

E: 01/14/97 12:54 # Rdgs/Pos: 1 Spacing: 0.50 Band Width: 4.7

Comment: good data, with some vibration

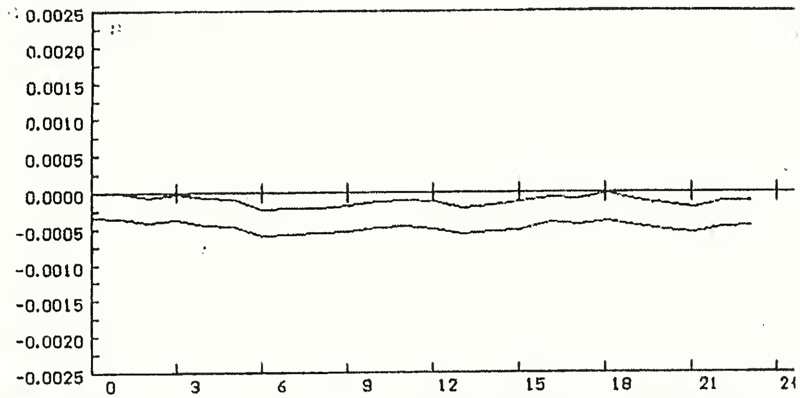
1:3:1 YAW xYAW

DIRECTION - X

LINE - 1

POS	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN 6	AVG
1	0.40000	-0.80000	-0.10000	0.60000	-0.60000	0.60000	0.01667
2	-0.60000	-1.00000	-0.90000	0.70000	-0.40000	0.10000	-0.35000
3	0.50000	-0.80000	-1.50000	-0.10000	-0.40000	-0.40000	-0.45000
4	0.80000	-1.20000	-1.80000	-1.00000	-0.60000	0.80000	-0.50000
5	0.60000	-1.30000	-2.40000	0.00000	0.30000	-0.30000	-0.55000
6	0.10000	-1.70000	-1.20000	1.00000	0.20000	-0.30000	-0.31667
7	-0.90000	-1.30000	-0.90000	1.40000	0.20000	-0.30000	-0.30000
8	-0.90000	-0.80000	-0.50000	1.80000	0.90000	0.00000	0.08333
9	-0.60000	-0.90000	-0.80000	1.20000	0.70000	-0.10000	-0.08333
10	0.20000	0.30000	-1.10000	-0.20000	1.40000	0.00000	0.10000
11	1.10000	0.90000	-1.20000	-0.20000	1.60000	0.40000	0.43333
12	1.00000	1.00000	-1.10000	-0.40000	1.60000	0.10000	0.36667
13	0.90000	1.20000	-1.50000	-0.60000	1.80000	0.70000	0.41667
14	1.50000	0.90000	-0.90000	-0.40000	1.40000	0.70000	0.53333
15	1.60000	0.90000	-0.90000	0.10000	1.30000	1.40000	0.73333
16	1.30000	0.60000	-0.20000	0.50000	1.40000	1.00000	0.76667
17	1.30000	0.40000	-0.30000	0.80000	1.60000	1.90000	0.95000
18	2.40000	1.00000	-0.60000	1.40000	1.60000	2.10000	1.30000
19	2.00000	1.20000	0.40000	1.40000	1.70000	2.50000	1.53333
20	2.90000	0.30000	1.40000	1.50000	2.20000	1.10000	1.40000
21	1.80000	1.50000	1.20000	1.60000	2.20000	0.90000	1.53333
22	1.70000	1.70000	-0.10000	1.40000	2.40000	0.80000	1.31667
23	2.10000	1.30000	0.10000	1.00000	2.60000	1.40000	1.41667
24	2.20000	1.30000	0.20000	0.20000	2.10000	0.60000	1.10000
25	1.60000	1.00000	0.40000	0.70000	1.50000	1.20000	1.06667
26	1.80000	1.10000	0.00000	0.70000	-0.70000	1.30000	0.93333
27	2.00000	0.70000	-0.30000	-0.30000	0.50000	0.40000	0.50000
28	2.10000	1.20000	-0.70000	0.30000	0.30000	0.30000	0.58333
29	1.90000	2.10000	-1.00000	0.80000	1.20000	0.50000	0.91667
30	2.30000	1.50000	-0.40000	2.30000	0.40000	0.30000	1.06667
31	1.60000	1.40000	-0.20000	2.80000	0.90000	-0.30000	1.03333
32	2.10000	1.50000	0.30000	2.60000	1.90000	-0.20000	1.36667
33	2.60000	1.70000	0.50000	2.50000	2.40000	-0.40000	1.55000
34	1.80000	2.10000	1.20000	2.40000	1.90000	-0.20000	1.53333
35	1.80000	1.50000	1.30000	2.70000	2.80000	0.70000	1.80000
36	1.60000	1.00000	0.60000	2.70000	1.60000	1.00000	1.41667
37	1.60000	0.50000	1.30000	2.60000	1.20000	0.00000	1.20000
38	2.00000	1.40000	1.80000	3.00000	0.50000	0.30000	1.50000
39	1.90000	1.40000	1.60000	2.30000	0.30000	-0.10000	1.23333
40	1.40000	1.80000	1.40000	2.10000	0.30000	-0.20000	1.13333
41	1.50000	1.70000	1.70000	3.40000	0.80000	0.10000	1.53333
42	1.80000	1.20000	1.70000	2.90000	0.10000	-0.10000	1.26667
43	1.50000	0.90000	1.80000	2.30000	0.80000	1.00000	1.38333
44	2.60000	1.40000	2.20000	2.10000	1.10000	0.40000	1.63333
45	2.40000	2.30000	2.40000	1.20000	1.80000	0.80000	1.81667
46	2.70000	2.70000	2.70000	1.60000	1.20000	0.90000	1.88333
47	2.20000	2.30000	1.90000	2.50000	1.50000	0.30000	1.78333
48	3.10000	1.10000	2.40000	2.40000	1.70000	0.70000	1.90000
51	2.40000	1.30000	1.80000	2.50000	1.30000	-0.10000	1.53333
52	2.20000	1.30000	2.10000	3.10000	1.30000	-0.50000	1.58333
53	2.00000	1.70000	2.30000	3.20000	0.70000	-0.40000	1.58333
54	1.70000	1.70000	7.80000	3.00000	0.30000	0.30000	1.63333
55	1.90000	2.10000	2.30000	2.50000	0.60000	0.40000	1.63333
56	2.10000	1.60000	2.30000	2.50000	0.30000	-0.20000	1.43333
57	1.60000	2.10000	2.50000	2.40000	0.00000	-0.50000	1.35000
58	1.50000	1.30000	2.30000	2.50000	0.50000	0.40000	1.38333
59	1.50000	2.60000	1.50000	2.80000	0.80000	0.30000	1.58333
60	2.00000	1.80000	1.50000	2.70000	1.60000	0.40000	1.66667
61	1.50000	0.50000	1.80000	3.10000	1.60000	0.30000	1.46667
62	1.00000	1.40000	1.70000	3.70000	1.70000	1.00000	1.75000
63	1.20000	2.60000	1.70000	4.10000	2.70000	2.00000	2.38333
64	1.80000	3.30000	2.30000	4.30000	1.90000	2.00000	2.60000
65	2.40000	3.50000	2.50000	4.60000	2.00000	2.10000	2.85000
66	2.30000	2.90000	2.40000	4.10000	1.80000	1.30000	2.46667
67	3.00000	3.40000	2.50000	4.70000	1.50000	1.90000	2.83333
68	3.30000	3.50000	2.30000	4.40000	1.80000	1.80000	2.85000
69	3.10000	3.50000	2.10000	4.50000	1.30000	0.50000	2.50000
70	3.20000	3.20000	1.50000	4.40000	1.60000	0.40000	2.38333
71	1.90000	3.30000	1.90000	4.50000	1.60000	0.30000	2.25000
72	2.50000	3.30000	2.10000	3.40000	2.20000	0.40000	2.31667
73	2.30000	2.90000	2.10000	3.10000	1.80000	1.30000	2.25000
74	2.10000	3.40000	2.40000	2.40000	1.20000	1.20000	2.11667
75	1.90000	3.40000	2.00000	2.80000	1.60000	1.30000	2.16667
76	2.20000	2.70000	1.50000	2.40000	1.70000	0.90000	1.90000
77	2.60000	2.90000	1.60000	2.30000	1.90000	0.80000	2.01667
78	2.70000	3.60000	1.80000	3.10000	2.30000	0.80000	2.38333
79	2.90000	3.60000	2.00000	2.30000	2.90000	0.60000	2.38333
80	3.00000	3.30000	2.70000	2.40000	2.50000	1.30000	2.53333
81	3.20000	3.60000	2.40000	2.60000	2.70000	1.40000	2.65000
82	4.20000	3.50000	1.80000	2.60000	3.50000	2.10000	2.95000
83	4.10000	3.30000	1.90000	2.40000	4.10000	1.40000	2.86667
84	3.70000	3.40000	2.50000	3.10000	3.60000	1.70000	3.00000
85	3.20000	4.30000	2.60000	2.60000	3.50000	1.80000	2.90000
86	[illegible]	4.90000	2.30000	3.10000	3.30000	2.10000	3.26667
87	4.30000	4.60000	2.20000	3.60000	3.40000	2.70000	3.38333
88	3.70000	3.90000	2.50000	3.40000	3.70000	2.00000	3.20000
89	[illegible]	4.70000	2.30000	3.40000	3.70000	3.10000	3.33332
90	3.50000	3.70000	2.30000	3.90000	3.50000	2.80000	3.28333
91	3.70000	[illegible]	2.60000	3.00000	3.80000	3.00000	3.26667
92	[illegible]	4.20000	2.80000	3.50000	3.70000	2.90000	3.55000
93	[illegible]	3.40000	2.80000	2.90000	3.80000	2.30000	3.00000
94	3.10000	4.30000	2.00000	2.70000	4.40000	3.10000	3.35000
95	[illegible]	3.00000	2.00000	3.00000	5.40000	3.80000	3.38333
96	3.40000	4.70000	1.70000	3.40000	6.00000	3.30000	3.75000
97	3.70000	4.80000	2.00000	3.80000	4.70000	2.80000	3.63333
98	3.80000	5.00000	2.80000	4.60000	4.00000	3.90000	4.01667
99	[illegible]	5.30000	1.70000	4.10000	3.90000	4.10000	3.85000
100	3.50000	4.90000	2.20000	4.20000	3.20000	4.30000	3.71667
101	3.60000	5.50000	3.10000	3.70000	3.80000	4.60000	3.96667
102	4.70000	5.30000	3.30000	4.40000	3.80000	3.90000	4.15000
103	3.70000	5.40000	2.50000	4.00000	3.40000	2.90000	3.65000
104	4.40000	5.70000	2.00000	2.90000	3.70000	3.30000	3.66667
105	3.70000	6.10000	1.60000	2.40000	3.10000	3.70000	3.46667
106	4.20000	6.50000	2.20000	2.60000	2.70000	4.10000	3.71667
107	4.50000	7.20000	2.20000	3.90000	1.90000	4.30000	4.00000
108	5.10000	7.10000	2.10000	3.50000	2.00000	4.10000	3.98333
109	4.90000	6.10000	1.80000	3.60000	2.10000	3.30000	3.63333
110	4.50000	5.90000	1.40000	4.70000	2.90000	3.60000	3.75000
111	3.70000	4.20000	0.80000	4.10000	2.70000	3.30000	3.16667
112	3.90000	4.40000	1.60000	3.60000	3.10000	3.60000	3.36667
113	3.80000	4.20000	1.30000	3.80000	3.40000	2.30000	3.13333
114	4.20000	4.10000	2.00000	4.10000	2.30000	3.10000	3.30000
117	2.90000	3.80000	2.00000	3.90000	3.30000	2.30000	3.03333
118	3.30000	3.20000	1.30000	3.50000	2.60000	2.30000	2.70000

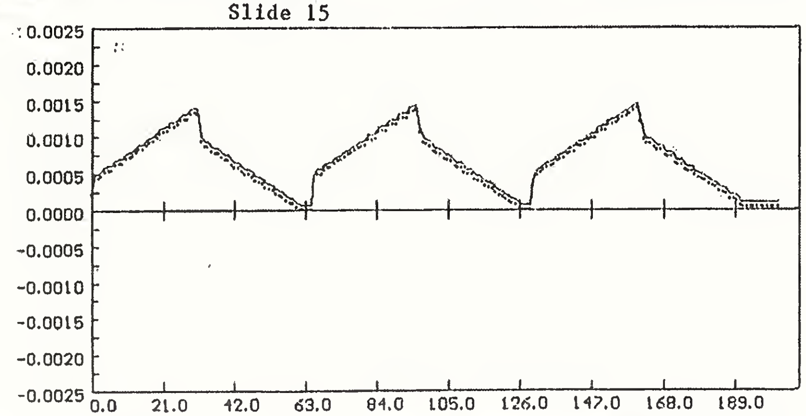
Slide 13



LOCUS XYZ 4.2 — Independent Quality Labs., Inc.

LOYD	INCHES (in)	HP Laser/GPIB	Data Fit: B5.54 ACC
S: 01/14/97 13:23	BOTH DIRECTIONS		Accuracy: 0.000600
E: 01/14/97 13:40	# Rdgs/Pos: 1	Spacing: 1.00	Max. R. Err: 0.000390
Comment: 75.2 avg #1 75.5 #2 74.96			Ave R. Err: 0.000360

Slide 15



LOCUS XYZ 4.2 — Independent Quality Labs., Inc.

LOYD	INCHES (in)	HP Laser/GPIB	Data Fit: LINEAR
S: 01/14/97 13:44	RUN # 1 OF 1		Max. Error: 0.001440
E: 01/14/97 13:49	# Rdgs/Pos: 1	Interval: 1.00	Band Width: 0.001380
Comment: good data, good test!			Time Unit: sec

UNIFORM 1:3:2 DRIFT TEST

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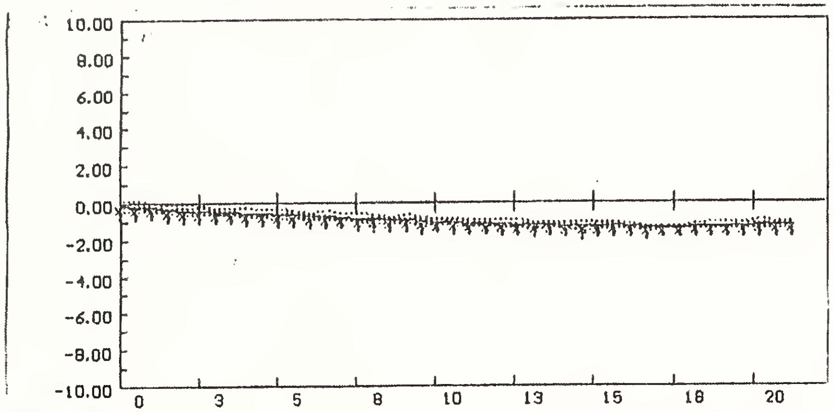
LOYD	INCHES (in)	HP Laser/GPIB	Data Fit: B5.54 ACC
S: 01/14/97 13:23	BOTH DIRECTIONS		Accuracy: 0.000600
E: 01/14/97 13:40	# Rdgs/Pos: 1	Spacing: 1.00	Max. R. Err: 0.00039
Comment: 75.2 avg #1 75.5 #2 74.96			Ave R. Err: 0.000360

1:3:1 LINEAR ACCURACY 11in

POS	A	A
1	-0.00001	-0.00035
2	-0.00001	-0.00037
3	-0.00007	-0.00043
4	-0.00003	-0.00039
5	-0.00008	-0.00045
6	-0.00010	-0.00048
7	-0.00024	-0.00061
8	-0.00025	-0.00059
9	-0.00022	-0.00057
10	-0.00019	-0.00054
11	-0.00013	-0.00049
12	-0.00011	-0.00048
13	-0.00014	-0.00051
14	-0.00022	-0.00059
15	-0.00019	-0.00055
16	-0.00013	-0.00052
17	-0.00008	-0.00043
18	-0.00009	-0.00045
19	-0.00003	-0.00040
20	-0.00011	-0.00048
21	-0.00017	-0.00053
[illegible]	[illegible]	[illegible]
23	-0.00014	-0.00049
24	-0.00014	-0.00047

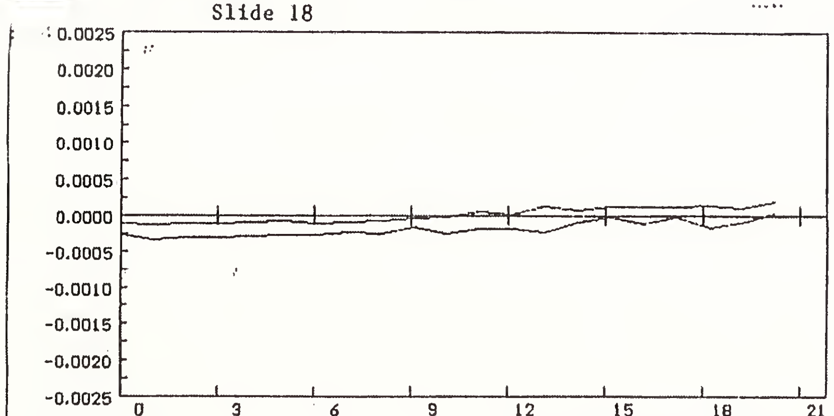
Slide 16



LOYD	ARC SEC	HP Laser/GPIB	Data Fit: ANGULAR
S: 01/14/97 14:45	ALL RUNS & AVG		Max. Error: -1.4
E: 01/14/97 14:49	# Rdgs/Pos: 1	Spacing: 0.50	Band Width: 1.2

Comment: good data

Slide 18



LOYD	INCHES (in)	HP Laser/GPIB	Data Fit: B5.54 ACC
S: 01/15/97 12:35	BOTH DIRECTIONS		Accuracy: 0.000547
E: 01/15/97 12:49	# Rdgs/Pos: 1	Spacing: 1.00	Max. R. Err: 0.000360
Comment: 77.5 avg #1 77.8 #2 77.15			Ave R. Err: 0.000198

1:3:1 LINEAR ACCURACY Ylin

Slide 17

LOYD	ARC SEC	HP Laser/GPIB	Data Fit: ANGULAR
S: 01/14/97 14:45	ALL RUNS & AVG		Max. Error: -1.4
E: 01/14/97 14:49	# Rdgs/Pos: 1	Spacing: 0.50	Band Width: 1.2

Comment: good data

1:3:1 YAW Zyaw

DIRECTION - X

LINE - 1

POS	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN 6	AVG
1	0.10000	-0.20000	-0.10000	-0.20000	-0.20000	-0.50000	-0.18333
2	0.10000	-0.30000	-0.20000	-0.30000	-0.30000	-0.50000	-0.25000
3	0.00000	-0.30000	-0.20000	-0.40000	-0.30000	-0.50000	-0.28333
4	-0.10000	-0.40000	-0.30000	-0.40000	-0.40000	-0.60000	-0.36667
5	-0.10000	-0.50000	-0.30000	-0.50000	-0.50000	-0.70000	-0.43333
6	-0.20000	-0.50000	-0.30000	-0.50000	-0.60000	-0.70000	-0.46667
7	-0.30000	-0.50000	-0.40000	-0.60000	-0.70000	-0.70000	-0.53333
8	-0.30000	-0.50000	-0.50000	-0.70000	-0.60000	-0.70000	-0.55000
9	-0.30000	-0.60000	-0.60000	-0.70000	-0.60000	-0.80000	-0.60000
10	-0.40000	-0.60000	-0.60000	-0.70000	-0.60000	-0.80000	-0.61667
11	-0.40000	-0.70000	-0.60000	-0.70000	-0.70000	-0.90000	-0.66667
12	-0.50000	-0.80000	-0.60000	-0.80000	-0.70000	-0.90000	-0.71667
13	-0.60000	-0.80000	-0.60000	-0.90000	-0.70000	-1.00000	-0.76667
14	-0.50000	-0.80000	-0.70000	-0.90000	-0.80000	-1.00000	-0.78333
15	-0.60000	-0.80000	-0.80000	-0.90000	-0.90000	-1.00000	-0.83333
16	-0.60000	-0.90000	-0.90000	-1.00000	-0.90000	-1.10000	-0.90000
17	-0.70000	-1.00000	-0.80000	-1.00000	-0.90000	-1.20000	-0.93333
18	-0.80000	-1.00000	-0.90000	-1.00000	-1.00000	-1.20000	-0.98333
19	-0.70000	-1.00000	-0.90000	-1.20000	-1.00000	-1.20000	-1.00000
20	-0.80000	-0.90000	-1.00000	-1.30000	-1.00000	-1.20000	-1.03333
21	-0.90000	-1.00000	-1.10000	-1.20000	-1.10000	-1.20000	-1.08333
22	-0.90000	-1.00000	-1.00000	-1.30000	-1.10000	-1.30000	-1.10000
23	-1.00000	-1.10000	-1.10000	-1.30000	-1.30000	-1.30000	-1.18333
24	-1.00000	-1.10000	-1.10000	-1.30000	-1.30000	-1.20000	-1.16667
25	-1.00000	-1.20000	-1.20000	-1.20000	-1.20000	-1.40000	-1.21667
26	-1.00000	-1.30000	-1.20000	-1.30000	-1.20000	-1.40000	-1.23333
27	-1.10000	-1.20000	-1.20000	-1.40000	-1.20000	-1.50000	-1.26667
28	-1.10000	-1.20000	-1.20000	-1.40000	-1.30000	-1.40000	-1.26667
29	-1.10000	-1.30000	-1.20000	-1.50000	-1.30000	-1.50000	-1.31667
30	-1.10000	-1.30000	-1.30000	-1.60000	-1.30000	-1.40000	-1.33333
31	-1.10000	-1.20000	-1.30000	-1.50000	-1.30000	-1.40000	-1.30000
32	-1.10000	-1.20000	-1.30000	-1.50000	-1.20000	-1.40000	-1.28333
33	-1.20000	-1.30000	-1.40000	-1.50000	-1.30000	-1.40000	-1.35000
34	-1.30000	-1.30000	-1.40000	-1.50000	-1.30000	-1.60000	-1.40000
35	-1.30000	-1.40000	-1.40000	-1.50000	-1.40000	-1.50000	-1.41667
36	-1.30000	-1.40000	-1.40000	-1.50000	-1.40000	-1.40000	-1.40000
37	-1.20000	-1.30000	-1.40000	-1.40000	-1.40000	-1.50000	-1.36667
38	-1.10000	-1.40000	-1.40000	-1.40000	-1.40000	-1.50000	-1.36667
39	-1.10000	-1.30000	-1.30000	-1.40000	-1.30000	-1.50000	-1.31667
40	-1.10000	-1.20000	-1.30000	-1.40000	-1.30000	-1.50000	-1.30000
41	-1.00000	-1.20000	-1.30000	-1.30000	-1.30000	-1.50000	-1.26667
42	-1.10000	-1.20000	-1.20000	-1.30000	-1.30000	-1.50000	-1.26667
43	-1.10000	-1.20000	-1.30000	-1.30000	-1.30000	-1.50000	-1.28333

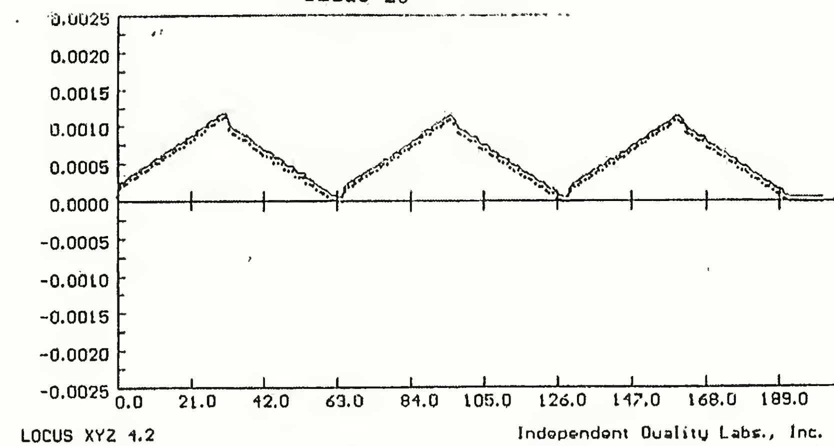
Slide 19

;;;; (tst ;;;; "LOYD	INCHES (in)	HP Laser/GPIB	Data Fit: 85.54 ACC
"S: 01/15/97 12:35	BOTH DIRECTIONS		Accuracy: 0.000547
"E: 01/15/97 17:49	# Rdgs/Pos: 1	Spacing: 1.00	Max. R. Err: 0.000360
"Comment: 77.5 avg #1 77.8 #2 77.15			Ave R. Err: 0.000198

1:3:1 LINEAR ACCURACY Y1in

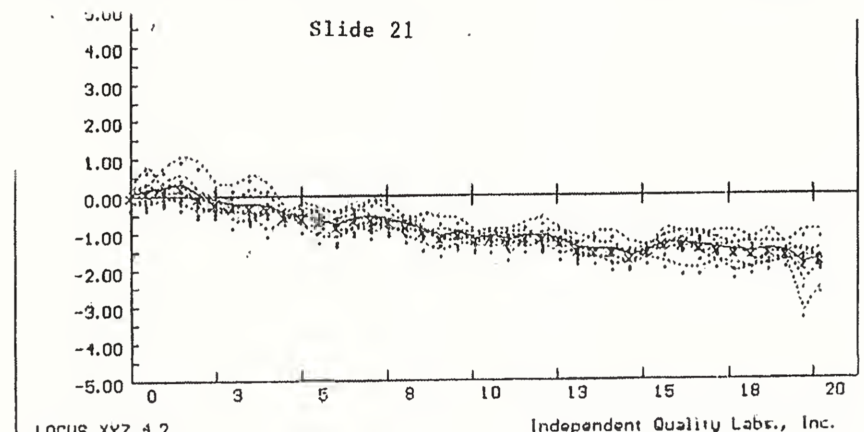
POS	+A	-A
1	-0.00011	-0.00027
2	-0.00013	-0.00035
3	-0.00011	-0.00032
4	-0.00012	-0.00032
5	-0.00010	-0.00030
6	-0.00008	-0.00028
7	-0.00011	-0.00027
8	-0.00009	-0.00024
9	-0.00007	-0.00025
10	[illegible]	-0.00017
11	-0.00003	-0.00025
12	[illegible]	-0.00010
13	0.00001	-0.00019
14	0.00011	-0.00025
15	0.00006	-0.00010
16	0.00012	-0.00003
17	0.00011	-0.00011
18	[illegible]	-0.00002
19	0.00013	-0.00018
20	[illegible]	-0.00009
21	0.00012	0.00003

Slide 20



LOYO	INCHES (in)	HP Laser/GPIB	Data Fit: LINEAR
S: 01/15/97 13:01	RUN # 1 OF 1		Max. Error: 0.001170
E: 01/15/97 13:06	# Rdgs/Pos: 1	Interval: 1.00	Band Width: 0.001130
Comment: good data good test! Zeroed			Time Unit: sec

Slide 21



LOYO	ARC SEC	HP Laser/GPIB	Data Fit: ANGULAR
S: 01/15/97 13:18	ALL RUNS @ AVG		Max. Error: -1.9
E: 01/15/97 13:24	# Rdgs/Pos: 1	Spacing: 0.50	Band Width: 2.2
Comment: good data			

1:3:1 PITCH Ypit

Slide 22

LOYD

S: 01/15/97 13:18 ALL RUNS & AVG Max. Error: -1.9

E: 01/15/97 13:24 # Rdgs/Pos: 1 Spacing: 0.50 Band Width: 2.2

Comment: good data

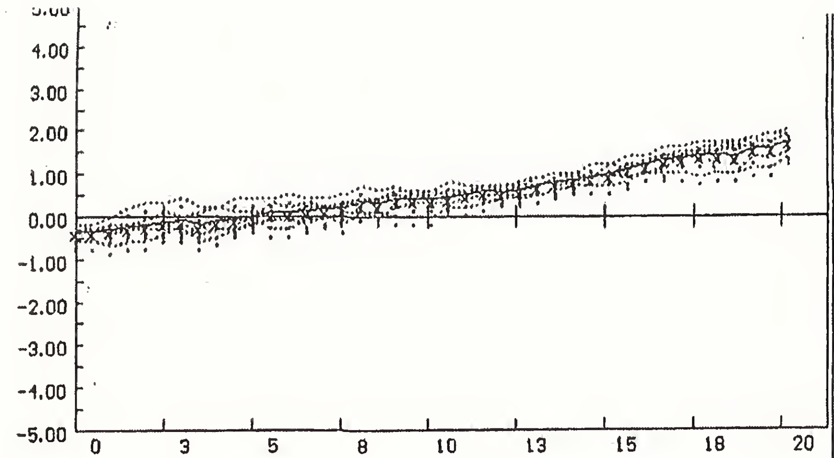
1:3:1 PITCH Ypit

DIRECTION - X"

LINE - 1"

POS	RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	RUN 6	AVG
1	0.10000	-0.20000	0.20000	0.20000	-0.20000	0.30000	0.06667
2	0.30000	-0.10000	-0.20000	0.30000	-0.20000	0.80000	0.15000
3	0.80000	0.30000	0.40000	0.00000	-0.10000	0.10000	0.25000
4	1.10000	0.30000	0.60000	-0.20000	0.00000	0.10000	0.31667
5	0.90000	-0.30000	0.10000	-0.40000	-0.10000	-0.10000	0.01667
6	0.30000	-0.40000	0.00000	-0.30000	-0.20000	-0.10000	-0.11667
7	0.30000	-0.40000	-0.10000	-0.40000	-0.20000	-0.70000	-0.25000
8	0.60000	-0.50000	0.20000	-0.50000	-0.60000	-0.60000	-0.23333
9	0.30000	-0.30000	0.00000	-0.40000	-0.90000	-0.40000	-0.28333
10	-0.40000	-0.60000	-0.50000	-0.40000	-0.60000	-0.50000	-0.50000
11	-0.20000	-0.30000	-0.50000	-0.80000	-0.50000	-0.80000	-0.51667
12	-0.30000	-0.50000	-0.40000	-1.10000	-0.80000	-0.80000	-0.65000
13	-0.50000	-0.90000	-0.40000	-1.10000	-1.20000	-0.60000	-0.78333
14	-0.30000	-0.90000	-0.20000	-0.80000	-0.80000	-0.50000	-0.58333
15	0.10000	[illegible]	-0.60000	-0.70000	-1.00000	-0.10000	-0.55000
16	-0.20000	-0.70000	-0.70000	-0.90000	-0.80000	-0.50000	-0.63333
17	-0.70000	-0.50000	-0.70000	-0.90000	-1.10000	-0.70000	-0.76667
18	-0.50000	-0.90000	-1.00000	-1.00000	-1.30000	-0.90000	-0.93333
19	[illegible]	-1.20000	-0.90000	-1.20000	-1.50000	-1.20000	-1.10000
20	-0.60000	-1.20000	-1.00000	-1.00000	-1.30000	-0.90000	-1.00000
21	-1.00000	-1.10000	-1.00000	-1.20000	-1.30000	-1.40000	-1.16667
22	-0.90000	-1.00000	-0.90000	-1.20000	-1.10000	-1.40000	-1.08333
23	[illegible]	-1.10000	-1.60000	-1.30000	-1.00000	-1.30000	-1.20000
24	-0.70000	-1.10000	-1.20000	-1.20000	-1.00000	-1.40000	-1.10000
25	-0.80000	[illegible]	-1.00000	-1.00000	-1.20000	-1.30000	-1.08333
26	-1.00000	-1.60000	-1.00000	-1.40000	-1.20000	-1.20000	-1.23333
27	-1.40000	-1.50000	-1.10000	-1.70000	-1.60000	-1.40000	-1.45000
28	-1.00000	-1.50000	-1.30000	-1.70000	-1.70000	-1.70000	-1.48333
29	-1.00000	-1.50000	-1.30000	-1.70000	-1.50000	-1.90000	-1.48333
30	-1.30000	-1.60000	-1.90000	-1.90000	-1.60000	-1.80000	-1.68333
31	-1.40000	-1.30000	-1.40000	-1.70000	-1.70000	-1.50000	-1.50000
32	-0.90000	-1.30000	-1.10000	-1.90000	-1.30000	-1.50000	-1.31667
33	-1.00000	-1.20000	-1.00000	-2.00000	-1.30000	-1.40000	-1.31667
34	-1.10000	-1.60000	-1.00000	-2.00000	-1.00000	-1.60000	-1.38333
35	-1.00000	-1.50000	-1.40000	-1.80000	-1.20000	-1.80000	-1.45000
36	-1.00000	-1.30000	-1.40000	-1.70000	-1.40000	-2.10000	-1.51667
37	-1.20000	-1.30000	-1.80000	-2.00000	-1.20000	-2.00000	-1.58333
38	-0.90000	-1.30000	-1.70000	-1.60000	-1.60000	-1.90000	-1.50000
39	-1.40000	-1.20000	-1.80000	-1.60000	-1.60000	-1.80000	-1.58333
40	-1.60000	-1.00000	-3.20000	-1.50000	-2.40000	-1.70000	-1.90000
41	-1.50000	-1.00000	-2.50000	-1.80000	-1.90000	-1.70000	-1.73333

Slide 23



LOCUS XYZ 4.2 Independent Quality Labs., Inc.

LOYD	ARC SEC	HP Laser/GPIB	Data Fit: ANGULAR
S: 01/15/97 13:31	ALL RUNS & AVG		Max. Error: 1.7
E: 01/15/97 13:36	# Rdgs/Pos: 1	Spacing: 0.50	Band Width: 2.1

Comment: good data

1:3:1 YAW Yyaw

Slide 24

"LOYO		ARC SEC	HP Laser/GPIB	Data Fit: ANGULAR
"S: 01/15/97	13:31	ALL RUNS & AVG		Max. Error: 1.7
"E: 01/15/97	13:36	# Rdgs/Pos: 1	Spacing: 0.50	Band Width: 2.1

"Comment: good data

1:3:1 YAW Yyaw

DIRECTION - X"

LINE - 1"

"POS""	RUN 1 ""	RUN 2 ""	RUN 3 ""	RUN 4 ""	RUN 5 ""	RUN 6 ""	AVG "
1	-0.20000	-0.20000	-0.30000	-0.40000	-0.30000	-0.60000	-0.33333
2	-0.20000	-0.30000	-0.30000	-0.30000	-0.30000	-0.60000	-0.33333
3	0.00000	-0.30000	-0.20000	-0.40000	-0.30000	-0.70000	-0.31667
4	0.20000	-0.30000	-0.20000	-0.30000	-0.30000	-0.60000	-0.25000
5	0.30000	-0.20000	-0.10000	-0.30000	-0.20000	-0.60000	-0.18333
6	0.30000	-0.20000	0.10000	-0.30000	-0.20000	-0.40000	-0.11667
7	0.40000	-0.40000	0.00000	-0.30000	-0.10000	-0.20000	-0.10000
8	0.20000	-0.30000	0.10000	-0.60000	-0.20000	-0.40000	-0.20000
9	0.20000	-0.10000	0.20000	-0.50000	-0.10000	-0.30000	-0.10000
10	0.40000	-0.20000	0.10000	-0.30000	-0.10000	-0.30000	-0.06667
11	0.40000	0.00000	0.10000	-0.20000	-0.10000	-0.10000	0.01667
12	0.40000	0.30000	0.10000	-0.10000	0.10000	-0.30000	0.08333
13	0.50000	0.20000	0.10000	-0.10000	0.10000	-0.30000	0.08333
14	0.40000	0.30000	0.20000	-0.20000	0.20000	-0.10000	0.13333
15	0.40000	0.20000	0.20000	0.00000	0.20000	-0.10000	0.15000
16	0.50000	0.20000	0.30000	-0.20000	0.30000	0.10000	0.20000
17	0.70000	0.40000	0.30000	0.10000	0.40000	0.10000	0.33333
18	0.60000	0.40000	0.40000	0.10000	0.30000	0.00000	0.30000
19	0.70000	0.50000	0.60000	0.00000	0.40000	0.20000	0.40000
20	0.50000	0.50000	0.60000	0.00000	0.50000	0.30000	0.40000
21	0.40000	0.60000	0.60000	0.00000	0.50000	0.30000	0.40000
22	0.40000	0.80000	0.50000	0.20000	0.60000	0.30000	0.46667
23	0.60000	0.70000	0.60000	0.20000	0.60000	0.40000	0.51667
24	0.70000	0.70000	0.70000	0.30000	0.60000	0.50000	0.58333
25	0.70000	0.60000	0.60000	0.40000	0.60000	0.50000	0.56667
26	0.80000	0.80000	0.70000	0.40000	0.60000	0.50000	0.63333
27	0.90000	0.90000	0.90000	0.50000	0.70000	0.50000	0.73333
28	0.70000	1.00000	1.00000	0.60000	0.90000	0.60000	0.80000
29	0.80000	1.00000	1.00000	0.70000	0.90000	0.70000	0.85000
30	0.90000	1.20000	0.90000	0.70000	0.90000	0.90000	0.91667
31	1.20000	1.20000	0.90000	0.70000	1.00000	0.90000	0.98333
32	1.40000	1.10000	1.10000	0.80000	1.20000	0.90000	1.08333
33	1.40000	1.30000	1.30000	1.00000	1.20000	1.00000	1.20000
34	1.60000	1.40000	1.40000	1.10000	1.40000	1.00000	1.31667
35	1.60000	1.40000	1.50000	1.40000	1.30000	1.00000	1.36667
36	1.70000	1.30000	1.50000	1.60000	1.50000	0.90000	1.41667
37	1.70000	1.70000	1.00000	1.60000	1.50000	1.00000	1.41667
38	1.70000	1.60000	1.00000	1.50000	1.60000	1.00000	1.40000
39	1.80000	1.80000	1.10000	1.70000	1.60000	1.40000	1.56667
40	1.90000	1.90000	1.10000	1.70000	1.60000	1.30000	1.58333
41	2.00000	1.90000	1.40000	1.90000	1.70000	1.50000	1.73333

LAWRENCE LIVERMORE NATIONAL LABORATORY
D. Krulewich

I know probably about half of the people here, so let me introduce myself. I used to work in the Machine Tool Development Group at Lawrence Livermore, which has recently been renamed the Precision Systems and Manufacturing Group. I've been in the group for about 5 years. We do a lot of machine characterization, driven differently than in industry, since we're not as concerned with high volume production and our precision requirements are higher.

I have two view graphs to show you. The first view-graph shows types of projects that deal with machine tool performance evaluation. First, we are involved with general machine testing, which we do well. When a new machine arrives at LLNL, we do a full characterization per B5.54 standard. Unfortunately, we're probably not as good at regularly maintaining our machines as we should be, or as we have been in the past. Instead, if a machine is having a problem, the machinists in our group would perform specific tests for diagnostic purposes.

I am involved in a couple of projects, including error compensation. For error compensation we are concerned with characterizing the machine so that we can remove the repeatable errors in the machine controller. We've done error compensation in the past using the conventional approach, which measures all of the separate 21 parametric errors for a 3-axis machine tool and then combines them to obtain the tool point error with respect to the workpiece. Don Carter did this on a DEA coordinate measuring machine. We are spending more effort to develop rapid methods of evaluating the machines. Our goal is to map all the machine errors in under 4 hours. This is an industry-driven requirement.

I've done a little bit of work in thermal error compensation. Thermal error compensation will relate the machine errors to discrete temperature measurements on the machine. In real-time, the machine controller must read these temperatures, determine the error, and then remove this error. We have some good ideas and I've done a little bit of work on the thermal growth of a spindle on a test stand.

The third area that I am involved with could benefit a great deal from the success of this meeting. The goal of this project is to develop a continuous spatial-frequency domain error budget. [The conventional Bob Donaldson Error Budget breaks the errors into different spatial-frequency bins]. Examples of this being form, waviness, and surface finish. This effort is driven by projects at Livermore that are now setting tolerances on the final part as a continuous power spectral density, such as the optics industry. The goal of this project is to develop a continuous spatial-frequency domain error budget where each machine component error and the errors due to cutting forces will be presented in the frequency domain. This error budget, similar to the Bob Donaldson Error Budget, can be used to set component tolerances during the design of a new machine tool to meet the end performance specifications. It can also be used to select the appropriate machine tool for a part and to provide information to the part designer to intelligently set tolerances. For example, I have recently been working on a BMDO project for the machining of optics for the space-based laser. In this project large silicon optics are diamond turned. There are dead zones on the optic where errors will not affect the functional performance, so we don't really care if there is a lobe pattern on the optic at the dead zone. We can possibly use the frequency domain error budget as a design tool and as an intelligent guide to setting the tolerances.

The last LLNL project that relates to the topic of this meeting is the development cutting models. There are two projects that our group has recently been involved with. The first was actually a summer student's project on the effect of imbalance on the grinding wheel. His goal was to determine what the resulting errors would be on a part given an imbalance on the grinding wheel, and he considered the trade-off between imbalance and run-out on the grinding wheel.

The second was also on the diamond turning of BMDO silicon optics. We needed to determine how to set the machining parameters for the silicon optics to optimize surface finish, sub-surface damage, and tool wear. We have a silicon machining workshop in March where this will be talked about more. We did a full parameter assessment using experimental design techniques to optimize the diamond turning process and to determine which parameters were significant and which ones weren't. The results were very beneficial because high velocity and high feed rate actually produced the best tool wear and the best sub-surface damage.

I think the data base can also address how to store cutting models. We ended up doing a lot of work that could have been avoided if previous results were available. We began this project with literature searches before we ended up doing this parameter assessment that helped us set the ranges for our parameter study. However, the literature did not supply us with enough information.

I also wanted to make a side comment on how to deal with errors in the measurements. There may be certain types of errors such as an outlier that your software can find, but I think it needs some intelligence. We still need human involvement in all of this. As an example, on the diamond turning experiment that we did, one of our performance evaluators was surface finish. The machinist gave me the data. After spending a significant amount of time studying the data, it didn't make any sense. I started looking more carefully at the data and found that there was an overlaying lower frequency error that we were picking up in our surface finish data that was specific to this machine. We think it was caused by the on-off of the coolant for the spindle. Since this error was machine dependent, it wasn't the measurement that we really wanted. So my point is that, the real information may be buried in noise and I think that there still needs to be some human intelligence involved.

I wrote down a couple issues that we've encountered that I think are going to be big issues. The first is data acquisition, which came up before, using the IQL software. Also, I wanted to mention we have tons of data. If you are interested in looking at different forms of the data, we have used IQL software, but right now we have Lab-View programs we run on the Macintosh with user-friendly interfaces for all of the B5.54 tests, ballbar, laser and levels, etc.

Some important issues that have not been addressed by the B5.54 or the axis of the rotation standards include sampling rate and filtering. Once you start taking digital data, you're going to have an alias if you don't filter samples at the correct rates. At the last American Society for Precision Engineering (ASPE) meeting I heard that the committee was planning on rewriting the axis of rotation standard to include frequency domain analysis. I think that there are a lot of important issues to address, especially with analog filtering and sampling . We often don't give these issues enough thought and probably do it wrong.

The next issue, sign convention, is extremely confusing. If the measurements are just for machine diagnostics, the sign convention probably doesn't matter as much. But for error compensation, when combining the parametric errors to build the volumetric error model, the sign convention is very important and it's also very confusing. The first time I was involved in taking all this data was on a

CRADA with Cincinnati Milacron. It took us probably a month to get the data, but I still made the machinist go back and take more data because the sign convention was not clear. The biggest confusion arises when your part is on a moving axis. The confusion stems from whether you're defining the sign convention from a stationary point that watches both the part and the tool, or if the coordinate system is attached to the part and watches the tool. Bob Hocken does error compensation using a stationary coordinate system. He looks at the positions of the part and the tool in a stationary coordinate system, and then subtracts the two to find the error of the tool point with respect to work piece. Now the problem is that the measurements of the moving part axis are opposite sign convention from what the applied standard specifies, since the B5 is specifying the tool point with respect to work piece. For the angular errors it's just a sign difference, but for the straightness it's not just a sign difference and requires a lot of math to convert it to the correct form.

Instead, I have defined a coordinate system attached to the part, so I start at the part and I just loop all the way around to find the position of the tool in the part coordinate system. This way all the sign conventions are consistent with the B5 standard as tool point with respect to the part. I have a strong opinion that we need to stay consistent with RS-267 so the errors are consistent with the right-hand coordinate system. It is a little confusing what a right-hand coordinate system is when the part moves, but I think we need to stay consistent .

When I was in Bob Hocken's tutorial at ASPE, he was advocating changing the definition of straightness in the standard because of the sign convention problem that arises when the part is moving . I think that would be a really bad idea. That's my opinion. I, however, do not think that's a good idea. I think we need to stay consistent with the right-hand coordinate system.

Steve mentioned a minute ago dealing with the non-repeatable errors. On the spatial-frequency domain error budget project, I am investigating how to characterize these non-repeatable errors and how to determine the magnitude of the non-repeatable component. One question is whether the apparently non-repeatable, or apparently random errors, are attributed to temperature or something else. At what level do you want to try to explain them and what level do you want to just say, "These are the error bands?". I've been in discussions before where people talked about the error distribution, which must be known to put confidence intervals around these measurements. I've heard people say they're uniform distribution, and I've heard people say it's bimodal because of hysteresis, but I've never come across anything that actually did a full study of the error distributions. That's one of the things we are investigating this summer.

The last concern deals with process-dependent errors. All the measurements that we've done have been static or point-to-point. We have a big question regarding the velocity dependency. Are the errors velocity dependent or do you reach some critical velocity and then from that point on they're no longer velocity dependent? This is another issue that I'm interested in investigating. Fixturing and load-induced errors are also issues that I'm not sure how you will handle, but are critical issues that we are interested in at Livermore.

Slide 1

Machine tool performance evaluation at LLNL

- General performance evaluation
  - per ASME B5.54
  - for machine characterization
  - machine tools and coordinate measuring machines
- Error compensation
  - conventional approach
  - rapid machine characterization
  - HP and ICON
- Frequency domain error budget
  - LDRD to develop continuous frequency domain error budget

Slide 2

Important Issues arising on LLNL projects

- Data Acquisition
  - We use LabView on Macintosh for most data acquisition needs
  - Important issues include analog filtering, spatial and temporal sampling rate
- Sign Convention
  - Sign convention is very important for error compensation, not as important for machine characterization.
  - Sign convention is very confusing, especially when the part is placed on moving axes.
  - I prefer a consistent right-handed coordinate system of the tool motion with respect to the part.
- Non-repeatable error characterization
  - What is the typical error distribution (uniform, bimodal, etc.)? Is there a typical error distribution?
  - How do we place confidence intervals on our error budgets?
- Cutting Models

UNIVERSITY OF NORTH CAROLINA AT CHARLOTTE
S. Patterson

Most of you saw the data I presented last time. That still remains the basis of the work we're doing, and I was just going to take a couple of minutes and catch you up on what's new, or where we're going at this point, and that occurs in two areas:

At the Center for Precision Metrology of the University of North Carolina at Charlotte, we have looked at a variety of data on the machine I presented last time, a regular 3-axis orthogonal milling machine, compared that data to a variety of test cuts on a nominally 300 mm scale length, cast iron work piece and, in general, come up with agreements that are in the neighborhood of 2 to 5 micrometers between the machine modeled error and the measured part error. Much of that 2 to 5 micrometers is tied up in the metrology error on the part. There is anyplace from 1 to 3 micrometers of repeatability issues and accuracy issues associated with the coordinate measuring machine used for that measurement data.

In the process of that, we've determined that there are errors arising from fixturing and errors that are arising from residual stress effects that are on the order of 20 micrometers in these parts. Considerable work on the actual process planning was necessary to get those errors down in the region where we could actually make a good correlation with the machine tool.

So, the first thing that I would point out on the virtual manufacturing side of the topic being addressed at this meeting is that I don't believe that we will be successful in a practical level of virtual manufacturing until we have a protocol and a data interchange, which can accommodate issues of fixturing and issues of basic work piece material conditions. That, I believe, we have demonstrated quite conclusively, at least for this class of parts.

I would also add the comment that machine-process interaction is probably on that list as well, although we don't have the experimental data for me to make that statement quite as strongly as I can with the other two sources.

The limitation on the work that we've done has turned out not to be the machine metrology data, or its communication, since we're doing this all in one place, although that would be a big issue if we were trying to work it with one of you, but actually the representation of the work piece itself. This was alluded to in Mr. Donmez's earlier comments, that there were limitations working in the Pro-E format of trying to get the detail information about the surface errors into the work piece model.

In our work we found it necessary to develop a modeling representation from scratch, basically, to contain all of the data that was present in the virtual manufacturing.

An interesting side note to this is that we are, in fact, able to machine parts at about twice the rate on the machine that we can on the computer.

There is a precedent for this, I might add, and that is to look at some of the work necessary for flight simulators. Flight simulators were invented to allow ground training of pilots originally, I believe, with some desire to reduce the cost of pilot training. It turns out now in most installations it is more expensive to run the simulator than it is to run the airplane. On the other hand, I might point out that I have to bracket that comment because that's not the case for the scenarios that involve crashing.

The same is true of machine tools. There are scenarios that involve crashing, there are scenarios that involve things that may be considered abusive machining. As we heard, with higher machining rates and very high spindle speeds, I think that we'll find a greater emphasis on desire for using virtual machine models for very similar reasons that have evolved in the flight training business.

I would also add, as an update to the last time, that we have established a controllable machine enclosure. For lack of a better term, we term it a "Factory Simulator," which is able to look at the very uncontrolled conditions that exist in some factory workplace environments. This allows us to take measurements of machine parameters at different temperatures and at different rates of change of temperatures. The result is a set of metrology data which reflects the behavior of the machine typically displaying its very deterministic response to environmental variables, and this is likely to get back into the questions that were raised earlier about distributions of errors on machines. If we have a large body of measurement data, I believe we're going to be forced to ask the question: what's the source of the distribution and, as Ms. Krulewich pointed out, what's the likely distribution of that? That may well have to do with the distribution of other variables. One of the things that you show fairly easily once you are able to control the environment is that, if you take a series of machine characterization runs over a variety of conditions that reflect what you saw in the workplace, you get an envelope. That envelope, if you choose then to make the statement that you are sampling the environmental conditions randomly, looks like a random distribution that could be termed a repeatability or an apparent repeatability error over long times.

Sorting this out in terms of how we actually use it in virtual manufacturing is one aspect that needs considerable work. Another one, which is more germane to this particular group, is how we represent that kind of data because, in some cases, the data will come in without prior knowledge of the range of environmental conditions and in other cases it will be very tightly coupled. The result, if there is not a distinguishing feature in the database, is going to be substantial confusion.

The other half of the program that we're involved with has to do more with the nature of implementing a virtual manufacturing requirement. There, most of the current work has gone into object modeling of the machine tools and processes, and I would point out that there are two aspects that are driving us right now:

One of them is a model for the treatment of metrology data itself. That is to say, right now, there are a number of ways that you can measure machine tools. You can use a Renishaw ballbar, you can use an API 5-D device, you can use a Hewlett-Packard system, and all of those systems tend to come with their own software for data handling. So, at a level before the metrology data repository kinds of questions, there is also a question of how can I treat with data in a fairly standard way. That, in fact, is an object model that we are beginning to explore now.

The other is the object model of the machine itself. How can I create a virtual machine, or a piece of a virtual machine, in a fairly standardized plug-in method which is independent of the program which is being used to, say, generate the work piece representation? You've heard that addressed here, the difference between the ADAMS modeler and the Pro-E model for the work piece. What we are involved with now is creating a C++ based object model where the definitions are made at the object call function level and the actual implementation inside the object is completely free. If we can gain some degree of commonality between other workers in the field in this regard, it will allow a lot of individual work to be done without having to reinvent the entire structure of the rest of the virtual manufacturing requirement. I believe this is something that is going to be quite vital in order to actually make this workable so there can be more players in the field and they don't have to have their entire deep super-structure of program modules.

Finally, there is another piece to the machine metrology business that we really have not much addressed. In the data that you saw this morning we have examples of metrology data taken on unloaded machines. As I indicated last time, we have one small piece of data that suggests the actual behavior of a machine in a systematic way may be different for a loaded machine than it is an unloaded machine. We're in the process of developing a loading mechanism that does not influence the machine other than constant load to try to be able to tie that down. I hope to be able to report in about another 6 months, or so, what B5 spindle drift tests taken with constant loads on spindles look like, as compared to unloaded results, to address some of the apparent data anomalies that I presented last time.

This is only the tip of the iceberg as relates to process interaction because, when we get to the stage--we get past the stage--that the machine is moving all by itself, then we get to "The Work Piece Strikes Back," and when the work piece begins pushing back on the tool you have issues of chatter involved, you have issues of dynamic change, and you have potentially changes in the static geometry of especially large machines. So, those are the areas that we're moving into now to try to produce a systematic modeling environment for machine tools.

CATERPILLAR, INC.
V. Chandrasekharan

Some of the things have already been addressed and in the previous meeting, Nandu Sirinivasan gave an overview of some of our requirements and scope, so I won't repeat much of that. You are also familiar with some of the work we're doing with University of North Carolina at Charlotte. We've been active in the virtual manufacturing and machining area for about 2 years now. I'll share some of the things that we've gone through in the last 6 months and give you an update, so to speak, instead of going through everything.

The simulation aspect of it is one important arm of the overall planning. Simply put, we look at it as a verification of the process plan. We're talking about the performance of machine tools, and we have to take a step back and go through the definitions of performance the way we're looking at it. Do we want to narrow it down purely on part quality? Do we want to take a step back and look at some of the other things such as cycle time, through-put, and then the up-time and efficiency? Some of these already come into play in the simulations that we do today and I'll talk about that next, where we are today and what we're doing today. I'd like to go through and address some of these things in the afternoon discussions as well, as we go through performance.

The importance of this work comes out in the way we end up layering the database, the data structure, and how we store the information. Some of the information will be available ahead of time, when you buy the machine tool, some of it has to be added on later when we use it, and we'd like to understand where the group is focused so we can address the other issues. We'd like to have one common database within the company where one might refer to the machine tool performance, the errors in the machine tool which may come out of NIST, or any company that finally maintains the database, and we'd like to point out that into the rest of the information that we have to maintain within the company. We have to maintain subsets of this information and we have to understand, as Caterpillar, how to maintain that information.

Currently, we have some databases which we talked about at the last meeting, information that's stored on CD-ROMs and on the Web; and then we have simulations, tool tip simulations and kinematic simulations. We have a variety of Virtual Numerical Control (VNC) and we use some of them. And we use soft machining on some of these things. We have a method of characterizing and reporting machine tool errors, the B5 standard. What's interesting is we're going through one of our first few experiences of actually trying to accept a machine with the standard and we're finding a lot of things that need to be added on and there is a lot of discrepancies in what the machine tool builder is trying to tell us and what we're trying to do with the standard. Those are issues we want some of these groups to address. I can see this that Hans Soons has written up, and a lot of these issues that I'll be mentioning are covered in that.

How do you address the way in which different hardware systems capture data that is reported? If you want to store raw data, there has to be a way of making this all common, otherwise we get into data reduction and models. Do we agree on the types of models that are here today? Do they capture everything and are they complete? So those will be the issues that will come up.

We went in and looked at this modeling of manufacturing resource information that NIST put out--Kevin Jurrens, James Fowler and Mary Beth Algeo--and we took the definitions of machine tools over here, then tried to recreate what's there in Gardener, and got fairly close. You can capture most of the physical descriptions. Maybe that's a starting point. Once you can get that and ensure the validity of that, then you get to the next task of assigning the performance of each axis, or the performance of the entire machine tool, because the information that's out there today is very useful in buying a machine and trying to narrow down the kinds of machines that will fit your description for manufacturing a part, so let's not leave that out.

The second one is supporting existing simulation tools. As I was reading Hans' write up on the axes, he has accelerations, decelerations and things like that, which were not there in the previous report, so I'm glad we're on the right track. Where we'd like to see this go is to automate, or electronically create a VNC model and run it through. How can we describe a machine tool? There are a lot of things in here on the information required to build a kinematic model. Obviously there are things that are not in here such as how do you physically describe the size of the machine tool. There are trade-offs. You can automate portions of it, maybe 80% of it; maybe you cannot get some of the information in. But that's okay; we just need to realize where it is and feed off as much as we can so we can at least run things that we have today and then figure out how to get to where we have to in the future with part quality.

With that, I'd like to get into some of the data storing and layering issues. We had thought about many things as we started looking at what is out there today and where we can add the error information and the machine tool characterization information. Of course, we don't have resources to answer all these questions internally. I'm glad that we're able to leverage NIST. NIST has taken the lead role in trying to get this accomplished. It helps to have a national standard.

First you need the physical description of the machine, because there is a lot of buying decisions made that are based on that.

Then what about the machine tool errors? When you have errors, do you associate them with a physical entity or do you have a separate pointer at the end that just talks about machine tool performance and then go out into this whole data that deals with performance? Or, if you have axes positioning errors, should it be associated with that axis? If you have repeatability errors, should it be associated with that physical entity? In these cases, there are some things that are still not clear where you associate those. I've listed some of those which are fairly obvious. Then you have, squareness error and you have to relate it to two different axes. How do you structure the data to orient it to a point from the X axis and the Y axis to get a squareness number? How does that data get defined? Thermal errors, for example, how do you characterize the effect of ambient? Do you want to have expansion coefficients on each axis, or do we want to characterize the thermal capability of the machine as a whole? Where does that field go? So, that was an issue that came up right away. It's been about two years that we've been characterizing machines at Caterpillar and trying to get this information and figure out how to store the information.

The easy way out seems to be that you have a separate button that says "Performance Information," and then you go into this whole area where you're trying to get this information and keep that consistent. Maybe that's the right thing to do, but we don't know yet.

There is some information that is available only at the beginning when you buy the machine, the footprint. If you want to look at the difference of environmental effects you only get that as you start using the machine and do periodic characterizations. So you have to have fields to keep adding this information continually.

There are other performance metrics that we can use as immediate feedback to the designer. We're looking at virtual manufacturing as a tool and it was interesting some of the issues that Mr. Loyd Bishop from Boeing brought up saying that some of the parts that he's looking at require accuracies in ten-thousandths of an inch. We have to decide where the trade-off is, where we want to run a simulation as opposed to where we won't, because the time to build a model, the time to add all this information and run a simulation is fairly high. Professor Patterson mentioned that he can cut a part a lot quicker than he can run a simulation. Building a model today takes a lot of time. Five years down the road we want to be a lot quicker and I think we will be. So, we have to be careful about where we run simulations. Today the calls we get from our plants are where they're trying to hold 2 and 5 micrometer straightness across 300 mm in length, bores that are maybe 30 mm in diameter. That's where some of the problems are today we need to fix. It does help running some simulations for that because the value added is tremendous and it's worth the time and the man hours that you put in running a simulation of that sort.

We have looked at the data on company-specific business information. Machine tool is an asset for the company. Also, I have to figure out how the asset is depreciating, what's the current value, and that's what upper management eventually wants. If I have to go in and make a case for increasing capacity I have to have information such as burden rate, asset value, etc. We might have a cell of about 20 machines that are identical running 600 parts and we want to know if you can add more parts, if you can get more efficiency out of the cell, or what's the quality and, if I get a new part, can I put it into this cell or not, and again the quality of the machines and things like that become an issue.

MR. CALLAGHAN: Under company-specific business information, could we add in there like the quality results of a particular machine, scrap rate, because that seems to be one of the things that seems to get buried?

MR. CHANDRASEKHARAN: Yes. In fact, that's the first thing people want to look at because that's the most tangible information for a foreman. Their metrics are the amount of scrap they make, scrap dollars, and that definitely is one of the issues here. It's a lot easier to feed back that information to a designer today, or to a guy that's planning a process, than running an extensive virtual manufacturing simulation and telling him if he's going to meet all his quality metrics.

Another issue with the data storing is: what happens if you want to store actual data? Of course, the problem is size and then you have the number of runs. We're assuming that the positional errors are independent of the approach in some cases. Now, if it does become a function of the approach and you start defining vectors, how many test data do you take? How do you store all that data?

The other issue is consistency across suppliers. That is definitely a very big issue for a company buying the machine tools, and I think this group and NIST is definitely the most capable organization here to address some of these issues.

The way the data is stored and processed is very unique and I think that came up in some of Loyd's presentation; such as how IQL stores it, and how he manipulates the data. Even when you present raw data it's still manipulated raw data, it's never completely raw data, so that becomes an issue as well.

There are issues about the different types of data. You get into the issues of not just floating points and numbers, integers, but the sampling. How do you sample them, how many fields do you allocate? I think we've already started addressing those and I wanted to bring that out and I think will come out in the discussions again.

We looked at model coefficients. There is the issue of how complete is a model coefficient? How complete are the models we are addressing today? Have we independently assessed the errors, for instance repeatability? If you take repetitions on the same measurement, is the variation a function of temperature? Is that the true repeatability of the machine? We were doing the tool change repeatability on our machine acceptance. Of course, if you change the tool you've got to move to a certain point and measure in the cap nest. There are positional repeatability errors that are associated with the tool change repeatability. As we were going through the machine acceptance, we were not sure how to actually sort those out accurately enough. There has to be some standard ways of sorting some of these issues out.

As research progresses in academia and in other places you'll always have more and different types of machine models involved. Do you want to restrict yourself to the type of models that we have today? Again, it goes back to the issue of how complete they are.

Another interesting thing that we found is the issue of scrap. Eventually the goal is to figure out how good is the part that you're going to machine. The B5 standard has a test block that you can go in and machine today and collect that data. But can we store that information some way? We haven't really addressed that issue yet. But taking that test block and inspection data from that, can we maybe characterize the repeatability of the machine? How do you standardize the tooling? How do you get the supplier to maintain that? When we buy a machine, let's say with a high-speed spindle or a high axis travel rate, we don't care if the accuracy of the machined test block is extremely good when it was cut with cutting parameters outside the range that we want to use the machine for. If it's running at slow spindle speeds and real axis travel rates, it may be a very accurate machine but it doesn't mean much. We want the test block to be machined at typical feeds, speeds and typical tooling that the machine will be used for.

The issue of chatter limits and stability data came up and I've already had some discussions here on how we can try and store that in the database. One issue that we're trying to do some research on at Caterpillar is assessing the joint stiffness and damping up to the spindle taper. Then, we add tooling information and determine the transfer function of the tool and then compute stability lobes and chatter limits based on that.

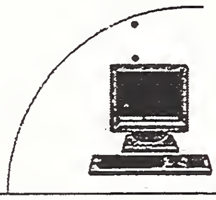
Finally, we have to address the database design, the structure, and the storage issues. We have to address the completeness of the models, completeness of the data, the way the data is parsed and sorted. Then show consistency, across suppliers, write down procedures, data collection methods, and how they report this information. Of course, we want to promote supplier acceptance and we'd like to see more machine tool builders here.

I think we want to not limit the scope of the data definitions to just simulation alone. Virtual manufacturing is definitely where we want to get to and we're working hard to get to that. We're already addressing some of the other issues of how you basically buy a machine by its work volume definitions as the starting point, and then go into the performance deeper later on.

We definitely are looking for more correlation of machine errors and the characterization to part errors. We've been involved in a lot of other issues such as modeling, fixture and process. We started modeling the process, the loads, the deflections, and fixture distortions because, in a lot of our cases, the fixture distortion is enormous and we get up to 120 to 150 micrometers of errors from fixture distortion. We want to, however, leave it out of the scope of what we're doing here and keep the scope restricted to machine tools, machine tool errors, and how that translates to part errors. Some of it might be a selfish interest because we are already working on the other issues and we're trying to plan on how to bring those in. The other reason is that the scope of the problem becomes enormous and, given the resources that we have, we think the focus will help us a lot more in organizing what we have today. We can definitely do a lot better with the data we're collecting today on machine tool characterization and storing that accurately.

In terms of the simulation tools, there are no CAD vendors here. That was another issue that we talked about from the previous meeting after we got back and tried to work out our strategy. We don't do too much research in the area of CAD at Caterpillar; we leave that to the vendor. When we start looking at different companies using different CAD systems, issues of part representation become more important. We definitely would like a graphic representation of the part down the road. But I think, as a starting point, we'd like to assume that the people that are calling out the specs on the part are doing something within reason by understanding the functionality of the part. We'd like to go back and compute those geometric dimensioning and tolerance specifications, match the calculated ones against the specifications as a first step and show that in some kind of a graphical form, as opposed to creating the entire representation of the part. That gets into a level of detail that we certainly don't understand and I think it would be more profitable if we'd try to focus on the areas of the machine tools and the characterizations and things like that.

Machine Tool Management & Machining Simulation



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Machine Tool Database - Scope Issues

- Types of Machine Tools
- Scope of use
  - Process planning
  - Process simulation (verification of process plan)
  - Asset Management (Machine tools)
  - Quality Information Feedback
- Definitions of Performance
  - part quality
  - cycle time / throughput
  - uptime/efficiency

Technical Center
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Precision Mfg. Technology
Mfg. & Logistics Technology Div.

What is out there today?

- Physical machine description database
- Machine tool kinematic simulation software
- B5 standard for reporting machine tool 'characterization'
- Different hardware to characterize 'subsets' of machine errors
- Data reduction and machine error models

Issues

- Are existing database fields covered?
- Support existing simulation tools
  - machine physical description
  - axis acceleration/deceleration

Technical Center
Caterpillar Inc.

Precision Mfg. Technology
Mfg. & Logistics Technology Div.

Data Storing / Layering

- Physical definitions
- Machine tool errors integral with physical entity or independent?
  - quasi static, thermal, tool change repeatability, spindle runout
- Machine in 'factory' data (periodic characterizations, maintenance, other performance metrics)
- Company specific business information (schedule, burden rate, asset value etc.)

Technical Center
Caterpillar Inc.

Precision Mfg. Technology
Mfg. & Logistics Technology Div.

Data Storing

- Actual data points
  - size
  - number of runs (approach, ambient, compensations etc.)
  - consistency across suppliers
  - uniqueness / limitations of instrument
  - types of data (quasi static, thermal, repeatability)
- Model coefficients
  - completeness of models
  - compounding of errors, consistency in separating
  - adding data such as ambient effects
  - future developments in models
- Cutting tests data
  - test part machining and inspection data
  - chatter limits, stability data

Technical Center
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Precision Mfg. Technology
Mfg. & Logistics Technology Div.

Caterpillar Perspective

- Data base design, structure, storage issues
- Completeness of data and models
- Consistency in data collection, reduction and reporting methods
- Supplier (machine tool builder) acceptance
- Scope of data definitions not limited to part quality, performance, simulation
- More data on correlation of machine error characterization data and models to machined part quality
- Simulation tools, part representation unique to company. Use only to validate data and models

AUTOMATED PRECISION, INC.
Q. Ma

API is a manufacturer of measuring instruments. We also are involved in a lot of machine measurements. The main reason for us trying to promote this new technology is the fact that just recently machine measurements have been accepted as a national standard.

Today, I would like to use the data from one machine we measured showing the types of measurements people usually want. Basically, the measurements people request are the ones described in ANSI/ASME B5.54 standard. Normally, they want to have a linear, straightness and angular error tests for each axis along with a periodical test, a bidirectional repeatability test, and the body diagonal displacement tests. The other tests people want are contouring performance in three different planes as well as squareness of axes. People are also interested in the spindle thermal growth. To complete a task, sometimes we measure the roll of the machine slides [Slide 1].

We use the 5-D laser system to measure 5 different types of errors at the same time [Slide 2]. For example, while measuring X axis linear displacement error, we also measure straightness in the vertical and horizontal planes as well as pitch and yaw errors simultaneously. This way we can reduce the measuring time by roughly about 80 percent. One can measure a 3-axis machine within 3-4 hours.

The other instrument we commonly use is the ballbar [Slide 3]. The third one is the spindle thermal measurement system, which is either capacitance or inductance based proximity measurement system measuring linear thermal growth of the spindle along three orthogonal axes as well as the tilt drift in two planes [Slide 4]. During these measurements we put thermal sensors on critical positions, like near the spindle bearings, and roughly see the correlation between the temperatures and the spindle drift.

When we are measuring a machine, involving many types of errors, we create a bunch of files that can prove really frustrating for the user. To handle these files we are developing software which is Microsoft Access-based. We call it the WINNER Data Management System. Basically, this software will group all the measurements together. We are also trying to set up a kind of a format for the file name [Slide 5].

For a filename in the MS-DOS work you can only have 8 characters. We use the first three as the machine's ID. The fourth character is the test type, and you assign each number based on what type of test you are doing. The fifth will be the axis being measured for different tests. The last three characters are used for test numbers. For example, 5131A001 indicates the machine ID as "513," and the "1" indicates it is a 5-D measurement. "A" is axis X, and "001" is the first of files. In this way we can clearly identify what tests they have done and then, later, when they put it into the program, the program will recognize it and put that file into the right space.

We also code error file format [Slide 6]. This one basically summarizes the measurement. Instead of 100 raw data, we just track all the key components from the data and then put it into a file. This file will be read by the database system. For example, for the linear measurement, we save the maximum error, maximum reverse error, then the increment for the measurement, the total travel, also the air temperature, the material temperature, and the starting position.

The primary layout of our system is shown in Slide 7. We have the main part where you can type into machine information. On the other side you can go into the real evaluation graphs and eventually print out a report.

Next I will just roughly show what the data looks like. This is the linear measurement of axes [Slide 8] and, in the meantime, we also record the straightness measurement and the angle [Slides 9 and 10]. All five of these measurements were done simultaneously. Then, we fit the data into this management software and create a report. And, if the people follow the instructions, they can see how the last column will automatically create this report [Slide 11].

This is the diagonal measurement [Slide 12]. Normally, we provide a diagram [Slide 13] as well as the summary information [Slide 14] showing machine body diagonals with repeat to machine axes.

A diagram of the repeatability measurement and a summary of the report are shown in Slides 15 and 16 respectively.

Periodical measurement is similar to the linear measurement. The results are shown in Slides 17 and 18.

Ballbar measurement data are shown in Slides 19, 20, and 21. We only identify backlash, servo error, periodic error, scale mismatch, and squareness using the ballbar because we feel that straightness is insignificant using the ballbar.

We created a measurement system for the spindle thermal growth measurements. Right now, not many people are really interested in the modeling, but they want to know how large the thermal growth is [Slide 22]. Measurement data and summary are shown in Slides 23 and 24 respectively.

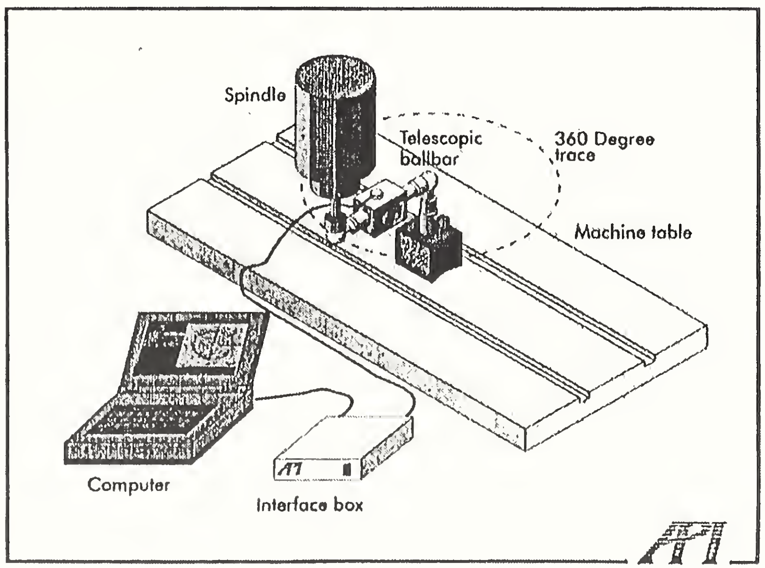
The last one is using the tilt sensor to measure roll. The set up sketch, data and summary are shown in Slides 25, 26, and 27.

Another thing we're trying to do is build up the model based on all the measurements so that the algorithms will probably be based on the model that has been developed at NIST and other institutes. Then our major challenge is how to fit the data into the model for different type of machines and for different set-ups. The sign will make a big difference. So we'll work on that.

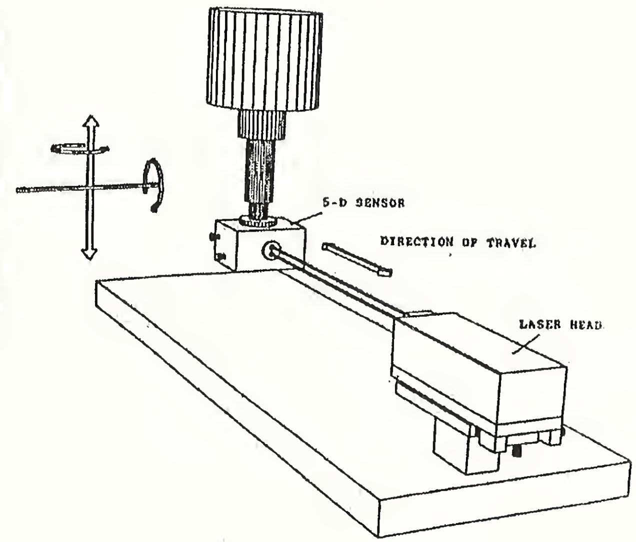
And my final comment is, based on our experience with the industry, the user is relying on the instrument itself to give them all these answers, like repeatability and uncertainties. The management doesn't want to have any guessing; they just want this to be automatic and as simple as possible.

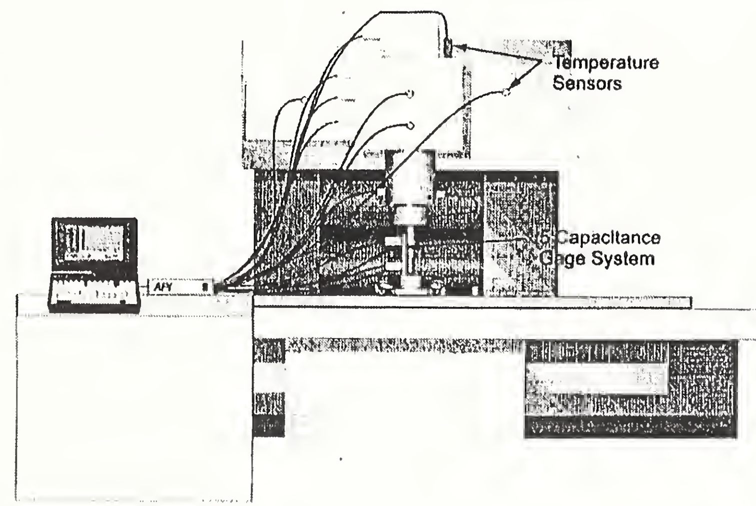
Machine Tool Performance Evaluation

Instruments	Measurement
5-D Laser System	- Linear, straightness and angle test - Periodic test - Bi-directional repeatability test - Body diagonal test
Telescopic Ballbar	- Contouring performance in three different planes - Squareness of axes
Spindle Thermal Analyzer	- Spindle thermal drift
Dual-Axis Tilt Sensor	- Roll angles of horizontal axes



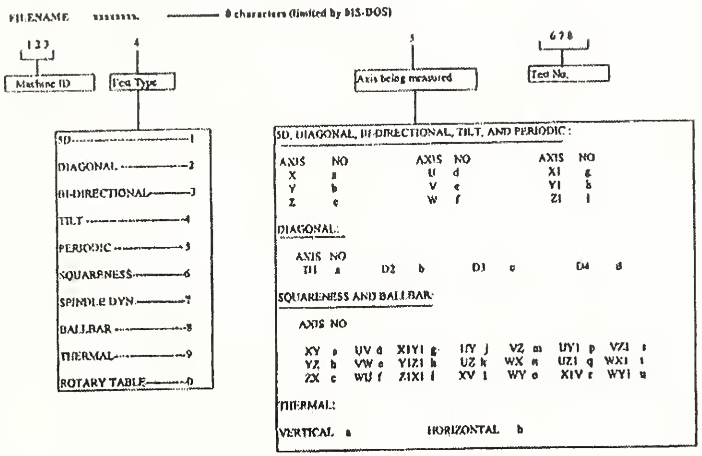
Hardware Configuration for Measurement Along X-Axis





API Thermac System

File Name Definition of API WINNER Data Management System



Error File Format of 5-D Laser System

Linear Measurement: *5131A001.erl*

Max. Error: 0.006121
Max. Rev. Err: 0.001414
Increment: 5.0000
Travel Length: 135.000
Unit of Length: inches
Air/Mat.Temp.(oF):77.9/77.6
Position: 0.000

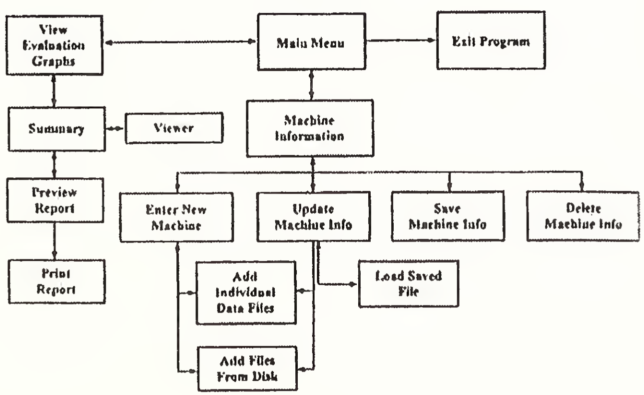
Angular Measurement: *5131A001.era*

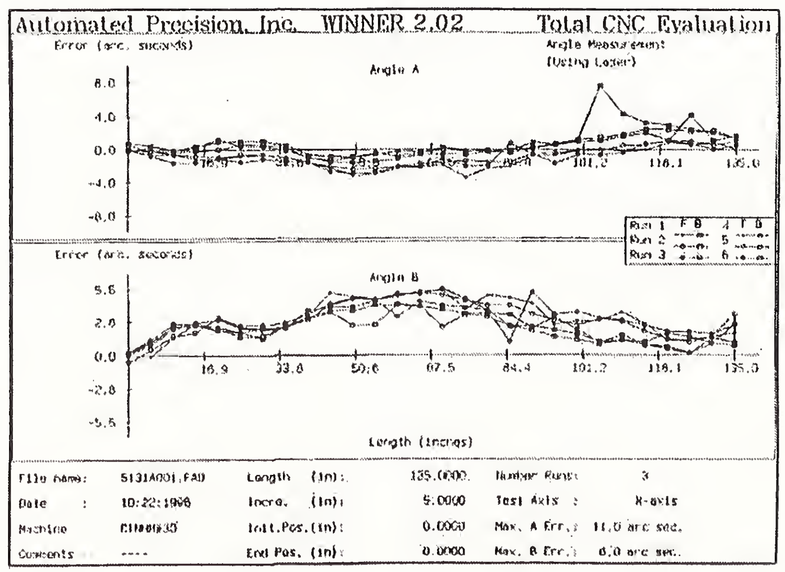
Max. Err. -A-: 11.0
Max. Err. -B-: 6.0
Increment: 5.000000
Travel Length: 135.000000
Unit of Length: inches

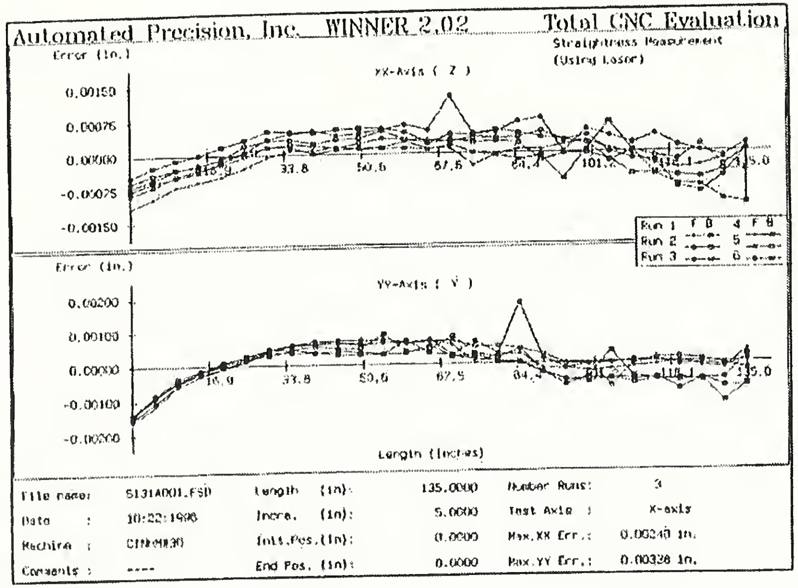
Straightness Measurement: *5131A001.ers*

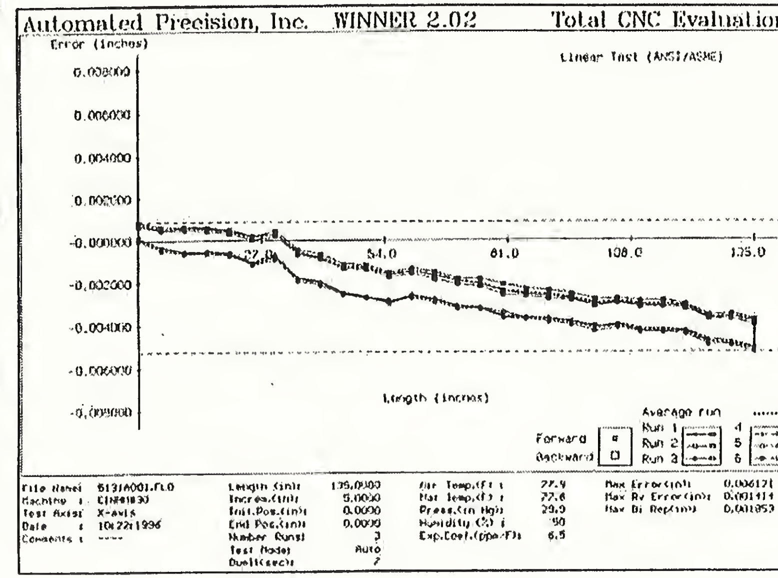
Max. Err. -XX-: 0.002401
Max. Err. -YY-: 0.003382
Increment: 5.000000
Travel Length: 135.000000
Unit of Length: inches

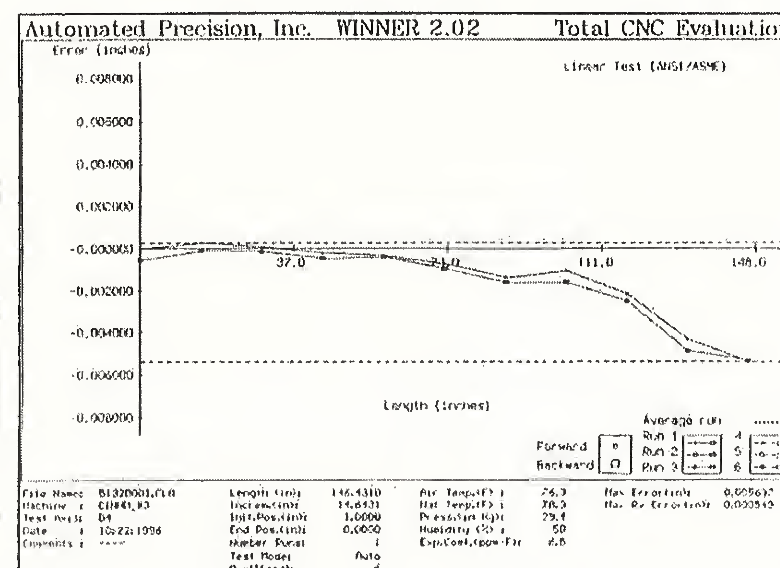
API Winner Data Management System (DMS) Flowchart











Machine Evaluation Summary

04 Nov 96

Laser Linear , Straightness and Angle Measurements

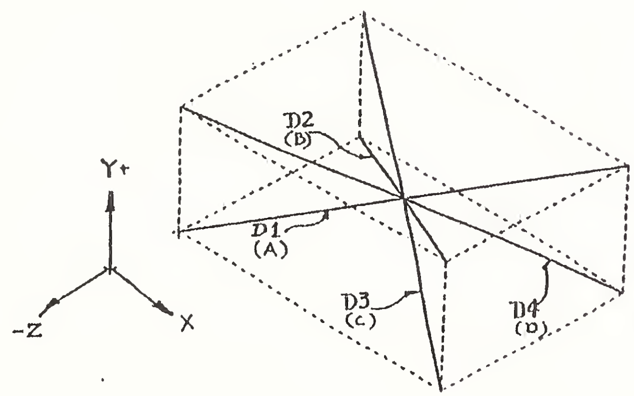
(Instrument:API 5-D Laser Measuring System)

Dimension Unit: Inches / Angle Unit: arc sec

	Linear Displacement			Straightness		Angle				
Axis	Max. Error	Max Avg Err	Max Rev. Err	Max. Err. -XX-	Max. Err. -YY-	Max. Err. -A-	Max. Err. -B-	Travel Length	Air/Mat.Temp.(oF)	Filename
X - AXIS	0.006121	0.005885	0.001414	0.002401 -Z-	0.003382 -Y-	11.0 -XZ-	6.0 -XY-	135.00	77.9/77.8	5131A001
Y - AXIS	0.003484	0.003279	0.000611	0.001262 -Z-	0.001490 -X-	11.4 -YZ-	10.4 -XY-	75.00	77.9/77.7	5131B001
Z - AXIS	0.007902	0.007677	0.003431	0.001558 -X-	0.000831 -Y-	9.3 -XZ-	9.9 -YZ-	28.00	76.5/78.3	5131C001

* -X-: Machine axis
  -Y-: Machine axis
  -Z-: Machine axis
  XY: Machine XY plane
  YZ: Machine YZ plane
  XZ: Machine XZ plane
* See attached plots according to each file name
* See coordinate system for each axis and error definition

Laser linear diagonal measurement
D1 - D4 direction



Machine Evaluation Summary

04-Nov-96

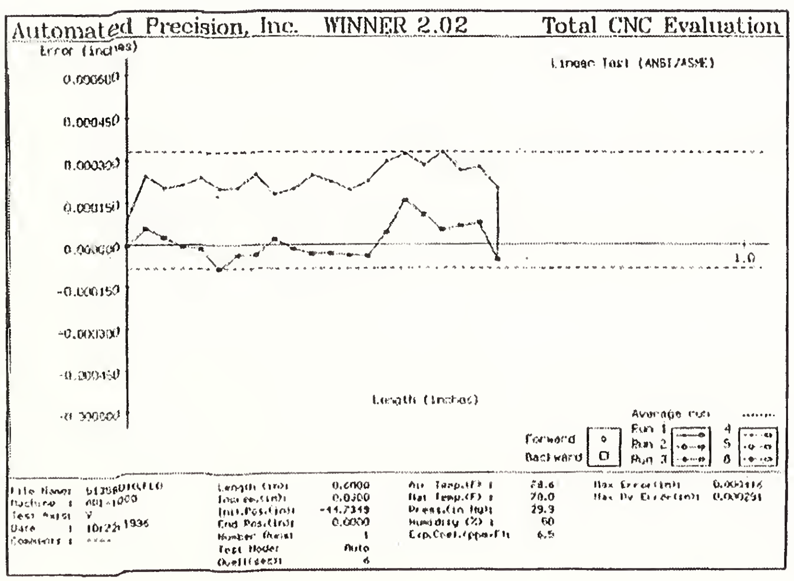
Diagonal Measurements

(Instrument: API Laser Linear Measuring System)

Dimension Unit: Inches

Axis	Max. Error	Max. Rev. Err	Air/Mat.Temp.(oF)	Travel Length	File Name	Comments
D2	0.018020	0.000874	78.9/78.3	153.15	5132B001	
D4	0.005637	0.000549	76.3/78.3	146.43	5132D001	

* See attached plots according to each file name
* See coordinate system for each axis and error definition



Machine Evaluation Summary

04-Nov-96

Periodic Measurements

(Instrument: API Laser Linear Measuring System)

Dimension Unit: Inches

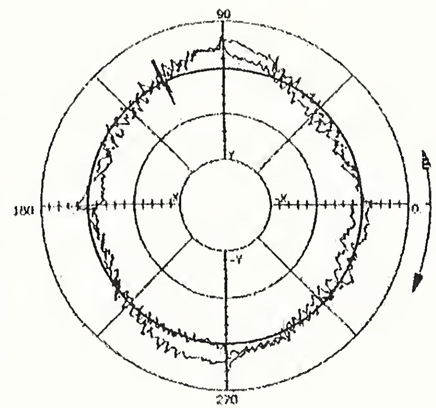
Axis	Max. Error	Max. Rev. Err	Air/Mat.Temp.(oF)	Position	File Name	Comments
X - AXIS	0.031289	0.001116	78.5/77.7	-41.60	5135A001	
Y - AXIS	0.000418	0.000291	78.6/78.0	-44.73	5135B010	
Z - AXIS	0.003733	0.003521	76.2/78.3	1.00	5135C001	

* See attached plots according to each file name
* See coordinate system for each axis and error definition

TELESCOPIC BALLBAR ANALYSIS – Version 2.10 API

Backlash	-X/ X	0.0002/0.0008 in
	Y/-Y	0.0002/0.0001 in
Backlash Comp. Overshoot	-X/ X	0.0000/0.0002 in
	Y/-Y	0.0002/0.0004 in
Servo Error		0.0002 in Y leading X
Periodic Error		Not significant
Scale Mismatch		Y longer by 0.0008 in. in 26.857 in. travel
Squareness		0.5 arc seconds (0.0000 in/ft)

File Name	5138a051.out	5138a052.out
Feed Rate	20 in/min	20 in/min
Direction	cw	ccw
Data Points	1075	1078
Test Date	10/21/98	10/21/98
Test Radius	13.428 in	13.428 in
Maximum Error	0.0011 in at 90.5 deg	0.0013 in at 90.8 deg
Minimum Error	-0.0009 in at 43.2 deg	-0.0011 in at 116.3 deg
Total Error	0.0020 in	0.0024 in
Center Offset	X: 0.0048 in Y: 0.0052 in	X: 0.0047 in Y: 0.0054 in

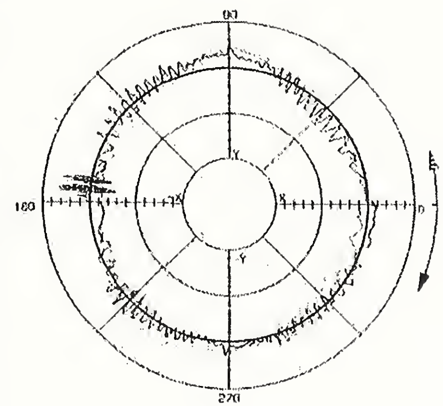


Scale: 0 0.0019 in

TELESCOPIC BALLBAR ANALYSIS – Version 1.20 API

Backlash	X/-X	0.0004/0.0006 in
	Y/-Y	0.0000/0.0001 in
Backlash Comp. Overshoot	X/-X	0.0002/0.0001 in
	Y/-Y	0.0003/0.0004 in
Servo Error		0.0002 in
Periodic Error		max p-p: 0.0005 in Significant
Scale Mismatch		Y longer by 0.0009 in. in 20.657 in. travel
Squareness		Servo dominant run lower feedrate

File Name	5138a151.out	5138a152.out
Feed Rate	50 in/min	50 in/min
Direction	cw	ccw
Test Radius	13.429 in	13.426 in
Maximum Error	0.0018 in at 174.9 deg	0.0014 in at 89.2 deg
Minimum Error	-0.0015 in at 174.5 deg	-0.0016 in at 162.4 deg
Total Error	0.0033 in	0.0032 in
Center Offset	X: 0.0048 in Y: 0.0052 in	X: 0.0046 in Y: 0.0063 in



Scale: 0 0.0027 in

Machine Evaluation Summary

04-Nov-98

Ballbar Measurements

(Instrument: API Telescopic Ballbar System)

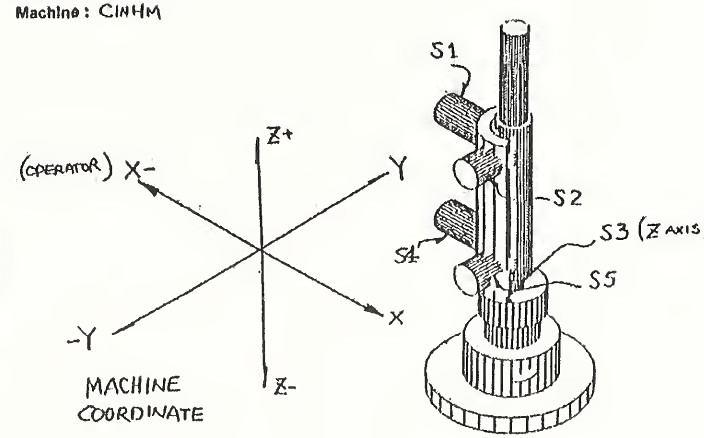
Dimension Unit: Inches

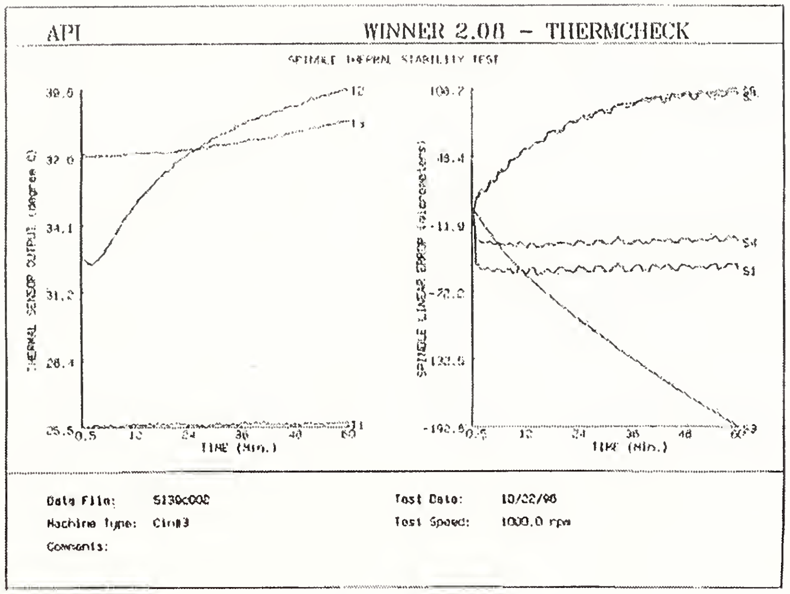
Test Plane	Max. Error	Ballbar Length	Direction	Feed Rate (in/min)	File Name	Comments
XY - AXES	0.0028	13.428	cw	10.	5138A001	
XY - AXES	0.0019	13.428	ccw	10.	5138A002	
XY - AXES	0.0019	13.428	cw	20.	5138A051	
XY - AXES	0.0023	13.428	ccw	20.	5138A052	
XY - AXES	0.0033	13.428	cw	50.	5138A151	
XY - AXES	0.0031	13.428	ccw	50.	5138A152	
YZ - AXES	0.0060	13.427	cw	10.	5138B001	
YZ - AXES	0.0049	13.427	ccw	10.	5138B002	
YZ - AXES	0.0077	13.427	cw	20.	5138B051	
YZ - AXES	0.0068	13.427	ccw	20.	5138B052	
YZ - AXES	0.0118	13.427	cw	50.	5138B151	
YZ - AXES	0.0107	13.427	ccw	50.	5138B152	
ZX - AXES	0.0047	13.427	cw	10.	5138C001	
ZX - AXES	0.0068	13.427	ccw	10.	5138C002	
ZX - AXES	0.0061	13.427	cw	20.	5138C051	
ZX - AXES	0.0064	13.427	ccw	20.	5138C052	
ZX - AXES	0.0109	13.427	cw	50.	5138C151	
ZX - AXES	0.0137	13.427	ccw	50.	5138C152	

* See attached plots according to each file name
* See coordinate system for each axis and error definition

Spindle Thermal Test

Machine : CINHM





Machine Evaluation Summary

04-Nov-96

Thermal Measurements

(Instrument: API Thermal Analysis System)

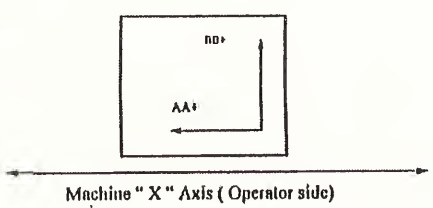
Dimension Unit: Inches

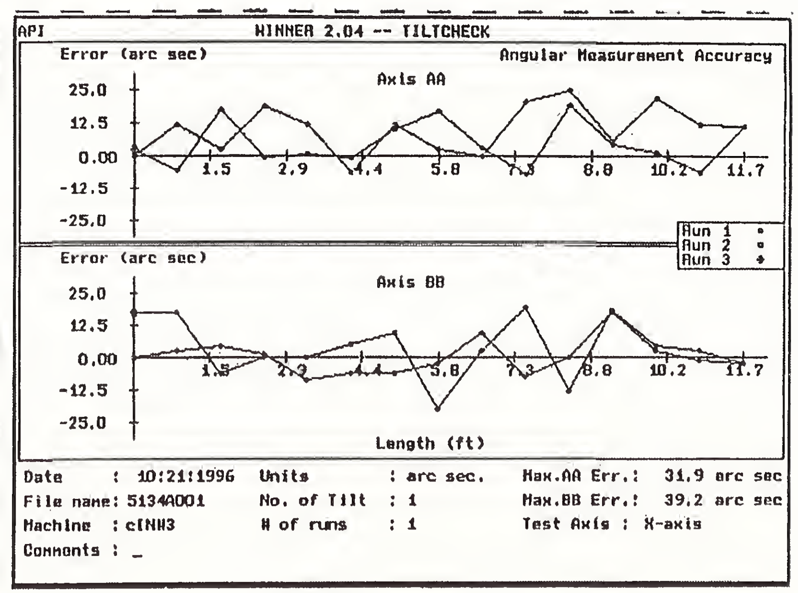
RPM	Drift(1&4)	Drift(2&5)	Drift(3)	Tilt(1&4)(in/ft)	Tilt(2&5)(in/ft)	File Name	Comments
0.0 rp	0.00127	0.00060	0.0008	0.0003	0.0003	5139C001	
1000.0 rp	0.00228	0.00424	0.0075	0.0030	0.0009	5139C002	

* See attached plots according to each file name
* See coordinate system for each axis and error definition

Roll Test Set-up
Machine:

TOP VIEW FOR "X" AXIS TEST





Machine Evaluation Summary

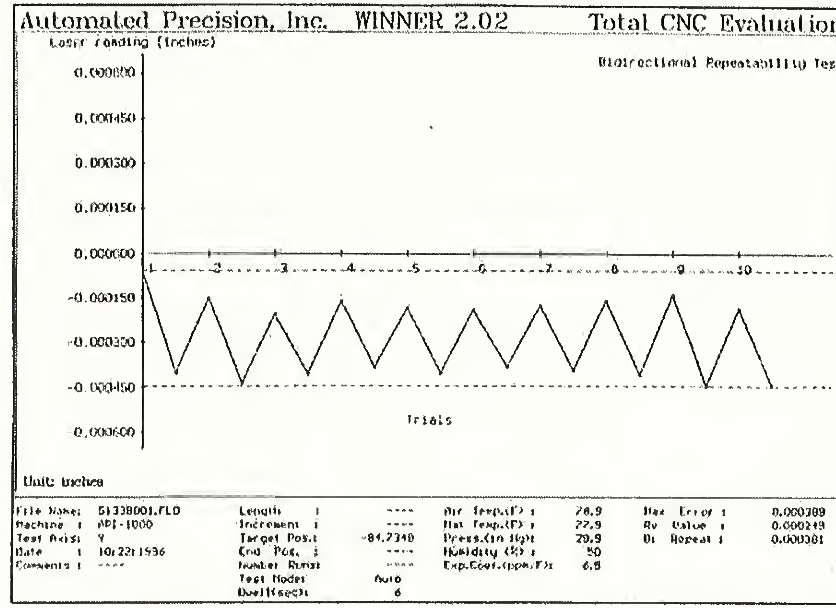
04-Nov-96

Roll Measurements

(Instrument: API Electronic level System)

Axis	Max. BB (arc sec)	File Name	Comments
X - AXIS	39.2	5134A001	Machine column vibrated

* See attached plots according to each file name
* See coordinate system for each axis and error definition



Machine Evaluation Summary

04-Nov-96

Bidirectional Repeatability Measurement

(Instrument: API Laser Linear Measuring System)

Dimension Unit: Inches

Axis	Max. Error	Rev. Value	Bi. Repeat.	Target Position	File Name	Comments
X - AXIS	0.000305	-0.000722	0.000966	-71.600	5133A001	
X - AXIS	0.001015	-0.000768	0.001067	8.399	5133A002	
Y - AXIS	0.000389	0.000249	0.000381	-84.734	5133B001	
Y - AXIS	0.000380	0.000283	0.000440	-24.734	5133B002	
Z - AXIS	0.003414	0.002567	0.003235	-28.075	5133C001	
Z - AXIS	0.002431	0.002347	0.002483	-10.073	5133C002	

* See attached plots according to each file name
* See coordinate system for each axis and error definition

INDEPENDENT QUALITY LABORATORIES
R. Callaghan

The group of people that spoke here the last session were primarily commercial people involved in the area. I thought I would give you an idea of where I thought the technology was right now from a commercial standpoint, such as what's available and what needs development and so forth, because we have quite a variety of interests in this group.

I've got a key here. "A" means it's available commercially, "B" means it requires some development, and "R" means it requires further research before we can begin to introduce this into the market. I will try to address some of the issues that I think are important when we get involved with this kind of measurement and this kind of data.

The first thing is repeatable measurements. That is, being able to describe how we set up the instrumentation. Secondly, providing it in text format, Loyd was showing you how he does it with his system. We also have some capability for doing digital imaging. There is a lot of software right now that's available with digital images or digital photographs. One issue that came up recently was video and sound. We work on the ground with the maintenance mechanics and these are some of the things that they've been asking for. They want more direction for the guys who are going to be capturing this data. If you ask somebody to capture this data, and if you are not explicit, you'll probably spend as much time trying to figure out what they've done as it would take you to go out there and do it yourself. So, these particular aspects are very important underlying issues relative to getting data that's going to be of value at all if we want to go forward with any of the other activities that we were talking about this morning.

Certainly, if we look at the choices of instrumentation, a lot of this instrumentation has been around for quite some time, although it hasn't had much acceptance in industry. There are a few opportunities here for further development and research in some products, but everything that we really need to make the measurements is available currently.

You heard Quan Ma mention what he perceives from his customers' standpoint, and that is the need to gather this data as automatically and as rapidly as possible. I think there are a number of software packages out there from a variety of manufacturers that can automatically gather this data. We have one issue, the sign conventions, that we need to develop. For me, right now, this is one of the most important issues that this group could deal with immediately. In fact, I called Jim Bryan on Friday to talk about this, to ask him what he did about sign conventions, and he says, "You know, I've been doing this for 50 years and I'm still confused. I still tell people to use the right-hand rule, but you've got to point your thumb north, or you've got to point it up, or point it east for a particular machine." He says, "I don't have anything solid yet in that area."

When we do these measurements out in the field one of our major costs right now are the machine tool part programs to exercise the machines. We've had innumerable cases where large quantities of time have been consumed on the shop floor in trying to get the machines to move so that we could take the data automatically. In fact, I did a demo at Boeing a few years ago and we stood for two hours in front of a machine with 28 people trying to make it go around in a circle and we finally abandoned that demonstration because we couldn't get it to do that. So that's another important issue. It probably doesn't require as much research as it does development, but I think a repository of machine tool part programs for making these measurements is a good idea. One other thing I wanted to mention is that there is a machine tool out there right now that has a hazard in it when we run these test programs. If you use a standard command, which is an M00, to stop this particular machine, it will orient the spindle. So, if you have a piece of instrumentation in that machine, you may get hurt by it. I've talked with their safety chief about this issue. It isn't such a problem when you're making parts. But when you have the instrumentation and use a standard part program, you're going to get some excitement.

I would recommend that, in the course of the next day, we look closely at the standard for axis and motion nomenclature for NC machine tools and see if it has value. I'm going to start to use it, because I just discovered it. It shows the right-hand rule for doing the sign conventions. In fact, this is out of the older standard; the newer one has quite a few more illustrations of machines, which I think is super. They have some of the filament winding machines, as well as the standard machine tools in it. This standard does relate to the part and not to the machine motions.

If we look at the methods of storage and retrieval, there are a lot of systems out right now that have proprietary data files and you can't get into them. Most of the systems now have ASCII data files and from the commercial side, I think what we need to be moving to is certainly the database standard format.

We've been working on national and international standards committees. These standards describe the methods for analysis of some of the data collected on machine tools for comparison and acceptance purposes. On the other hand, the maintenance managers are asking us more and more for information so that we can automatically guide the maintenance mechanics in repairing the machines. They're not as interested in simulations at the moment, but they just want some nice, simple form of the data so we can say, "Okay, here is where you have to straighten the machine, here's where you've got to correct the servo gain error." There are a number of software packages now that are going along with the ballbar systems that seem to be effective. Shop floor maintenance mechanics like that type of thing. But I think there is an awful lot more opportunity in this area for the short-term gain and I think we haven't discussed that at all yet. From a commercial standpoint, the simulations to benefit the maintenance mechanics will have a lot more bang for the buck than the factory simulation.

I view the methods of applying this technology in several ways. Buying and selling is one of them. Companies are wrestling with their suppliers over the application of the standards. Maintenance support is the other application area. If we take a look at a typical machine in the shop and the way they're being applied, I usually tell our customers that we can take and improve the volumetric performance of a machine by a factor of 2 without much difficulty at all. It's simply because people in the past have not had enough information about what this machine can do. You can see from the earlier discussions we had today about the repeatability of these machines--they're incredible--and the problem with the machines has been that they have not been set up correctly. If we had some way of visually presenting the error conditions, or simulating the error conditions in the machines, we could explain the maintenance mechanics and their supervisors what the real problems are and how to correct them easily.

If we go a little further, we have the issues of the error compensation. Lead screw error compensation has been around for a long time, although it's misused quite frequently. 3D volumetric compensation is available, I think, from all the (Coordinate Measuring Machine) CMM manufacturers right now. There are a few people that have 3D volumetric corrections for machine tools, although I think it requires a lot more development and research. We have thermal error compensations available.

The machine simulations and factory simulations are areas that we need to do a lot more research. I put "D" in the machine simulations because I think that's an important point right now to get people looking at this data in a little bit different form than they have in the past.

There was one other issue that I didn't put here. That was the frequency content of data. We need to do something in studying that because I'm finding that there is an awful lot of variation in the data that comes from the test procedure itself, particularly depending on how you filter the data, and a lot of the commercial products have filtering built in. You wouldn't even know what it is. We have it with the electronic levels, we have laser interferometers, and all those devices have built-in filtering. We need to come up with methods of filtering the noise out of the data and yet keep the basic information about the real machine errors.

MR. BISHOP: I saw on TV an advertisement that Casio has digitized pictures. You can look in the back of the camera and actually see what you're going to either save, or erase. Do you have this kind of capability with your software, because I think that is really a nice feature, where you can go out and take a picture of your set-up and include that right in on the computer screen.

MR. CALLAGHAN: Actually not. But if anybody is interested, we can talk about it off-line.

MR. BISHOP: Well, I thought that was really important for the documentation and the repeatability of the tests. I don't have a problem because I'm the same guy that does the tests over and over, so I can document it and I can pretty much go back and test it over time. If I test something and I tell maintenance mechanics they need to repair it, then it would be really good if I had a digitized picture on the computer screen so he could duplicate the test, duplicate the error, and correct the problem.

MR. CALLAGHAN: I think this is something else that should go along with that repository of information. If you're a scientist or an engineer who is studying a particular data set and you don't have access to this thing you're wasting your time. You have to know, for example, at what plane a laser shot was taken. You also have to know the direction and where the temperature probes are. One way to get that in the database is with the actual digital images.

Slide 1

IQL

Independent Quality Labs, Inc.

MACHINE TOOL

PERFORMANCE MEASUREMENTS

OVERVIEW

PREPARED BY:

Robert P. Callaghan

SPECIALISTS IN PRECISION 3D MEASUREMENT

Slide 2

IQL

Independent Quality Labs, Inc.

REPEATABLE MEASUREMENTS

Setup Descriptions	A
Text	A
Digital Images	A
Video/Sound	D

KEY:

A - Available Commercially
D - Require Development
R - Require (further) Research

SPECIALISTS IN PRECISION 3D MEASUREMENT

Slide 3

IQL

Independent Quality Labs, Inc.

CHOICES OF INSTRUMENTS

Electronic Gages	A		
Electronic Levels	A		
Laser Interferometers	A		
5d Laser Systems	A	D	R
Short Range Ball Bar	A		
Long Range Ball Bar	A	D	R
Spindle Analyzers	A	D	
Indexing Tables	A		

Slide 4

IQL

Independent Quality Labs, Inc.

METHODS OF DATA CAPTURE

Automatic Data Gathering	A		
Sign Conventions		D	
Machine Tool Part Programs	A	D	R

Slide 5

AMERICAN NATIONAL STANDARD
ANSI/EIA RS-267-A - 1968
APPROVED MARCH 12, 1968

EIA STANDARD

AXIS AND MOTION NOMENCLATURE FOR NUMERICALLY CONTROLLED MACHINES

RS-267-A

(Revision of RS-267)

JUNE 1967
(Reaffirmed June, 1973)

Engineering Department

ELECTRONIC INDUSTRIES ASSOCIATION

Slide 6

RS-267-A
PAGE 3

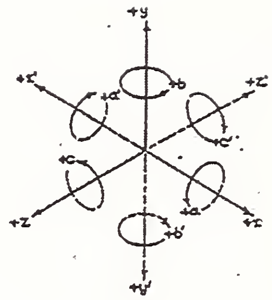


FIG. 1A

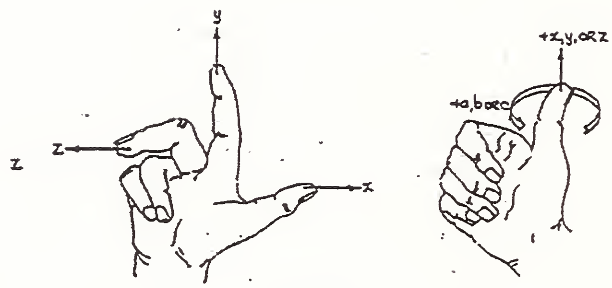


FIG. 1B
RIGHT HAND COORDINATE SYSTEM

Slide 7

RS-267-A
PAGE 7

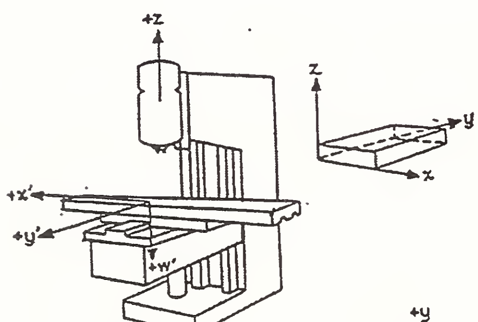


FIG. 7
VERTICAL KNEE MILL
DRILLING MACHINE
JIG BORER

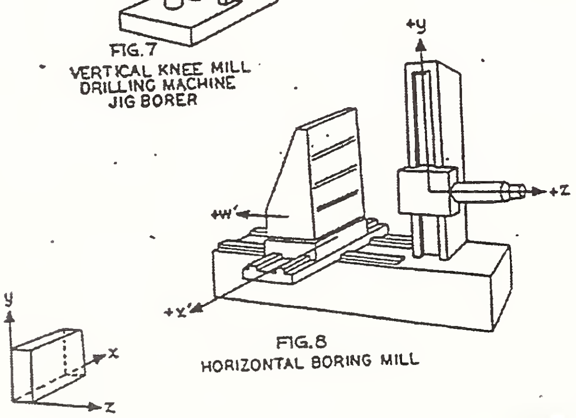


FIG. 8
HORIZONTAL BORING MILL

Slide 8

IQL

Independent Quality Labs, Inc.

METHODS OF STORAGE

AND

RETRIEVAL

Proprietary Data Files	A		
ASCII Data Files	A	D	
Data Base /Standard Format		D	R

Slide 9

IQL

Independent Quality Labs, Inc.

METHODS OF ANALYSIS

National Standards	A	D	
International Standards	A	D	
Other	A	D	R

SPECIALISTS IN PRECISION 3D MEASUREMENT

Slide 10

IQL

Independent Quality Labs, Inc.

METHODS OF APPLICATION

Buy/Sell	A		
Maintenance Support	A		
Error Comp;			
1d Lead screw	A		
3d Volumetric (CMM)	A		
3d Volumetric (Machine Tool)		D	R
Thermal		D	R
Machine Simulations		D	R
Factory Simulations			R

SPECIALISTS IN PRECISION 3D MEASUREMENT

NIST PRESENTATIONS

MACHINE TOOL METROLOGY INFORMATION MODELING

S. Frechette

I would like to spend a few minutes discussing information modeling and how we intend to use it in this project. Why use information modeling? Because it provides a basis for common understanding and communications among domain experts and application developers. In order to develop software applications that are capable of exchanging data, we must devise a mechanism to express knowledge from domain experts in a form that application developers can understand.

The goal, therefore, is to share data. We need to define the data requirements for our systems. In addition, we need to enable the development of systems -- software systems in this case -- to exchange information. For example, company A has just completed a ball bar test and wants to transfer that data to company B who will analyze it. To accomplish this, the receiver must be able to understand the format the sender is using. At this point, questions arise: "How can I take your data? What format is it in? What system are you using?" The goal is to have the information flow seamlessly either from system to system or from system to database to system.

Slide 5 shows a typical modeling process. In practice, the modeling process is not linear but iterative in nature. One must know something about an application before one develops a scope, but when viewed as a linear process, we develop a scope, an activity model, as well as define our activities and identify what data is flowing between them. An information model will further define the data. And, if done correctly, may be processed into a computer-interpretable form such as EXPRESS. This is a form that an application developer can understand and it is possible to generate database calls and schema directly from an EXPRESS representation.

Application development is an iterative process with several activities occurring in parallel. At this point, we are in the activity modeling phase as shown in slide 6. Yet we will probably have to revisit the scope because I do not think we have defined it well enough. It is also not yet clear what applications we are targeting. The target applications have significant impact on the scope and data model development.

In terms of the scope, we need to understand the process. There have been several viewpoints expressed here today. Are we looking at machine tools in terms of purchasing? Analysis? Maintenance? These are all valid but different viewpoints which may have different data requirements. What information do I need to know about a machine tool to purchase one effectively? Why is this machine not functioning correctly? I need to fix it. What information do I need? I need to understand the application and understand the process. We need to establish a reference architecture, so people from different industries and different viewpoints can discuss the information requirements.

Slide 7 shows an activity model. Essentially, an activity and information flowing in and out of that activity. This example shows two activities (boxes) with information flowing from one to the other (from Activity 1 into Activity 2). The data flowing between the activities is what we are really trying to capture. One way to accomplish this is to define all of our activities and identify all the data flowing into and out of each activity.

Slide 8 shows an example of an activity model operating conditions for a process are being measured. Environment data is flowing into the first activity. Temperature data is flowing between the monitor activity and controller activity. Perhaps, if the temperature is too high, the controller will put out a danger signal. This information may be used in some other activity, for example, to start a cooler or shut down a machine.

We can see inn slide 9 how involved an actual model becomes when a number of activities are defined. Each activity (box) on this page will devolve into a separate diagram. This refinement continues until the desired level of detail is achieved.

The activity model is only a tool to help identify the data requirements. Essentially we are left with lists of data elements. Now we must organize these lists and arrive at a common understanding of the terminology. For example, if I ask person A to make me a list of all the data he needs to understand a machine tool, and then I ask person B to do the same thing, the chances that I will receive incompatible results are high. Person A recorded his data in one column and used capital letters. Person B used all lower-case letters and recorded his data in rows using commas as delimiters. I will not be able to compare the lists.

With the list of data elements established, we will use a standard format, such as EXPRESS to unify our approach to organizing the data as shown in slide 10. We will identify data entities, assign attributes to those entities, determine data types, and most importantly, we will establish concise definitions for all terms in the model. This will allow us to share the model with other people.

Slide 11 shows a list of several modeling languages. IDEF 10 is a language used for activity modeling. Other modeling languages are available. EXPRESS will be used for this project.

Slide 12 provides a brief overview of EXPRESS syntax. The schema is a domain, a collection of EXPRESS statements, which describe information. An EXPRESS model is made up of entities. These entities have attributes, and those attributes have types. Attributes can be inherited from other entities There are also rules and functions--such as supertypes and subtypes. I will not go into any more detail. I am sure most everyone on the room is familiar with computer languages and should have no trouble with the EXPRESS overview in the handout.

Slide 13 shows a diagram from the RRM tooling database. Tool assembly is an entity; it has an attribute "magazine slot number." That attribute is type "Integer." At some point, tool assembly was identified as an important piece of data. One of its attributes is slot number which should be an integer. Similarly, one can follow the rest of the attributes. Every line coming out of "Tool Assembly" is an attribute. It has a name and it has a type. The dotted lines mean it is a defined type. The "ABS" means it is an abstract entity. For comparison, the textual version of EXPRESS is on the left-hand side. EXPRESS is text. EXPRESS G is the graphical representation.

Slide 14 shows the list of machine tool data which was used to create the machine tool metrology model. The list represents data elements important to machine tool metrology. Once these elements are identified, data types must be determined and relationships between elements must be established. If this is done using a known format, such as EXPRESS, it may then be processed directly into function calls for our database [e.g., SQL (Standard Query Language) calls]. This will be the basis for the database schema.

The current Machine Tool Metrology model (in EXPRESS) is with your handout. I will put up just the first page as shown on slide 15. We can see the "Machine Tool Performance" entity with three attributes--File Header, Equipment Artifact, and Test Run. The circular, or rounded, boxes on the bottom are references to other pages where the model is continued.

MS. KRULEWICH: Will the plan in the future be for participants to enter data into this model? Will there be a user interface that prompts me for these questions? Or do I have to actually learn this language?

MR. FRECHETTE: No, you do not have to learn the language. Ultimately, what we want to do to is construct a commercial application. To accomplish this, we need to communicate how the data should be structured and the desired data format to the applications developers. This is where the EXPRESS language (or the IDEF 10 language) is used. The initial data modeling effort attempts to determine what data is required and the desired format for the data. This step is, more or less, the development a series of lists. We may use IDEF to help identify what data is required, but expertise in using EXPRESS is not necessary. I believe participants will just provide files representing the data they use. As the data repository is developed, data entry methods will be refined.

MS. KRULEWICH: One other question. You have that list that Steve gave you of all the important information. It seems like that is an important issue - what information would you want to get reported in here. It might be interesting to do a survey of IQL software and the different existing commercial packages and see what data is reported.

MR. FRECHETTE: I agree completely. The list we started with was, as you know, by no means definitive. That is a very difficult process; deciding where I am going to define the data and where is the data defined? Do I go look at existing applications and just list down all the data that they deal with? That is one part of the process. I think that this is what this is all about. Talking to industry experts and trying to get input on data for future use. One thing we want to do is look toward the future and look at what applications might be doing. And it is my opinion that a lot of the people in this room are really cutting-edge when it comes to that.

MR. CALLAHAN: Dave Hemerle just asked me a few questions which I had actually thought about earlier. Who is going to own this database? Who is going to pay for the database? Where is it going to reside? Has that been discussed?

MR. DONMEZ: Well, that question came up in our last workshop, and I think what we are intending to do is to develop the structure of this database, develop the methodology, decide how to provide access to it, and hope that industry will take these structures and start building for their own use. Then, somebody can come in and develop a more accessible global database. That issue is important, but I think companies like Caterpillar, General Electric, and General Motors would be more interested in using it for their own, that is, if they see that it is advantageous. Then it will expand to other companies, maybe as a more global type of repository. That is our view.

MR. CALLAHAN: Could we get some big companies to comment on that?

MR. BISHOP: What I hope would happen is that this could serve as a framework for all the vendors out there who are producing software products so we do not have to. At Boeing, amass data elements and build parsing routines for each and every package that comes out. We could have a standard that different vendors would work to. That is what I am hoping will happen.

MR. FRECHETTE: That is the direction in which we should be headed. NIST can act as a catalyst by developing a draft data structure and once there is enough momentum, an industry group will get together and say, "Okay, now we need to step back and do a very rigorous data mapping exercise." This will lead to some type of industry standard, a commercial standard, which will allow software applications to exchange information and to users, like Caterpillar, it would be invisible. Users would not have to develop their own software to integrate various commercial applications.

MR. CALLAGHAN: I'm wondering whether we should have some experimental database residing at NIST?

MR. DONMEZ: That's what we're trying to do right now, an experimental database.

MR. CALLAHAN: But what I was going to suggest is that the users subscribe to that by providing information and you just dump it in there and then we would have access to work with that database just for experimental purposes. I think some kind of formal structure has to be put in place that says, "Okay, Boeing, GE, Pratt and Whitney are going to contribute data on, for example, horizontal boring machines, and then they're going to have access to the database. The other piece of it is to have some formal structure to get that data into the repository where the people who are participating are going to have access to it.

MS. McMILLAN: We already have a data model and database and data entities and relationships all lined up. I don't know what it would take, but I'd like to share input with you so that we don't have to change things later. But we've been working on it for a while now and we've got something that we think covers everything we've seen so far.

MR. DONMEZ: So, we need your input on the discussion right now that we're going to be showing some of the data types and formats. Hans Soons will lead that discussion. Then, once we get your input, we'll find out how much we're off and what type of modifications we need to do in order to come to a more standard format.

MS. McMILLAN: Well, I would not run anything through our Legal Department yet.

MR. CALLAHAN: That's why I raised the issue. We went through this same problem about 15 years ago relative to the coordinate measurement machines. All the builders of coordinate measuring machines were going to submit similar kinds of information to the B89 standards committee at that time and it took around three years of legal wrangling to be able to get even just a small bit of that data. We wanted to see how well the B89 standard was working. We've got the same problem here. We want to see how well these database structures are going to work.

MR. DONMEZ: We are aware of some of the legal problems and some of the reluctance from the machine tool builders; that issue came up in the last meeting. I think at this point we are not going to be relying on machine tool builders to provide the data. Instead, we are relying on the users to provide the data. The way to protect against the legal issues is to not put any labels to the machines. There will be generic names--Machine A from Company B. We should put only the data not the real names of user companies nor machine builders.

MR. CALLAHAN: When will you be able to start shipping raw data and some specifications of that raw data to us? Are we talking about something that you could start today, next month, six months from now?

MR. DONMEZ: As you'll see a little later, Larry Welsch will show you an experimental repository that we have been playing with for the last month or so. There are some data in that repository already.

MR. CALLAHAN: I want to raise one other question. I've got probably one of the largest repositories of this kind of information in the country right now. I have, on several occasions, gone back to my customers and said, "I have a bunch of data from General Motors I was going to give to Steve Patterson." They went back and went through their legal department and they said, "What's in it for General Motors?" Without an answer, they didn't give us the data. So, what I'm searching for here is some give and take, so that if I put a bunch of data into the system I have access to do something with that database. I'm sure everybody who is going to have to release data into this database is going to have the same problem. Therefore, it's going to have to be a give and take situation. So, we need to put together a structure that says, "Okay, if I put 10,000 hours work of data into this system, I'm going to have access to information on 100 machines of this particular configuration, or 10 machines of that configuration."

MR. DONMEZ: Yes. But I think when we put data in, for example, we should not associate that data to GM or Cincinnati Milacron.

MR. CALLAHAN: Right. I agree. There still has to be give and take.

MR. CHANDRASEKHARAN: A couple of comments. On the previous one that you talked about, who owns this database or how it gets used, there is a similar effort in Europe for the DIN 4000 standard for tooling information. That evolved over the last few years and now there is a company called SIM that actually sells CD-ROMs, which they update using the database format. It's working really good in Europe because now Kennametal, Valenite and Sandvik, in Europe, have combined together and formed a consortium with this database developer and they've changed the database structure to make common data. In fact, if they were the same tools that we manufacture, it's three times as much data. And the database starts getting huge. Now they've leveraged that kind of work and they have formed together and it's working really well over there. Unfortunately, it hasn't moved into the United States as much as we'd like.

The second point is from a user perspective, that we would be very willing to put data into a repository like this first, because we learn how to use the data. Also, we learn how the applications coming out of data like this can work and what benefit it has to a company like Caterpillar. For these reasons, as long as our name is not associated with the data we put in, I think we'd be very willing to put anything into it. We're also going to help the development of smaller companies like what SIM. If it's cost-effective enough we might just take the entire database development on our own. A company like GM or Ford might just do that, whereas a company like Caterpillar might just choose to pay an annual fee to get the database and regular updates periodically once a month. So it's just an evolving business which has worked really well in Europe.

MR. PATTERSON: I think it's important that we distinguish several things that we could be doing here. There are really four topics that seem to be circulating here in a perhaps unfortunately interchangeable way. There is an information model to be developed about the process itself. Then we've been talking about the design of the database, which is basically a way of structuring that informational model in a useful way. What we have assumed, but haven't identified explicitly, is a file format for the interchange of that data, which is an additional definition thing. And then what we've started to spin up to high order here is repository management. Now, I would offer that three of those four things are essentially technical in nature and there is no roadblock to developing them and they have significant benefit to a wide variety of us. If we crash on the shoals of politics and legalism in terms of maintaining a large repository of data in a centralized location, that makes it no less useful, at least for the data which I'm perfectly happy to send to IQL, since I'm not as parsimonious about the data as GE, or General Motors, or somebody else may be. The results are still highly useful. I hope we didn't get sidetracked on legal issues when we probably have about the right audience in this group to make an awful lot of progress on the three technical issues in front of us.

MR. DONMEZ: Based on Steve's classification, information models, design of database and file formats are the three technical issues that we should concentrate on. We should leave aside the fourth item, repository management, for now.

Machine Tool Metrology Information Modeling

Simon Frechette

National Institute of Standards and Technology
Manufacturing Engineering Laboratory

2/18/97

Outline

Information Modeling Overview
- Purpose
- Mechanisms

Overview of EXPRESS
- Syntax
- Example

Draft Model for Machine Tool Metrology

Handouts

Goal of Information Modeling

Define the data requirements for a system.

Enable the development of systems (usually software) that can exchange of information.

Why Perform Information Modeling?

Translate expert's knowledge into form that can be understood by application developers.

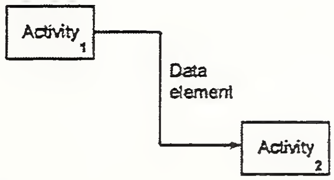
Typical Modeling Process (Simplified)

Activity Scope
↘ Activity Model
↘ Information Model
↘ Application

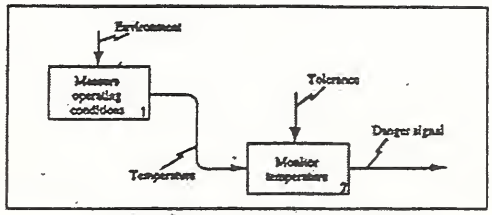
Activity Modeling

- Refine scope
- Define activities and data requirements
- Understand current processes better
- Provide reference architecture for systems analysis
- Provide means of communication among analysts, designers, users, and managers

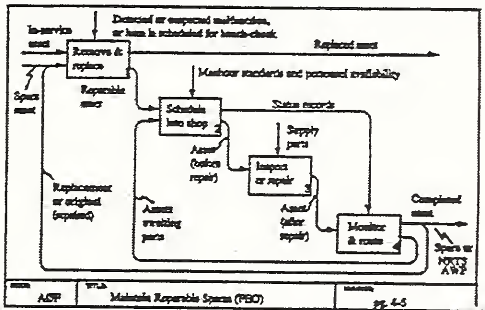
Activity Model IDEF10



IDEF10 Example



IDEF10 Example



Information Modeling

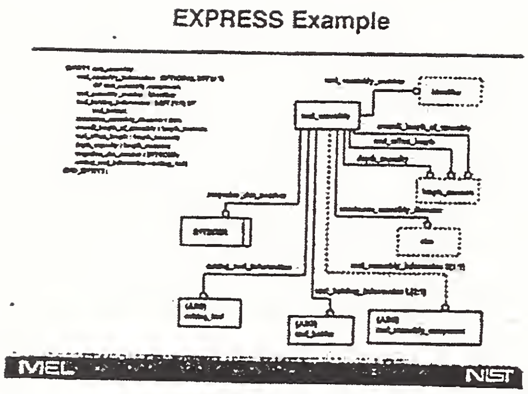
- Develop lists of data elements - pieces of data that must be modeled
- Identify data "entities"
- Assign attributes to entities
- Determine data types
- Formally document this information in a standard format (modeling language) so it can be shared with other developers

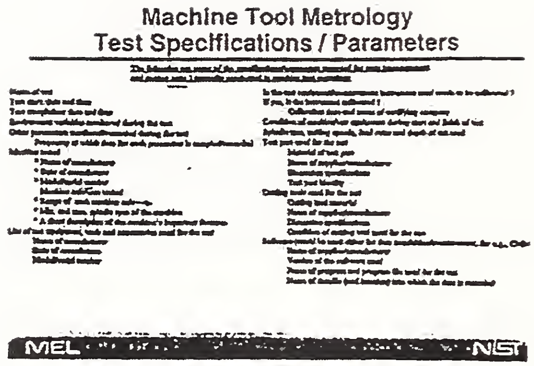
Modeling Languages

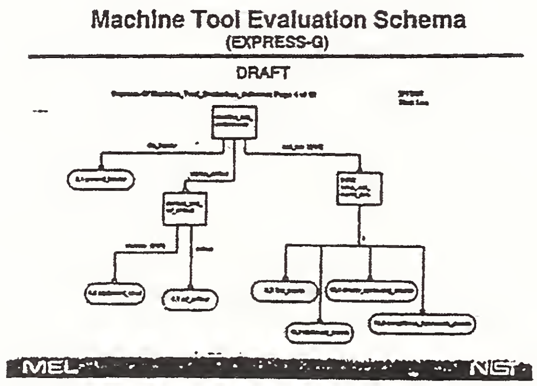
- Integration Definition for Function Modeling (IDEF0)
- Entity Relationship (ER)
- Nijssen's Information Analysis Methodology (NIAM)
- Integration Definition for Information Modeling (IDEF1X)
- PDDI Data Specification Language (DSL)
- STEP EXPRESS
- Semantic Association Model (SAM)

EXPRESS Syntax

- SCHEMA - collection of EXPRESS statements which describes the information for a particular domain.
- ENTITIES - grouping of data elements. Entities describe complex structures similar to a _table_ in a relational database or a _class_ in an object-oriented system. Entities have attributes, attributes have types.
- TYPES - describes the kind of values that an object can take on. Types are similar to "data types" in a computer language.
- SUPERTYPE / SUBTYPE - entities can have subtypes or belong to a supertype. An entity inherits the attributes of its supertype.
- RULES - used to describe relationships among entities. Rules are represented as procedural algorithms.
- FUNCTIONS - used to encapsulate a procedure which may be reused. Functions are used in WHERE clauses and in RULES


EXPRESS Example
MEL
NIST


Machine Tool Metrology
Test Specifications / Parameters
MEL
NIST


Machine Tool Evaluation Schema
(EXPRESS-G)
DRAFT
MEL
NIST

COMMUNICATION AND STORAGE OF MACHINE TOOL DATA

H. Soons

I would like to discuss information elements and possible formats that can be used to communicate and store the properties of a machine tool. The goal is to assess, update, store, and retrieve machine tool data necessary for virtual machining. You received two documents that accompany this presentation. One is called "Some Notes on the Machine Tool Database," and the other one is "Communication and Storage of Performance Evaluation Data."

To determine what data is needed, we need to define virtual machining. In a broad sense a virtual machine tool is a model, usually implemented in software, that predicts the output of the machining process by simulating the actions of the machine tool in response to the part program and the environment. As we discussed already this morning, the output of a virtual machine tool can be more than the tolerances of the part. Other possible results are the time required to make the part, the verification of the part program, tool life, and maintenance schedule.

A critical enabler to virtual machining is an efficient access to relevant data on the part we want to make, the method used to make it, the machine tools that we are going to use, the tools, and, of course, the machine environment. In this presentation I would like to concentrate on the third issue: what information do we need about the machine tool.

Machine tool data can be divided into two parts. One class is data that applies to all machines of a series. Usually these are specifications or design data published by the machine tool builder. The first document that you received, "Some Notes on the Machine Tool Database," contains a list of information elements that belong to this class. This data addresses the classification of the machine such as: is it a lathe or a grinder, is it a vertical or horizontal machine, or how many spindles and axes of motion does the machine have. It contains the information that we need to build the kinematic model of the machine; information on the axes and spindles, such as allowed feed rates, range, minimum increments; information about tool and workpiece management, for example the kind of pallets used; information about the controller such as the available error compensation parameters, which parameters are accessible to the user, enabled canned cycles. Finally, there are the accuracy specifications, often stated as a set of numbers that summarize the effects of certain error sources. Accuracy specifications and means to verify them are defined by performance evaluation standards such as the ANSI B5.54 and the ISO 230 series. Not all machine tool manufacturers follow these standards when specifying the accuracy of their machines.

Sometimes the machine data available for virtual machining is limited to this class. For example, virtual machining can be used to select the machine tool that has to be purchased to manufacture certain parts. In this case, detailed performance data is usually not available. Indeed the machine often has not yet been built.

The second class of machine data is that which applies to a specific machine at a specific site. This data comprises the compensation parameters of the machine, adjustments that have been made to that machine, any special modifications, and of course, actual performance evaluation data. We prefer a layered approach in the storage of this performance data. At the lowest level there is the raw measurement data. At higher levels, performance parameters are stored. An example of this would be the squareness error of two axes. Such a squareness error parameter will have a pointer to the test data used to calculate it, e.g., the data of two straightness measurements. The motivation for this approach is that we do not want to lose the raw measurement data. Machine tool error modeling and performance monitoring is still an evolving field. It is therefore not prudent to summarize and discard the measurement data based on the currently available parameters.

I would like to focus this presentation on how to store and communicate the description and measurement data of performance evaluations. There exists a variety of software packages for the performance evaluation of machine tools. Many of these are made by the manufacturer of a particular measurement device, such as a laser interferometer or a ballbar, and tailored to that particular instrument. The software packages use different data models and associated formats to store the measurement data. Sometimes these formats are proprietary. The data is hidden in a binary file whose content can only be retrieved by the software and in a form dictated by the software. Other packages use a more accessible format in ASCII.

Not all relevant information about a certain test is assessed and stored in particular information about the measurement set-up. Usually, the only information that is stored is the information required to produce the graphs and numbers specified in the various standards. For example, most software packages do not store or ask where in the machine workspace the test is executed or what the effective tool offset is. This information is essential for many analyses that go beyond the graphs and numbers specified in the standards, especially when results of several tests are combined or compared. In practice, this information is often lost or recorded in notebooks that have a life separate from that of the data files.

Most formats are tailored towards a specific type of performance test. If the device is used for a test not found in the standards, or for a recently standardized test, the format is often not useful or incomplete.

What is necessary is a unified definition of information elements and a related data format to allow for: first, the straightforward interchange of performance test data. Second, the communication and storage of all relevant information, not just the information, needed to produce a certain performance parameter or graph. And third, the description of non-standardized tests.

The information elements and data format should enable the reconstruction of the nature of the test and why, when, and by whom it was conducted. They should enable the identification of the equipment that was used to assess the data and which buttons were being pushed. They should enable a reconstruction of the measurement set-up, the machine movements, the applied warm-up procedure, and the environmental conditions.

Other criteria are: an efficient description of both standardized and non-standardized tests plus an efficient communication and storage of user-defined data. Both criteria are related to the fact that machine tool error modeling, performance evaluation testing, and condition monitoring are evolving. What is important tomorrow may not be important today. Also it is difficult if not impossible to anticipate all the information elements that may be important for a particular application or user.

The recording of all information relevant to a particular test should not be enforced. Sometimes, only a quick check is desired. Furthermore, it is not necessary to record all the information that would be required for an error compensation procedure. The format associated with the information elements should have a man-readable equivalent in ASCII, so that it is multi-platform. Finally, the organization and nature of the information elements should be such that queries can be handled very efficiently.

This slide shows an example of a data file generated by a commercial data acquisition package. The data describes the measurement results and some set-up information of a circular ballbar test. The used format is such that the information elements can be easily identified. As is usually the case, the test and measurement data are organized into runs. A run is a certain motion pattern of the machine during which errors are measured. A performance evaluation test consists of several runs which can differ in minor parameters. In this case, runs differ in the direction of motion: clockwise or counter-clockwise. The run data is preceded by a general header that contains common information for all the runs. Examples of these are: name of the machine and operator, date, information about the equipment, for example whether the ballbar has a calibrated length or not.

I would now like to discuss some ideas on the data structure and required information elements to describe performance evaluation data using a file format as an example. Measurement data is organized into runs. Each run has a header that only applies to the data in that run. The header of a run can modify the parameters contained in the general header. For example, the general header can specify a feed rate of 2 000 mm/min. The header of run 2 might modify this to 1 000 mm/min. This feedrate of 1 000 mm/min then only applies to run 2.

The data is organized into data blocks each with a keyword followed by data. For example, a block can contain the keyword "Operator" followed by the name of the operator. A dictionary of keywords with definitions has to be constructed. There should also be a mechanism for user defined keywords as is shown in this example. The presence of information elements should not be enforced, unless they are necessary. The sequence of the information elements should be arbitrary when possible.

A mechanism is needed to organize data into structures or sets, such as allowing multiple data blocks into the data field of a data block. Also, a mechanism is needed to give a data set a name and refer to it. In this example we define a device, which is a read-out device that measures temperature. Some information is supplied about the device, such as the units, the resolution setting, and the manufacturer. Here we define a temperature sensor that uses the previously defined read-out device. Extra information is given that pertains to this particular sensor, such as the channel number and where the sensor is located.

Defaults have to be defined. For example, all units are metric unless specified otherwise. If angles are measured and specified in inches per foot, there should be an appropriate statement.

A mechanism is needed to format data, storing it in tabular form. This is an example for a spindle drift test. The data has a header that defines what each column of the table contains. Items of the header may be labels that point to devices that are specified elsewhere. In this example, the table contains time, spindle speed, an indicator reader, and two temperatures. After the header follows the data. A symbol will be needed to identify missing data.

A challenge in describing a performance evaluation test is that various items are measured or changed during the test at different times. Plus, a mechanism is needed to synchronize these events. For example, a drift test may involve the measurement of drift and temperature over time, as well as a change in spindle speed at a certain instance. There are several possible mechanisms to describe the sequence of events. Probably several of these specifications should be allowed.

The first example is to list all items that are either measured or subject to change in one table. This format is, for instance, suitable for drift measurements where temperature and drift are measured every minute. Note that one column contains the spindle speed. Another method is to chronologically record each event. For example, the first entry is a change in spindle speed. The temperature and indicator readings are recorded for a certain time. Then the spindle speed is changed and temperature and indicator readings are resumed.

Another method is to sort events into blocks: one block with spindle speed data, one block with temperature data, and one block with indicator readings. Synchronization can be achieved using a time stamp as is done on the left side. The example on the right shows an implicit synchronization where the temperature data applies to all measurements of the run in which it is recorded. If more than one temperature reading is present, the readings are assumed to be distributed over the complete run.

In the next slides, I would like to discuss the information elements that are needed to describe a performance evaluation test. I already mentioned that the data is organized into measurement runs and a general header that contains data pertaining to all the runs. Now, I would like to start with a more detailed description of this header.

First, the format used to store the data should be specified. Second, a record that identifies the machine is needed. The operator needs to be identified and the date or dates when the test was executed. A formalized method is needed to describe the test so that queries to a particular kind of test can be handled efficiently. A start can be made by categorizing all tests in the current standards. The test description would include the standard used. A statement as to why the test was conducted can be useful.

An important section of the general header is a description of the test equipment, both measurement devices and artifacts such as ring gauges and straightedges. The description of a measurement device should contain the used settings and properties of that device, so that the precise meaning of a measurement value can be reconstructed. Examples are: units, resolution, applied compensations, settle time, number of samples averaged, and sample frequency. For artifacts, the data may involve the dimensions of the reference features of the artifact, and the effective coefficient of expansion. The data of equipment and artifacts should contain identification information that points to more detailed information stored elsewhere. Finally, the test equipment section contains set-up information. I will explain that in more detail later on.

A section of the general header may describe the status of the machine, such as applied compensations, whether or not the coolant was on, if any axes were clamped and the applied warm-up procedure. Statements and measurement data about the machine environment may also be included in the header. If detailed information is available, like multiple sensor readings over time, it can also be included in the data section of a run. Finally, the general header will possibly have a comments section organized using keywords

During the final part of this presentation, I would like to discuss the information elements needed to describe the measurement set-up and the machine motion pattern. Performance tests can be classified into groups that share a similar measurement set-up and motion pattern. The first class are tests where the machine is moved along a line in the machine axes space. Examples of such tests are the roll, pitch, yaw, straightness and positional error measurements of an axis, and diagonal displacement tests.

The second class consists of the "stationary" tests. Here errors in the position of the tool relative to the table are measured at one point in the machine workspace. Between measurements, machine axes may be moved, after which the tool is returned to the measurement point. An example of such a test is the environmental temperature variation test. It involves measurement of the drift in the position and orientation of the tool over time. Other examples are the spindle thermal stability tests, composite drift tests, subsystem repeatability tests, and spindle axis of rotation measurements.

Other classes are circular contouring tests, compliance and hysteresis tests, and machining tests. Note that this classification does not address the purpose of the test nor the components tested, but rather the set-up and machine motion pattern.

As an example, I would like to discuss the information elements required to describe a performance evaluation test that involves machine motion along a line. First, the machine motion pattern needs to be defined. This requires specification of the used feed rate between the target points, or an indication that the machine is moved manually. For each run, the approach direction has to be specified, which can be a positive approach, negative approach, or a pelgrim approach. There are several methods to specify the target points. One method is to record the position of all the machine axes at each target point. Another is to define a start position, the direction of positive machine motion, and target the amount of travel along the line for each. The direction can be defined in several ways: using a direction vector, by specifying the axis that is moved, or by specifying a start and end position. In the example at the bottom of the slide, the target points are defined by a start point, an end point and a sampling interval. In case of a dynamic measurement, a sampling frequency can be used.

In addition to the motion pattern of the machine, the measurement set-up needs to be defined. A test can involve several sensors. For example, there are set-ups where angular, straightness, and positioning errors are measured simultaneously. Each sensor requires the specification of whether it measures an angular or a displacement error, which machine component is the target and which the reference, this is especially important for machines with multiple spindles and turrets, the direction of positive error motion of the target, and the effective tool offset associated with the sensor. The orientation of the used reference, such as a straightedge, may be important, for example, for reversal purposes.

The next slide shows the example of a Z-axis pitch measurement of a lathe. In this block the used measurement device is specified, including the set-up. The device has been given the name "Laser". So, if a data table contains the label "Laser" in the header, we know that the respective data has been obtained using the device specified in this block. Various device-specific settings are specified such as: the nature of the measurand, in this case an angle, the direction of positive error motion, in this case a rotation around the positive Y-axis, the units of the measurand, the sample frequency before averaging, the number of samples averaged, the settling time, the machine components to which the reference and target are attached, and the effective tool offset.

I hope that this presentation gave you an impression of information elements and possible formats that can be used to communicate and store performance data of machine tools. I focused on the measurement data and description of performance tests. Further formalization requires choices and more information. For both, we need your participation. Today we would like to know if further formalization of information elements and formats is a useful effort, if the chosen approach and focus are right, if essential elements are missing, and what we need to change. We also are very interested in the kind of information you currently record during performance tests, the formats used, and what you do with the data.

DISCUSSION

MR. CALLAGHAN: Do you see this as a file-based system or a database system? Has that not yet been determined?

MR. SOONS: Our primary focus was to identify the information required to describe a performance evaluation test and its results. Regarding the format, I focused on a system where all data of a particular performance evaluation test can be contained in one file. We hope that by defining the format in the right way, for example by using some of the EXPRESS formalism, it will also be useful in the design of a database that contains many performance evaluation measurements. In that case, the file format may only be used to communicate performance evaluation data.

MR. CALLAGHAN: One of the problems I have is, obviously, the limitations of files. Also, the file naming convention is a huge handicap. At Renishaw, for example, I ran 100 machines and I ran ballbar tests on a weekly basis. It is very clear that we had to develop some method of organizing all that data. There is no way to do it with the conventional file naming conventions. You have to translate it into a database format. So, that is the direction in which I have been heading. So I was just wondering if, perhaps, that is the direction that you all want to consider. When you are talking about a large number of machines and a large amount of data, then a file format does not usually satisfy performance. Also, for the textual file formats, we have to build programs to strip the data out of these files to put it into the database. So if we can agree on some methodology where we could already be in an Access type format database, or something, then that would go a long way toward helping us organize our data. As opposed to staying in an ASCII file format structure.

MR. SOONS: I was trying to do both. I find file formats very useful to store data when measurements are taken, as a backup of unprocessed data, and aim to communicate data. I do not think transporting the data into a database will be a major problem.

MS. McMILLAN: When you have such large amounts of data I think it can be. It is for us.

MR. CALLAGHAN: The file formats tie you back to the vendor-specific software in the analysis tools which is not always where you want to be. We would like to be able to extract the data and use it either way; we could use the vendor software to process it or we could use our own tools to process the data.

Renishaw uses one format and API probably uses another. If I want to use both tools, or combine data from both tools, I have a problem. Both talk about roll, pitch, yaw and squareness, but the way they format them in their files is totally different. In many cases we have multiple packages in-house.

MR. FRECHETTE: What if those vendors gave you the choice of a standard format?

MR. CALLAGHAN: Precisely. I am hoping that we can agree on what such a file format might look like. So when you talk about roll, roll looks like this, defined characters and defined field size. So that no matter where you get the data from, it will always look the same.

MR. SOONS: This is one of the things we hope to achieve, and that manufacturers of software and measurement devices will take it over. When this is achieved, I think that translation into a database is not much of a problem, because you only have to do it once for each file.

MR. CALLAGHAN: That would work. That would be a good step in the right direction for us.

MR. CALLAHAN: I think you need to specify the file formats to even understand what we have to put in the database. Some very important issues have been mentioned today. Issues that become important as you begin to use this data more extensively than we have in the past. With the file format we can play for a while before we build this big database.

MR. CALLAGHAN: I am not sure every vendor is going to want to incorporate every single element that every other vendor has. There should be some nucleus.

MR. SOONS: That is why I think it is important not to enforce the presence of all information elements. We want to define the keywords, definitions, and possible data structures and formats to be able to include information, not to enforce it.

MR. FRECHETTE: You are going to run into a problem with that because, if somebody is expecting a sample frequency then their system is going to crash if it is not in the file. You need to institute a minimum subset where at least you will get the functionality of the applications. That is what we have done in the auto industry; we have established a minimum subset for configuration management data and then, if you don't want the entire set, you do not need to deal with it.

MR. SOONS: If we abandon the file format, are we not abandoning a large part of the customer base? The use of databases to analyze and store performance evaluation data is not common. Often, only the software that came with the measurement device is used to analyze the data.

MR. WELSCH: There is an even bigger problem. The database community itself has not agreed upon interchange standards and that is a very serious problem. What they have agreed upon is a query language, so we are kind of stuck with defining an interchange format.

MS. McMILLAN: Do we have any standards yet for data exchange?

QUESTION: Well what about STEP? They are a series of protocols that apply to a variety of things. A review of those might be useful in this area.

MR. FRECHETTE: I don't think there are any existing application protocols that cover this domain.

MR. WELSCH: It is a matter of the level of abstraction of the problem. If you look way down low, there are many standards for doing this, and if you start looking way up high, towards only machine tools, I don't think there are any. Where we are in that spectrum is any place you want to pick, and there is not one that is quite right.

MR. MA: Back to the database. I like to group the information into three groups. One is machine-related, one instrument-related, and one measurement-related. A vendor could already store most of the instrument-related information. All three groups would make the measurement file pretty immense. The three groups can be stored separately and merged together when put into a database.

MR. PATTERSON: I don't think that is inconsistent with what is being done here. However, I was thinking about how we would implement this internally. One of the beauties of working from an information model downward in both the database and the exchange format, with a common dictionary for the terms, is that I have all the pieces together. The dictionary for the terms gives me the references I need for a standard query language. The file format lets me send something, and then I can organize the data your way in my internal database. I can put an identifier with the measurement instrument and use a relational database property to store that information in one place once. So in my database, I will have the table of instruments, the table of machines, and the table of measurements. Then, in proper and normal relational database fashion, when I need to send an experimental result to Debbie, who has a different set of local instruments and the like, I can append the header in the way Hans has laid it out so that the full set of information gets transmitted on the exchange. And, if there is some consistency in the data validation, that can be done in an unambiguous and common way.

MR. WELSCH: One of the very real problems that I have observed in other fields, and I am not from the manufacturing field initially, is the issue of consistency that he just raised. How do we arrive at that consistency in the dictionary with the very subtle differences in meanings that different manufacturers will apply to the same name that we, as humans, deal with very easily but software has a miserable time dealing with?

MR. DONMEZ: That is why manufacturers should be involved.

MR. CHANDRASEKHARAN: A good instance for that is chatter or stability. How do you tell a computer what is chatter or what is stability? You never get that threshold point defined mathematically. Some things are difficult to put numbers on.

MR. MA: I have a question on the definition of the data. If you look at the data, what does it mean? Different people a have different interpretations. People give us data and often we have to ask what it means. What is the X,Y, and Z? There are two definitions. One is from the plot coordinates, another from the controller. Sometimes the controller does not have right-hand coordinates. But in software we usually apply right-hand coordinates. Different people give different definitions. For example, with the pitch, yaw and roll, which is pitch? Therefore I think, in addition to the format, the data itself should have a clear definition.

MR. SOONS: Indeed we need definitions at several levels. First, the meaning of the keywords that identify the information contained in a data field need to be precisely defined. Then the format of the data field needs to be defined, for example if a date is going to be in a day, month, year format or a month, day, year format. As you mentioned, some terms and tests are not well defined in the standards, a typical example is the sign of positive error motions. We will have to have a close look at that.

MR. DONMEZ: For example to resolve the confusion about the definition of pitch and yaw, we may have to define the plane of the angle.

Is there anything in the list that you have seen that seems to be missing?

MR. CALLAGHAN: There are a few things that we do not have, and we probably have a few things that you do not have, but we are pretty much on the same track. I think this is a really good start and it encompasses much of what we have to do. We have many internal things that we have to deal with in terms of the organizations in which our machines are and other kinds of things that a group like this will not have to deal with.

MS. McMILLAN: I think we need to take a closer look at the different options for data modeling.

MR. DONMEZ: What kind of data modeling tools do you use?

MS. McMILLAN: We have two different kinds. We were using Accelerator and we just purchased a new one. Both of these packages are IDEF-based. I am anxious to find out more about the data modeling. Maybe have a group lay out a proposed high-level model and start going down. That is how we did it.

MR. FRECHETTE: But you have a model now?

MR. CALLAGHAN: Yes, but it is somewhat specific to our particular application. It encompasses machine measurement, but it also encompasses many other factors that would be specific to Boeing, as opposed to, perhaps, other vendors.

MR. FRECHETTE: How long did it take you to develop that model?

MS. McMILLAN: It has been off and on for probably two years now because of funding issues and the amount of people that we can put on it. The focused time is probably at least six months, but it has not been a big effort, just a couple of people.

MR. CALLAGHAN: Obviously, we want to make sure we are paralleling this effort as much as possible, and we can learn from things that we do not have.

MR. DONMEZ: We want to learn from your experience too.

MS. McMILLAN: As technology moves on, I think you want to be less and less file-based because even the smaller vendors can use packages like Access and make a nice relational database out of that. You can do a better analysis quicker, and get to the information that you need quicker. We set up little committees to look at different tools to do this.

QUESTION: Is your model something you can share easily, taking away the Boeing-specific part of it?

MR. BISHOP: She's got to run it through Legal and Public Relations. We don't know right now.

MR. MA: What did you use for your model? Did you concentrate on just one machine to see which machine can be used for what parts?

MR. CALLAGHAN: Yes, and we monitor the health of the machines. We use statistical tools on our data.

MR. CALLAHAN: We monitor over time and we look at all the different tests as to what is happening over time. We run frequency tests as well as the baseline measurements. We have many different tests, almost everything in the B5.54. We keep track of what tests we run. All the things that he had outlined are pretty much in our system.

MR. SOONS: Have you already put the mechanisms in place to combine and correlate data so that if, for example, you have positional, squareness, pitch, yaw and roll measurements you try to see if that correlates to what you are seeing in other tests or your parts. Also regarding variations in time.

MS. McMILLAN: That is the next phase. And that will need more of an analysis, which things need to be correlated and which ones don't, and which variation factors are more important than others. I foresee it getting knowledge-base oriented.

MR. CALLAGHAN: We need to get our data together so we can look at the spectrum of the information. We don't have that capability right now. The data resides on various files, in various places, and in various systems. Our intent is to bring it all together so we can start looking at all of our machines simultaneously. We have not done the kind of analysis that you're talking about, but we don't see an easy way to do that until we have all the data at our fingertips.

MR. DONMEZ: Any other comments?

MR. CALLAGHAN: Can we create a mechanism for the exchanges that are going to be necessary in order to compile a more complete list?

MR. DONMEZ: Yes. Let's wait until after the coffee break when Larry shows the web site. Maybe we can put some data in the web site and communicate through the web.

MS. McMILLAN: Does NIST already have a data definition list, a data dictionary of standard terms?

MR. SOONS: The two documents that I described are our first effort towards that goal. They try to give an overview of the information elements required to store the results of performance evaluation tests. They do not yet give a formal list of keywords, definitions, and relations. That will be the next step.

MR. CALLAGHAN: It's a really good start though.

Communication and Storage of Machine Tool Data

Hans A. Soons
Automated Production Technology Division
National Institute of Standards and Technology

February 18, 1997

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Virtual Machining

Virtual machine tool:

A model, usually implemented in software, that predicts an output of the machining process by simulating the actions of the machine tool in response to the part program and the environment.

Output:

- Tolerances part
- Time required to make the part
- Verification part program
- Tool life
- ......

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Required information

Critical enabler is efficient access to relevant data on:

- The part (geometry, tolerances, material)
- The process plan (part program, setup and fixturing)
- The machine tool(s)
- The tool(s)
- The machine environment

Machine tool information:

- **Data that applies to machines of a series**
  "Design data": Classification, kinematic model, axis and spindle data, tool and workpiece management, controller, accuracy specifications, ...
- **Data that applies to a specific machine**
  - Compensations, adjustments
  - Performance evaluation data (tests, parts)
  Layered approach: raw data -> performance parameters

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Performance evaluation data

Currently:

- Many formats
- Not all relevant information is stored
- Application limited to standardized tests

Unified definition for a flexible data format:

- Straightforward interchange of test data
- Communication and storage of all relevant information
- Non-standard tests

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Criteria information elements and format

- Enable reconstruction of:
  - The nature of the test and why, when, and by whom
  - The equipment used and settings
  - The measurement setup
  - The status and motion pattern of the machine
  - Measurement data
  - Environmental conditions
- Efficient description of standardized and special tests
- Efficient communication and storage of user defined data
- No enforcement of information
- Man-readable equivalent in ASCII
- Efficient handling of queries

- EXPRESS

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Format example

```
HEADER::
File type: [illegible]
Owner: [illegible]
Version no: [illegible]

MACHINE::
Machine: [illegible]
Date: [illegible] Nov 22 [illegible]
By: Hans Soons
Length: [illegible]
Plane: XY
Radius: [illegible]
Feedrate: [illegible]
Data Start: 0.000000
Data End: 360.000000
Ang over: [illegible]
Stat/Dyn: S
Dir: A
Cal Lens: C
Run Count: 4
Serial Number: [illegible]

Gauge Exp Coeff: [illegible]
Machine Exp Coeff: [illegible]
Max Targets: [illegible]

DATA::
Direction: 1
Sample Rate: [illegible]
Best R: [illegible]
Best X: [illegible]
Best Y: [illegible]
Datacount: [illegible]
Gauge Temperature: [illegible]
Machine Temperature: [illegible]
Point Raw-data:
0 +0.0566
1 +0.0707
2 +0.0877
: :
[illegible]

EOF::
```

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Format example

```
HP 5529A: Linear Error Plot - X-Axis
Filename: c:\[illegible]
Acquisition date: [illegible] PM
Current date: 4/29/96 [illegible] PM
Measurement Type: LINEAR / Calibrator
Sign Convention
Axis: X
Travel Mode: Bidirectional
Number of Target Positions: [illegible]
Number of total data pairs: [illegible]
Number of total data runs: 12
Expansion Coefficient: [illegible]
Position Value Units: millimeters
Error Value Units - micrometers

environmental data - MIN MAX AVG
Air Temp (C) [illegible] [illegible] [illegible]
Air Prs (mm) [illegible] [illegible] [illegible]
Air Hmd (%) [illegible] [illegible] [illegible]
MT1 Temp (C) [illegible] [illegible] [illegible]
MT2 Temp (C) [illegible] [illegible] [illegible]
```

```
Sorted by run number
Run #Pos #Target Value Error
Value Out of spec.
1 1 [illegible]
1 2 [illegible]
1 3 [illegible]
1 4 [illegible]

2 1 [illegible]
:  :    :     :
10 51 [illegible] *
10 52 [illegible] *
10 53 [illegible] *
```

General structure and concepts

File structure:

```
<GENERAL HEADER>

<HEADER RUN 1>
<MEASUREMENT DATA RUN1>

<HEADER RUN2>
<MEASUREMENT DATA RUN2>

Etc.
```

← Modifies or augments general header, (information applies only to this run)

Information organized in blocks (key word: data):

```
Operator: L. Pavarotti
User(Reliability data): low
```

Presence blocks not enforced and sequence arbitrary (some restrictions apply)

General structure and concepts

A block can contain other blocks, referencing mechanism:

```
Device(Readout 1):
   Measurand: Temperature
   Manufacturer: XYZ
   Serial number: 123ABC
   Units: degrees C
   Resolution: 0.01
   Sample frequency: [illegible]
End

Device(T1):
   Readout: Readout 1
   Channel: 1
   Location: Spindle collet
End
```

Defaults and mechanism for changing defaults:

```
Units(Angle): Inches per Foot
```

General structure and concepts

Mechanism for formatting data:

```
Data(run 1):
   Time, Spindle speed, Indicator 1, T1, T2:
   13:01   2000   234  24.2  23.2
   13:02   2000   232  24.1  23.2
   13:03   2000   231  24.3  23.5
   13:04   0      222  24.5  23.7
End
```

Mechanisms for synchronizing data.

```
Data(run 1):
   Time, spindle speed: 13:01 2000
   Time, Indicator 1, T1, T2:
      13:02  224  24.2  23.2
      13:03  231  24.3  23.5
   End
   Time, spindle speed: 13:04 0
   Time, indicator 1, T1, T2:  13:01  234  24.2  23.3
End
```

General structure and concepts

```
Data(run 1):
   Data(spindle speed):
      Time, speed:
      13:01   2000
      13:04   0
   End
   Data(displacement):
      Time, indicator 1:
      13:01   234
      13:03   233
      13:04   230
   End
   Data(temperature):
      Time, T1, T2:
      13:01   24.2  23.3
      13:03   24.4  23.4
      13:04   24.4  23.3
   End
End
```

```
Data(run 1):
   Feedrate: 1200
   Motion: clockwise
   T1:  24.2
   T2:  23.3
   Ballbar:
      234
      230
      222
      232
   End
End
```

General information

- Format identification
- Machine identification:

```
Machine(Kugster grinder):
        Manufacturer: Kugster
        Model number: ABC
        Serial number: 98-759847
        Plant: Shops
End
```

- Operator identification
- Date and time
- Test description (enable efficient handling of queries):

```
Test: X-axis yaw error
```

- Why was the test executed

General information

- Test equipment (measurement devices and artifacts)
  - identification, type, manufacturer
  - settings
    - applied compensations and used sensor(s)
    - settle time and trigger window
    - number of samples averaged and sample frequency
    - range/resolution setting
    - unit
    - scale factor
    - sign
    - software and software version
  - properties
    - dimensions, geometry, reference feature(s)
    - material, effective coefficient of expansion
  - setup

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General information

- Status of the machine
  - applied compensations
  - coolant
  - clamped axes
  - applied warm-up procedure
- Status of the machine environment
- Comments

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Setup and machine motion pattern

Classification according to setup and motion pattern:

- Angular or displacement measurements along a "line":
  - geometric accuracy of an axis (roll, pitch, yaw, straightness, positional)
  - drift test of an axis
  - diagonal displacement test
  - critical alignments
- Stationary tests:
  - ETVE
  - spindle thermal stability,
  - moving axes drift, composite drift,
  - tool change repeatability, axis repeatability,
  - spindle error motion
- Circular contouring tests
- Compliance and hysteresis tests
- ....

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Measurements along a line

Motion pattern

- Feed rate (or manual motion)
- Approach direction:
  - Positive
  - Negative
  - Positive pilgrim
  - Negative pilgrim
- Target points:

```
Targets:
   Target #, X, Y, Z, A:
   0  10  301  220  0
   1  30  301  220  0
   2  50  301  220  0
End
```

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Measurements along a line

```
Targets:
   Start position: X: 10, Y: 301, Z: 220, A: 0
   Direction: X: 1, Y: 0, Z: 0, A: 0
   Target #, Travel:
      0   0
      1   20
      2   40
   End
End
```

The direction can be defined using:

- A direction vector: `Direction: X: 1, Y: 0, Z: 0, A: 0`
- An axis designation: `Direction: X`
- An end position: `End position: X: 50, Y: 301, Z: 220, A: 0`

```
Targets:
   Start position: X: 10, Y: 301, Z: 220, A: 0
   End position: X: 50, Y: 301, Z: 220, A: 0
   Intervals: 20
End
```

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Measurements along a line

Setup and measurand(s):

- angular or displacement error
- direction positive error motion
- effective tool offset
- machine components whose relative error motion is measured
- orientation (e.g., for reversal purposes)
- fixturing

Note: a measurand can involve a combination of devices and artifacts.

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Measurements along a line

Example: Z-axis pitch measurement on a lathe

```
Device[Laser]:
   Type: laser interferometer
   Measurand: Angle
   Direction error: Y
   Manufacturer: XYZ
   Model number: DEFG
   Serial number: ABC123
   Software: [illegible]
   Software version: 2.1
   Units: arcsec
   Resolution: 0.01
   Sample frequency: 40
   Samples averaged: 10
   Settle time: [illegible]
   Reference on: Spindle [illegible]
   Target on: Turret [illegible]
   Tool offset: X: +40, Y: 0, Z: -10
End
```

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Discussion

Information elements and formats to store and communicate performance data

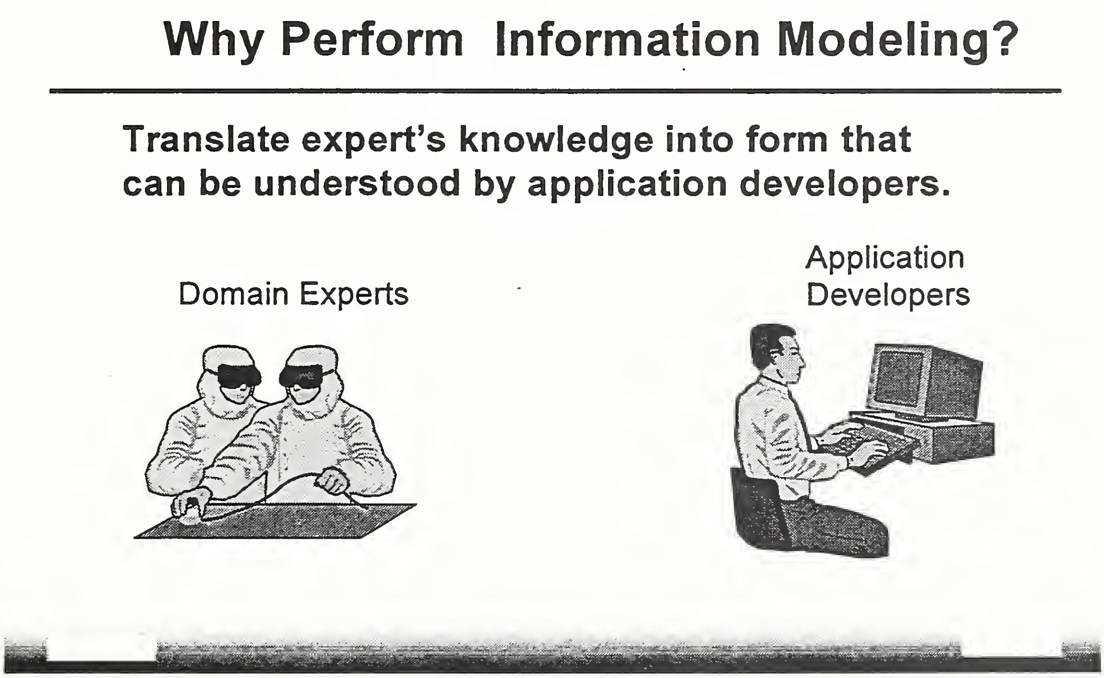
- Is further formalizing of information elements and formats useful
- How do we increase participation?
- Are the chosen approach and focus right?
- Are essential elements missing?
- What information do you record about performance tests?
- Which formats do you use?
- What do you do with the data?

MEL NIST

DEMONSTRATION OF A WEB-BASED EXPERIMENTAL REPOSITORY
L. Welsch

I like to start with some background on myself so you know where I am coming from. Up until this past August, I was a manager for NIST in the Information Technology Laboratory. I worked primarily on the issues of document interchange. I currently work for NIST's Manufacturing Engineering Laboratory and I have been working on technology aspects related to manufacturing since last August.

Mr. Donmez asked me to relate this work closely with Mr. Frechette's presentation. I am speaking as a programmer today. I do not understand the manufacturing aspects, so if misuse a term, please let me



know. I will be the contact for a while as far as this particular project in terms of the web development prototype is concerned. To test our repository, we need as much data as possible. You may contact me at 301-975-3198 or by e-mailing LWelsch@nist.gov if you want to ship data to me.

About six or seven weeks ago, I met with Mr. Donmez and he started asking, "What's real? You are talking about all this EXPRESS. What's real? Can you do something to make this real?"

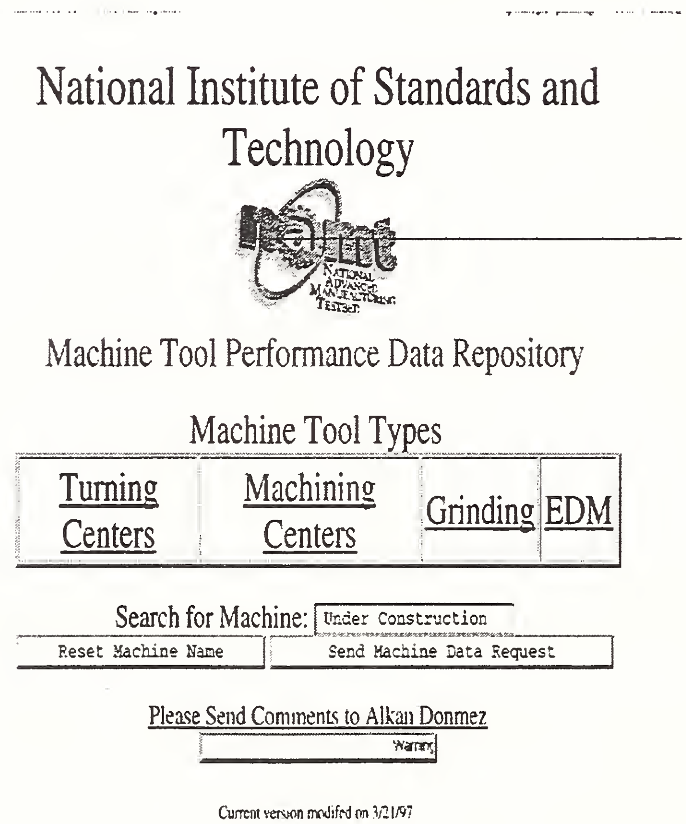
I finally got Mr. Donmez's point and said, "Using Web technology, we can build realistic examples quickly."

I talked about being able to show some retrieval with web technology with about six files. This presentation represents a team effort. Ms. Ling built one of the system components, Mr. Soons wrote all of the analysis code, Mr. Gilsinn provided reality checks, and Mr. Wilkin put together the structure of the site and built most of the Web Site you are going to see. I built the infrastructure.

Six weeks ago we did not even have a computer to run on. We (1) ordered memory, (2) bought software, and (3) configured a computer system. We built this system in less than six weeks. Please bear with me. Many links will not work right.

DEMONSTRATION

I am moving from the Sensor Systems group home page to the home page of the repository.

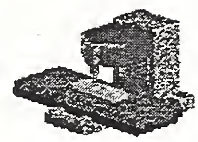


We divided the world into different classes of machine tool types. Content is associated with each link. Today the content is very incomplete. We will look at one particular path that I know is mostly present.[1]

We are going to look at Machining Centers. Note that Machining Centers is sub-divided into vertical and

---

[1]A path is a collection of pages. Links written in HTML connect the pages to each other. HTML (Hyper-Text Markup Language) is a language for designing web pages.



Machining Centers

[Vertical Machining Centers]

[Horizontal Machining Centers]

[NAMT Repository Home Page]

horizontal machining centers.

Vertical Machining Centers

Vertical Machine A
Vertical Machine B
Vertical Machine C

Return To Machining Centers Page
Return To Repository Home Page

Updated 5/29/97

Next we select vertical machining centers.

From vertical machining centers we select "Vertical Machine B." Then, we get the data in Data Set

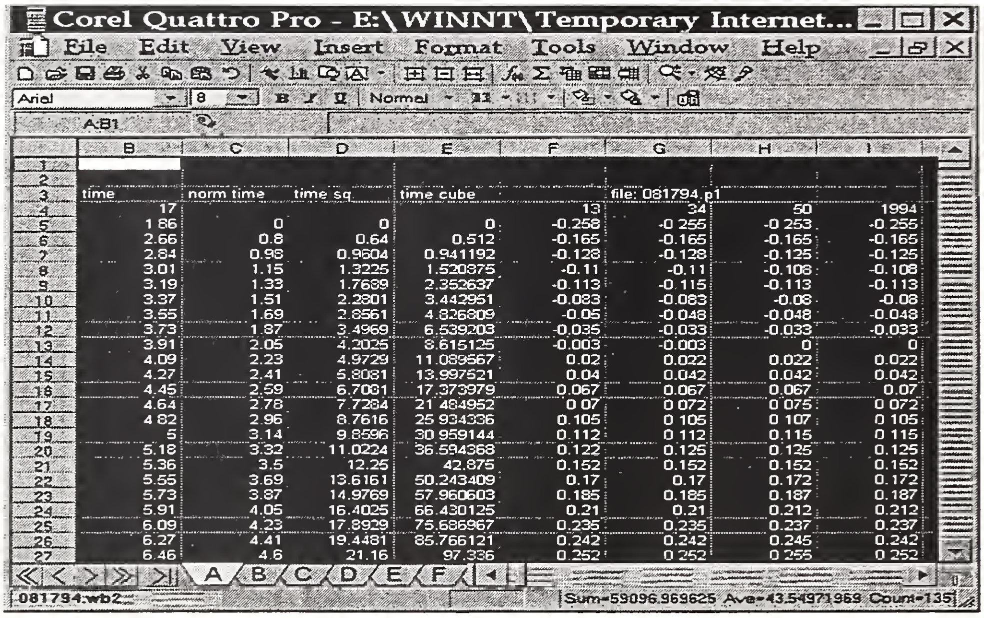
Vertical Machine B

Data Set Number 1
graph1.gif
Request Ballbar Data

Return To Vertical Machining Centers Page
Return To Machining Centers Page
Return To Repository Home Page

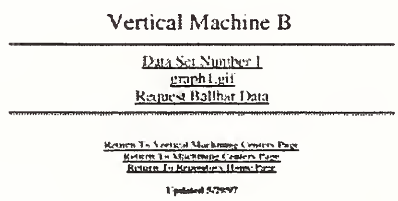
Updated 5/29/97

Number 1. The data is stored as a Quattro Pro spread sheet.

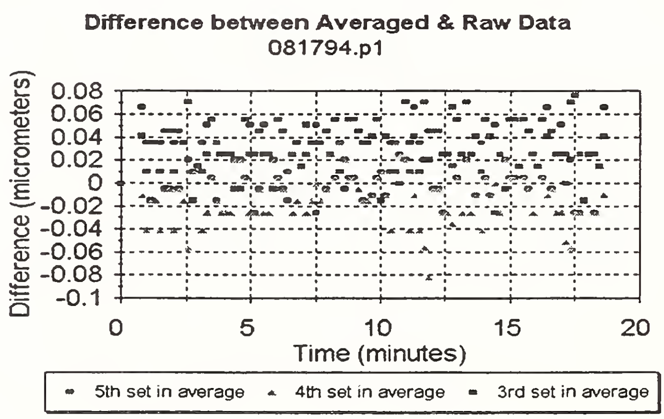


	B	C	D	E	F	G	H	I
3	time	norm time	time sq.	time cube		file: 081794.p1		
4	17				13	34	50	1994
5	1.86	0	0	0	-0.258	-0.255	-0.253	-0.255
6	2.66	0.8	0.64	0.512	-0.165	-0.165	-0.165	-0.165
7	2.84	0.98	0.9604	0.941192	-0.128	-0.128	-0.125	-0.125
8	3.01	1.15	1.3225	1.520875	-0.11	-0.11	-0.108	-0.108
9	3.19	1.33	1.7689	2.352637	-0.113	-0.115	-0.113	-0.113
10	3.37	1.51	2.2801	3.442951	-0.083	-0.083	-0.08	-0.08
11	3.55	1.69	2.8561	4.826809	-0.05	-0.048	-0.048	-0.048
12	3.73	1.87	3.4969	6.539203	-0.035	-0.033	-0.033	-0.033
13	3.91	2.05	4.2025	8.615125	-0.003	-0.003	0	0
14	4.09	2.23	4.9729	11.089567	0.02	0.022	0.022	0.022
15	4.27	2.41	5.8081	13.997521	0.04	0.042	0.042	0.042
16	4.45	2.59	6.7081	17.373979	0.067	0.067	0.067	0.07
17	4.64	2.78	7.7284	21.484952	0.07	0.072	0.075	0.072
18	4.82	2.96	8.7616	25.934336	0.105	0.105	0.107	0.105
19	5	3.14	9.8596	30.959144	0.112	0.112	0.115	0.115
20	5.18	3.32	11.0224	36.594368	0.122	0.125	0.125	0.125
21	5.36	3.5	12.25	42.875	0.152	0.152	0.152	0.152
22	5.55	3.69	13.6161	50.243409	0.17	0.17	0.172	0.172
23	5.73	3.87	14.9769	57.960603	0.185	0.185	0.187	0.187
24	5.91	4.05	16.4025	66.430125	0.21	0.21	0.212	0.212
25	6.09	4.23	17.8929	75.686967	0.235	0.235	0.237	0.237
26	6.27	4.41	19.4481	85.766121	0.242	0.242	0.245	0.242
27	6.46	4.6	21.16	97.336	0.252	0.252	0.255	0.252

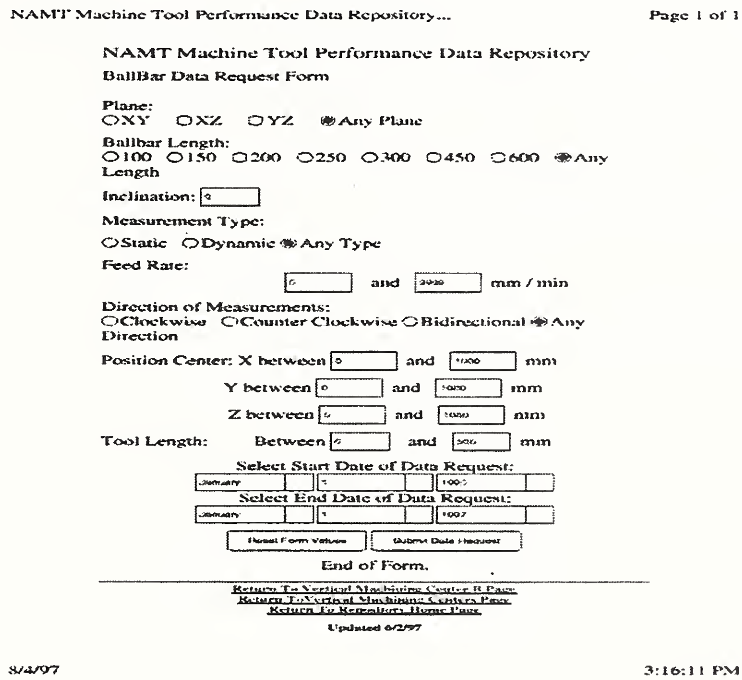
Dumping the data from the server system at NIST to this system, is an important step. Because the data is in the form of a spread sheet, the user may use the spread sheet to analyze the data.



The next capability we will demonstrate is viewing an analysis that has already been performed. Returning to Virtual Machine B, we will now download graph1.gif.



The last thing that we wanted to do was to show a search followed by an analysis of the data sets found. Mr. Soons put together the form below. The form allows users to set values on parameters that one might


NAMT Machine Tool Performance Data Repository... Page 1 of 1

NAMT Machine Tool Performance Data Repository

BallBar Data Request Form

Plane:
○XY ○XZ ○YZ ◉Any Plane

Ballbar Length:
○100 ○150 ○200 ○250 ○300 ○450 ○600 ◉Any Length

Inclination: [0]

Measurement Type:
○Static ○Dynamic ◉Any Type

Feed Rate: [0] and [3930] mm / min

Direction of Measurements:
○Clockwise ○Counter Clockwise ○Bidirectional ◉Any Direction

Position Center: X between [0] and [1000] mm
Y between [0] and [1000] mm
Z between [0] and [1000] mm

Tool Length: Between [0] and [500] mm

Select Start Date of Data Request:
[January] [1] [1993]

Select End Date of Data Request:
[January] [1] [1997]

[Reset Form Values] [Submit Data Request]

End of Form.

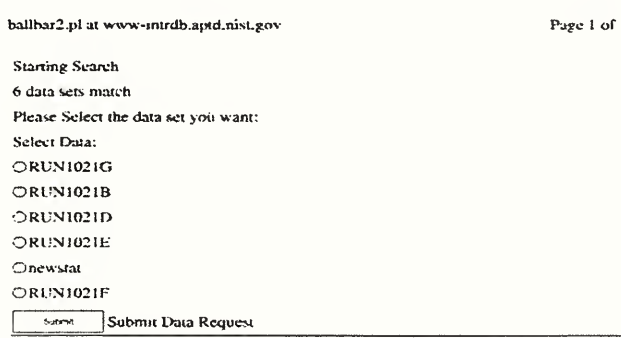
Return To Vertical Machining Center B Page
Return To Vertical Machining Centers Page
Return To Repository Home Page

Updated 6/2/97

8/4/97 3:16:11 PM

use to search a data base containing ballbar[2] data sets. One important question, that we need your help on, is: What parameters should be used to search the database? We do not expect this question answered today. There are only two parameters we can search with today, and one is the plane. We will select the X-Z plane. The other parameter is measurement type. Measurement type may be either static or dynamic. We will select dynamic.

Part of what makes Web technology attractive is building the user interface. User interface construction is a complicated part of application development. For example, Volumes 1 and 2 of the Microsoft® Win32


ballbar2.pl at www-mtrdb.aptd.nist.gov Page 1 of 1

Starting Search

6 data sets match

Please Select the data set you want:

Select Data:

○RUN1021G
○RUN1021B
○RUN1021D
○RUN1021E
○newstat
○RUN1021F

[Submit] Submit Data Request

[2]Ballbar data refers to data collected with a type of machine tool measurement device called a telescoping ballbar.

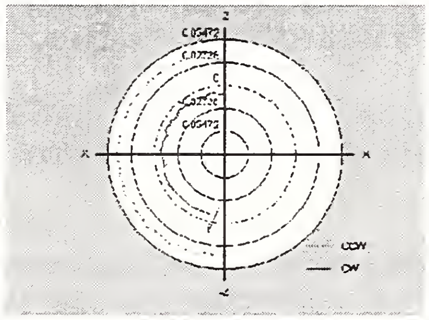
Programmer's Reference is almost entirely devoted to user interface issues.[3] Also built, was the structure of the form using Web technology. I used the structure Mr. Wilkin built to generate what you see.

Mr. Wilkin built the query form. The programs I built used the form to construct the query. The programs did a search of about 7 or 8 files. We slightly modified the representation of the data that searched. The system analyzed the raw data in its original form as collected by the ballbar.

Now, the big thing that I didn't want to do, and that isn't quite working, is the actual analysis part of the system. As I was sitting here talking, MATLAB® was running. MATLAB executed an analysis program.[4]

Dynamic Ballbar Measurement

Data file: run1021h.nh Operator: Neil Wilkin Machine: Monarch Ballbar Serial: 13611 Date: 18:02 Oct 21 1994	Circularity: 85.9 um Min error: -32.4 um Max error: 53.5 um Error best radius: (14.1 um) X offset: -3.2 um Y offset: 0.3 um
Feed: 3000.0 mm/min Sample frequency: 75.0 Hz Ballbar length: 150.0 mm Inclination angle: 0.0 deg Data start: 90.0 deg Data end: 270.0 deg Data overshoot: 5.0 deg	Runs CW: 2 Runs CCW: 1 Best center removed: NO Best radius removed: NO



.... Clockwise ___ Counter clockwise

Mr. Soons wrote the analysis program. MATLAB, in real-time, generated the text data that you see in the figure above. MATLAB also generated the same graphical figure that you see above. However, the system is displaying a different figure than the one MATLAB generated. This is due to not understanding how all of the different technologies we used worked together.[5]

One questions I have is: What capabilities for analysis should be in the repository? How robust should the repository be?

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[3]Win32 is the name of the application programmer interface for the Microsoft Windows 95 and NT operating environments. That so much of the description of the interface is devoted to the user interface, provides insight into how difficult application user interfaces are to design.

[4]The MATLAB system executes programs written in the MATLAB language. The programs may be either written in real time by the programmer, or written and stored as ".m" files.

[5]Since giving this presentation we have developed a better understanding of how the technologies work together and fixed this problem.

DISCUSSION

MR. CALLAGHAN: Are you accessing a file, or generating some sort of file? I'm not sure how you're doing that. Is this a bitmap that I'm seeing here, or an actual generation?

MR. WELSCH: You're seeing a graphic file that I created. I wish you were seeing the actual generation. That's just a matter of time.

MR. CALLAGHAN: Do you think you can do that? Can you actually generate it on the web page?

MR. WELSCH: Yes. As a matter of fact, the biggest issue is that we happen to be generating Postscript® and if we wanted to dump the Postscript image down to Ghostscript[6], we could be doing the imaging with the MATLAB generated image in real time. Mr. Soons felt that it was important to have the image on the same page with the description. Unfortunately, the one part of the system we were not able to get working in time for the demo was the conversion of Postscript to GIF[7] or JPEG.[8] Once the graphic is in either GIF or JPEG format we can combine the Graphic with the HTML page and ship the page to the browser. The image, in the sense of the postscript file from which this image was created, was generated just now as I was talking. The system attempted to convert the image to GIF. Unfortunately, there is a bug and the system failed.

MS. McMILLAN: Was it built in Unix™ or was that the picture itself?

MR. WELSCH: Was what built in Unix?

MS. McMILLAN: The actual graphic.

MR. WELSCH: The image was created running MATLAB on an Windows NT™ machine in Postscript. The actual code that I'm using to do the interfacing is written in Perl, which comes from the Unix community. I am also using a version of KornShell developed by the Mortice Kern Systems as the main shell interface.

MR. CALLAGHAN: One last question. Are you accessing the raw files in this native language that this data was taken in? How is that being reported? Do you have directories out there that just store the files for each of these, and if so, how do you do that?

MR. WELSCH: The search is being done on some files that I actually did a little bit of manipulation on. I created a separate directory and broke each file into two parts. One part was the header information and the second part was what I believe Mr. Soons called each "run." We used Perl to do the search. It's a simple linear search that is easy to build, but very computation intensive. I believe we will need to build

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[6]GhostScript is the name of a Postscript imaging engine readily available on the Internet.

[7]GIF - Graphics Interchange Format is a bitmap graphics format developed by CompuServe Inc.

[8]JPEG - Joint Photographic Experts Group is a bitmap graphics format developed by the ISO standards committee with the same name.

indices and use a database engine for the search.

We are providing the MATLAB programs with the original file of raw data. I believe that there will come a point when we will freeze this work and create a new design.

That concludes all the remarks that I had and the demo that I wanted to show.

MR. CALLAGHAN: Is this accessible on the web, or will it be in the near future accessible to us, from outside? I'd like to be able to access it. Could you post it?

MR. WELSCH: This is a Netscape browser. Right now we are limiting access through the server. I would certainly like to see work that I contributed to being used. I think it's absolutely necessary to get feedback first. I hope to be able to make the program accessible, however, as to what time frame, I can't answer you on that.

MR. DONMEZ: We have an internal policy that whatever we put in the public domain we have to go through some management approval process. So, as soon as we complete those, were able to open up a little bit.

MR. CALLAGHAN: Will this be a good candidate for that then, as far as you're concerned?

MR. WELSCH: Yes. Without question. I'd like to see it out there.

MR. BLOMQUIST: Why don't we get a show of interest on how many people would be interested in using it?

MS. McMILLAN: Well, we definitely want to look at it.

MR. CALLAGHAN: I don't know about using, but I'd definitely investigate it.

MR. MCCLURE: I have a question. Up to now I think we've been talking about something that's a data storage and retrieval system. Why is the analysis provided? Why would you store something like MATLAB in the background that you could go in and treat as a column of numbers? Why would you do that?

MR. DONMEZ: There are several reasons. I think what we would like to do is look at the future, how are these repositories to be used and, if we can do some of the experimentation of the usage, then we can modify the repository structure accordingly. If we don't do any of these tests now, then the repository that is going to be built may be not adequate and we want to test these. The MATLAB that we use is for prototyping purposes only.

MR. MCCLURE: I have an answer to that. I think you can extend the use of the web site to promote the development of standards. I mean, we're talking about standards that are static, too slow to develop, non-existent and we've got to fill those gaps. This process can go on until actually the site establishes a series of links, so that certified packages could be accessed directly and maybe more than once. It sure would add incentive to the vendors to get active and put more into it than they are now in working towards some kind of an agreement on standards. It took ten years to develop a digital filter for the surface finish data, still not every company has fully agreed to it. There is the problem of the software that we had with the software on measuring machines.

MR. CHANDRASEKHARAN: I have a question on the development of this web site and making it available publicly. Now, as a participant in this project, are we (1) gaining anything out of this by making this open to the public, (2) is it going to be "public" limited to the participants of this project, or (3) is it going to be publicly available to anyone that comes on board later on?

MR. WELSCH: I'd like to take my stab at that as a developer, not just strictly as a programmer. Receiving 10,000 comments on something is not very useful. Opening up so that we can receive a few comments from those people who are expert in the field and who want to see this type of work occur, can be tremendously beneficial in the sense of the development. At this particular phase, I, as a developer, am looking for a community such as represented here to start giving us feedback back and forth.

Now, I think in terms of the end, we're not going to be in the data repository business. We certainly want somebody to come in and make this into a commercial product. That would be great to see that happen, just as it would be great to see the standards work stimulated, and I believe the term was, "short-circuited" by that type of an investment. And you had a second part to your question?

MR. CHANDRASEKHARAN: The other one is, is the best bet for us to validate the definitions of the data that we're going through and establishing the scope, in which case the investment of the man-hours that go into validation and developing it--and that relates back to what the gentleman was saying about developing links where it goes off to certify people--and you know that's a classic way of people developing algorithms and scheduling and things like that. You have problems against which you benchmark how you do things and that's essentially what we're doing. If we put in data, let's say baseline data, with stripped off headers from Caterpillar, Boeing, and GE, and somebody wants to develop tools, they can use it as data. That has positive points and negative points. However, is there a mechanism, or is there something in the pipeline to figure out the charter of what we're trying to do? What is the scope?

MR. WELSCH: As a developer, that is precisely where I would like to see this go. I really want to see this be a type of stimulus, and/or type of catalyst, for industry. In broad terms, that type of catalyst is what NIST is all about. The next steps as to what and where we want to go are something that we need to discuss and we need to listen to you about. If that is high on your priority list, that's where we will head from my perspective.

MR. DONMEZ: What we'd like to do is to experiment with this repository by having the data from people like yourselves to see where the shortcomings are. As Larry pointed out, this particular repository is not going to be the same six months from now. It's going to continuously change, and we will be testing continuously with the data that you are providing.

MR. BLOMQUIST: I think Larry has a good point by saying he'd rather have 50 intelligent comments than 10,000 from the masses. So how do we do that? By making people *want* to participate as members of a consortium that has no cost to them. Hopefully, we can do some filtering so we don't have the entire world.

MR. CALLAGHAN: This morning, I suggested a place for members to deposit some data. What kinds of data do you accept?

MR. WELSCH: Right now the types of data that we have are a collection of ballbar data, an assortment of spreadsheets and some graphs. Now, I'm a computer buff and C language programmer. One of my particular interests in this project, as a computer person, is the question of how robust an interface can I build for accepting data in different forms. That is an open, very difficult problem, for in the sense of what type of data we want to accept right now, I don't have a good answer. And yet, the first person who gives me data will be the first one that I'll try to put.

MR. ZIEGERT: I'm a little unclear as to what value lays with regards to having a specific, national repository of tests. You can have two machine tools by the same manufacturer sitting side-by-side in a facility, and each one is going to have different results to these tests depending on how that machine tool was assembled and what has transpired as far as maintenance history . What's the value of having a national repository of data that's specific to a particular machine tool?

MS. McMILLAN: Well, I don't want there to be national repository. Although, I do want tools to help me do what I need to do. Furthermore, it would be great if a consortium would help develop those tools because then I know I'm in the right direction.

MR. DONMEZ: This is nothing like a national repository. As was mentioned earlier, we're trying to establish some structures and methodologies of how to store this information, and how to get access to it and analyze it. As we said before, there are two reasons why companies want to use this information: (1) to simulate their processes and (2) to find out their capabilities. Additionally, from the research perspective, it gives us a lot of data to test our models and their robustness, though it doesn't have to be a national repository. Based on the structures and definitions we're proposing and will be generated within this kind of consortium, everybody should be able to duplicate their own repositories according to their needs.

There will be a repository which we will be developing with the help of the members here, and everyone else who will provide help. This united effort would then result in an experimental repository to test the ideas and concepts. Caterpillar, Boeing, and others will then create their own repositories based on these standard formats and their needs. In turn, they can share their repositories with their suppliers or ask their suppliers to put their information in that repository to find out whether or not they have a capability for a given product. It is therefore the users decision how to use these type of repositories. If we have the infrastructure defined, then everyone can do what they want to do. The software developers will eventually develop their software based on these data structures.

MR. ZIEGERT: One issue I see with people contributing data to you, Larry, is that it's kind of a cart-horse problem. A lot of data exists and it exists in all kinds of different formats and structures so in order for me, Boeing Wichita, or anyone else to send you data, you have to be able to make sense of it and know what it means. Essentially, we have to convert it into the format that you'd like to see it in. So we can't send you data until we know what that format is and you're saying you can't create the format until you have the data. So, where do we start?

MR. WELSCH: From my perspective, we start by taking a look at the specifications that you have for the data. Now, I know is that if the data happens to be in ASCII files or happens to be easily converted to them, there are many tools out there for merging the data and putting it into a database.

You're absolutely right that specifications are needed and I would like to see examples of what is being done using the tools that we currently have available, try to put it into a data repository for prototyping. If I make some mistakes, I don't really care. The question is: can we learn from attempting to actually do it? I'm going to work with you and with these specifications that you currently have.

MR. PATTERSON: Am I correct that you presently have the software to take data in the format which Hans outlined earlier in this meeting?

MR. WELSCH: Yes.

MR. PATTERSON: Okay. We also have at least two of the major data formats represented in the crowd here. Many of us have data in the form of either API or IQL formats. Are you suggesting that if the file formats were made available, that overnight you'd be able to take data from any of those three formats if they give you the data and the format definitions?

MR. WELSCH: Yes.

MR. PATTERSON: Would it be fair to ask if those format definitions could be made available?

MR. MA: Oh yes, I can work on that with Larry.

MR. PATTERSON: That means I can send you my IQL data tomorrow after I get home?

MR. WELSCH: Actually, I'd like to start the discussions with you early next week about it and how to receive it. From the time-frame of these types of projects, the answer is yes. We have to start making progress now, otherwise I don't think it's going to happen.

MR. PATTERSON: I guess I'm suggesting that those are some fairly concrete steps that would represent a significant step forward and give us some experience with moving data around. Inconsequentially this might up the ante towards pressuring some of the other players to make their data formats available for the same purpose.

MR. MA: Yes. I spoke with Hans earlier. I think we'd like to combine our efforts with the NIST format. Our data is ASCII readable. Also, we'd like to provide what is necessary. Additionally, if this is really the format that people believe in, we'd like to put some effort into it.

MR. WELSCH: As far as this being the way to go, I don't know. This is to experiment with different approaches so we can determine what doesn't work. The data transfer is certainly a major problem and, as our previous speaker mentioned, the consistency of both the dictionaries and the meanings of the terms starts to become absolutely vital.

MR. ZIEGERT: Momentarily, I want to get back to the question about the national repository. I am not a manufacturing engineer, but a design engineer. From the designing aspect, the house is a growing awareness, and there always has been a need for it. Keep in mind that when we design products we need to understand how they're going to be manufactured in order to improve the products, make them more producible and more affordable. After all, manufacturers can only build what a designer gives them to build. Furthermore, it can only be as good as it is described. There is a tremendous effort going into to trying to make a connection with tools being developed, some of them being internal to different companies. Some of the CAD systems are considering the ability to embed or manufacture capability data into databases. The purpose is for the data to be loaded into a CAD database to then flag the engineer when they do something wrong. But, a significant amount of the tools will not really be available to a lot of companies because if they have to go collect their own process capability data. They can't do it; they may not be as financially capable as GE's and Boeing's and some of the larger companies. So, I see that there is going to be a need for that. It's coming to the point where you're not going to be able to compete in designing products and you're not going to be able to stay in business if you don't understand how these things are going to be manufactured. That's one need for that kind of database. Some standards need to be set in order for the developed tools to use the established data.

MR. DONMEZ: If you look at it from the big companies' perspective, they're doing more and more supplier certification. When Boeing asks their supplier what type of capacities they have, the supplier might provide some help to measure these machines, if they don't do it themselves. Meanwhile, the funding issues would be resolved. Eventually more and more small companies will provide that kind of information to large companies if they want to provide services to them.

MR. BLOMQUIST: One of the aspects of this is mass characterization of machine tools. If it takes a month to characterize a machine tool and nobody can do it, there isn't much value. However, a lot of people are working on fast characterization of machine tools. Therefore, there is pressure to drive the cost down. If you believe that there is going to be a lot of out-sourcing, then the small company is going to be able to afford it.

MR. CALLAHAN: I will comment on that as well. A lot of our service work has started to increase as a result. It's being driven by no particular size company. We also see it coming from General Motors and some other big names.

Before we get away from the web concept, I would like to have a net site that we could go to and talk about issues, exchange information and such. This concept is based on this set of issues that we're talking about. It would be a place, which may be restricted, where we could discuss any problems and/or issues related to either the database or data dictionary.

MR. CHANDRASEKHARAN: With what Hans has right now, we'd like to see some way of getting comments on that and set time lines. Either mailing it to us or put it up on the web so we can review it independently by a certain date.

MR. DONMEZ: As an action item, we should establish a web site for everyone to have access to as well as be able to put their comments on. We will also put the documents that we are distributing here today on the web site. The documents will take a little more time because they all have to go through an approval process, but the web site itself, I'm assuming, can be approved shortly.

MR. CHANDRASEKHARAN: It doesn't have to be the web. It could start off by just routing documents. We'd like to get some of what Hans has. I fully endorse what Professor Patterson said. Let's try to take it to the next level; not just looking at the ballbar, but start looking at the other devices too. Let's try and consolidate on the data definitions and start moving in order to set a schedule. Maybe we could initiate something within the group to speed up some of these ideas and move from the ballbar to a full characterization of a machine. Hopefully, we'll have solved these problems by our next meeting.

MR. SOONS: I would just like to reiterate the status of the formatting issue. What we currently have, and what I've tried to write down, is basically a lot of ideas about what such a format could look like. It is definitely not the final choice, but it cannot be left at this stage. But one thing I would like input on is what our next move should be from that point. Should we formalize it into a strawman model so people can review it or should we have some collaborative effort in progress? What is our next move?

MR. CHANDRASEKHARAN: Get started. You've got enough for a strawman. Just table that and we'll respond. We've got plenty in here.

MR. ZIEGERT: I was going to suggest some reasonable metrics to measure the completeness of the data format as the first step. There has to be enough information there, that a person could go in and recreate the exact test that developed the data and presumably get the same data. Keeping in mind the eventual goal of virtual manufacturing, there should also probably be enough data for it to then be used in the machine models and in the virtual model. Those might be reasonable metrics against which to judge what needs to be there and what doesn't need to be there.

MR. CHANDRASEKHARAN: I think we also need to focus on where this fits in the hierarchical nature of the final database that we're talking about with physical descriptions and such. I don't know if you want to put some thoughts together on that; merging what you have in performance with what you had in the previous definitions as to where you see the performance metrics going. Is that going to be inclusive, or are you still going to keep them independent like this?

MR. SOONS: If I were to continue with this, I would probably take that second document on performance evaluation and start working that one out, because that can be reasonably self-contained, and start with the general machine data on there.

MR. DONMEZ: I think we have to keep in mind that whatever we end up with will have some layered structure, starting from very raw data all the way through. There may be a few numbers of information about the machine. Depending on the need, you can go in different layers: (1) to either duplicate the information, (2) use the information in the models to create the simulation or (3) compare a few numbers from Machine A to Machine B.

MR. CALLAGHAN: The people here are used to looking at all these charts, analyzing them and understanding what they mean. In my world, I have to translate all that into something, simple and concise enough for a manager to look at and help him make decisions. A lot of what I was commenting on to Steve earlier, is probably of interest to only half a percent of the people at my company. I have to figure out a way to bring that to a much higher level and make sense out of it at a machine shop management level, so they can make decisions. We need to synthesize all of this ground-level data into something for them to make decisions at a high level. We can keep the low level information, but we don't want to lose sight of who a lot of our end-users will be.

MS. McMILLAN: Can we start a formal data dictionary in which we can have input? Then at the next meeting maybe we can review that list and get started?

MR. WELSCH: I think we will put that out on the web site as well.

MR. DEFORGE: As a virtual manufacturing modeler who does this for a living, I find the information in the sub-notes on the machine tool data base document, appear to be of more value to me than what we spent a great deal of time talking about today. As far as working with these types of measurements, I understand the value. Don't get me wrong. I understand how important they are to an individual company and to bridging that gap between virtual reality and calibrating your virtual environment to what's actually taking place down on the factory floor. From my perspective, I'd rather see some more work go into these definitions as to what we need to create virtual machines. What kind of information do we need, as modelers, to rapidly build a machine tool in a virtual environment that will give you a tool for bridging the gap between design and manufacturing?

If I have to hunt all over the country for information on how the axes of this particular machine tool are supposed to operate, which controller they marry up with, and what features we actually took advantage of for this machine tool, that becomes a month long process in building a virtual machine tool; not necessarily taking a look at these measurements and calibrating my virtual environment to the real environment. It is sometimes very difficult to gather some of this information. The machine tool builders aren't walking up to us and saying, "Here is everything you need." I'm wondering if we're backing into this when we should be approaching from a higher level.

MR. CHANDRASEKHARAN: That's part of what I had in my slides too. Are we enabling everything that's happening today? Are we supporting the current database that's out there, the current simulation tools, with what we're developing, or are we getting to a level of detail that is far beyond? I think if we can generate a model out of the data structure that we're developing, can we give it enough information to get an accurate cycle time analysis, and/or an accurate collision check analysis? That's what virtual manufacturing is for us today, though it's not down to the level of detail where we want to be five years from now. Given the data definitions that we have, can we do that any better?

MR. DONMEZ: As a matter of fact, that's exactly why we put the discussion on simulation tools as our priority tomorrow. I think we should address those needs and requirements. For those simulation tools: what type of data, what type of information do we need for them to simulate realistically, and not in nominal terms?

MR. ESTERLING: If what you were even providing us either parametrically defined error functions or a look-up table, all of those are just perturbations of what we've been doing already in terms of modeling. I don't think the format matters that much. I think if the information is complete and clearly defined we can proceed without any problem. If it's not complete, then we simply assume there are no errors in that particular type of degree of freedom and continue.

MR. DONMEZ: You're saying the information that is provided is incomplete. Well, we'd like to find out what type of information, and in what form we should provide it for a package like yours and Deneb's, and how that package would utilize that information.

MR. ESTERLING: Our package accepts where the machine tool is going, and currently it accepts it on block-by-block code. Now, if you start having errors in there, all of a sudden a long tool move might be broken down into smaller steps, but we just need to know where the tool is going. Then we can go off and cut. If there is an error function, some perturbation to be imposed on that, that's what we can do.

MR. DONMEZ: But what we'd like to do is have a generic way of interfacing with packages like yours. You can do it for your own package, but it may not be generic. I don't know if Deneb can do it the same way, or in any other way, as long as we provide that generic information.

MR. ZIEGERT: In looking at the information that's on this particular form here, I'd say approximately 85 percent of that is information that I need to make an accurate representation of both the kinematics and all the peripheral devices and everything else that's involved in a particular machine center. It's very valuable information. I mean, I'd love to be able to go to the web and make a few clicks like we saw here today and get all the information that I needed to put together a machine tool to marry up this machine tool, in this configuration, with this particular controller, and be able to walk out in a couple of days with a model to be able to hand Boeing, GE, General Motors, or anybody else. I don't want this to be lost.

MR. DONMEZ: What we'd like to see is not a couple of days, but maybe a couple of hours.

REFERENCES

1. (Reference to Simon Frechette's presentation in this document).

2. Wilson, P.R. Express Tools and Services. Working Manuscript. NIST. Gaithersburg, Maryland. 1995.

3. Massachusetts Institute of Technology, Laboratory for Computer Science. The World Wide Web Consortium. The Consortium. Cambridge, MA. [computer file] http://www.w3.org/.

4. Werbach, K. The Barebones guide to HTML. [computer file] http://werbach.com/barebones/barebone.html.

5. Microsoft Corporation. Microsoft Win32 Programmer's Reference. Microsoft Press, One Microsoft Way, Redmond, Washington. 1993.

6. The Math Works, Inc. Using MATLAB. The MathWorks, Inc. 24 Prime Park Way, Natick, MA. December 1996.

7. Adobe Systems Incorporated. PostScript Language Reference Manual. Addison-Wesley Publishing Company, Reading, MA. 1990.

8. Wall, L., Christiansen, T. & Schwartz, R. Programming Perl. O'Reilly & Associates, Inc., Sebastopol, CA. 1996.

9. Bolsky, M. I. & Korn, D.G. The KornShell Command and Programming Language. Prentice Hall, Englewood Cliffs, N.J. 1989.

10. Mortice Kern Systems Inc. MKS Toolkit Reference Manual. Mortice Kern Systems Inc. Waterloo, Ontario, Canada. 1995.

11. Simpson, A. Netscape Navigator Gold 3.0 Book. Ventana Communications Group, Inc. Research Triangle Park, NC. 1996.

DISCUSSIONS ON NEEDS AND REQUIREMENTS FOR INTERIM MACHINE PERFORMANCE DATA

MR. DONMEZ: I have asked Loyd Bishop to give us some directions on the interim checks because he has done quite a bit of work on them. We need to discuss what the optimum amount of data is that will be useful for periodic machine checking.

MR. BISHOP: In the last workshop, I pointed out that we have a lot of probing data sets from our tower artifact. But it's an application-specific test for this machine that we've had notorious problems with in terms of the B and C axes. As we accept parts from machine tool probing data, we want to evaluate our machine tools as measuring machines. So, for interim checks, if they're bridge-type machines or if they're vertical spindle-type machines, I'd like to encourage the use of the NIST interim test artifact developed for Coordinate Measuring Machines.

With horizontal machining centers, we're asking the machine to go out and perform a duty cycle on some specific parts that we've got and then drive that pallet out, bring a dedicated pallet with the step gauge, and measure linear displacement errors along X and then along Y directions. Since this is a horizontal spindle we're going to tilt the step gauge 45 degrees and measure it as a combination of Y and Z. And then I want to turn it 45 degrees so I can get one body diagonal and then 90 degrees back the other direction. And get another body diagonal, so I can evaluate that machining center as a measuring machine. So, those are the kinds of interim checks I'd like to see run. And I think they would be quite meaningful to us.

MR. CALLAHAN: How long will they take, Loyd?

MR. BISHOP: We're not sure yet. We're still working on that because the controllers aren't very friendly. They don't work the same as coordinate measuring machines do. With our specific integrated probing system, they're telling me there is an offset, but it will be an equal offset each time when they rotate the pallet. So I really don't know. We're just scratching the surface on this right now. We have run the NIST interim test artifact on some machine tools but not with much success due to the amount of probing. Triggering pressure is like 65 grams on the machine tool probes, so we think the balls were actually being twitched out of the kinematic mouse. I received some new brackets that have stronger magnets. We're going to try that and see if we have some success with it.

MR. DONMEZ: How often do you foresee the need to carry out these interim checks?

MR. BISHOP: That's a good question. I'd like to abandon this tower check we have because it's really just a check for a specific part. It does a lot of things. It tells us the health of the B and C axes. We started doing this test because we have very expensive parts to make and we wanted to make sure that the machine was functioning properly before we went out and scrapped one of those very expensive parts. We've got approximately 1,300 or 1,400 datasets, just as a six minute quick check to determine if there is a problem with the B and C axes and also to create our tool point compensation files. That has been approved through our Legal and Public Relations Department, so I can get you a copy of that.

MR. CALLAGHAN: Loyd, how much of the work envelope does that cover?

MR. BISHOP: Not very much, and that's a real concern as well. But NIST is supposed to be making the bigger brackets for the 900 and 1,500 mm ballbar. We would like to use an artifact that's pretty much a replica of the 3D volume part that we've got but in some cases we can't always do that. So we try to use the largest thing we have, then we look at the laser diagonal displacement errors and we make some assumptions about how the machine would measure throughout that big volume. But, they're not always good assumptions.

MR. CHANDRASEKHARAN: Depending on the parts that you're machining, you might want to check only a few characteristics instead of characterizing the entire machine, as opposed to trying to build ambient models, so you have different uses for it. We don't have a clear picture of all the interim checks we have to measure, but I think, from a virtual manufacturing standpoint, that is an issue that came up, but, we haven't given it extensive thought. I don't have too much data on it to share at this point, but we certainly can look into it some more and get back to you about it.

MR. DONMEZ: What do you think, as far as the company's perspective, is an affordable amount of tests that you want to carry out periodically?

MR. CHANDRASEKHARAN: We would like to see the ballbar done once every month on our machine--that's what we're trying to recommend to our plants--and a full characterization definitely after any major breakdown. As we start building models, we may be carrying them out once every six months in the summer and winter times, after that, it might be periodically every year. But we haven't gone into that level of detail of putting together a strategy. Again, it depends on how quickly we can measure these errors. We're starting to use ballbars on a more periodic basis, but full characterization of the machine depends on the success of the projects we have on rapid error assessments.

MR. ZIEGERT: It strikes me, from Loyd's description of what they'd like to do for interim performance checks on probing step gauges and various orientations, that the kind of data you would generate there would be a real challenge to incorporate in the data structure that we've put up here so far. The implicit data structure that Hans has put up here kind of follows the classical notion of machine metrology of 21 errors or 6 degrees of freedom per axis, and axis alignments. It's not immediately clear to me how machine performance, as a measuring machine, over some arbitrary artifact in some arbitrary orientation is going to be characterized successfully in this database. I think that might be a real challenge.

MR. SOONS: I think, once you start using the machine as a measuring machine and you use artifacts, and probe them, you should use the appropriate standard--in this case it would be a Dimensional Measurement Inspection Specification (DMIS) format, or something like that--to describe it. I don't think we should try to replicate DMIS within a format like this.

MR. DONMEZ: But I'm not even sure if DMIS really covers that capability issue.

MR. SOONS: It describes basically all the things that a coordinate measuring machine can do. I think it comes close to the application that was being described here.

MR. ZIEGERT: Of course there aren't any CMMs with A, B, and C axes on them, at least not very many.

MR. DONMEZ: It would probably be more related to the B89 standard than DMIS, because you are using the machine as a CMM and then you have to follow the B89 definitions of performance.

MR. CHANDRASEKHARAN: What if the metrics you measure from the artifact are converted back to any of the other high level metrics like squareness and displacement, errors like that, so if you get to that level of definition and extract those parameters out of the artifact you can still populate and update those fields.

MR. DONMEZ: For some of the features, yes, you can do that, but some of them will be real complicated.

MR. CHANDRASEKHARAN: Right. Raw data is going to be a different issue.

MR. SOONS: What we could think of is a data file that basically contains your usual header information, in this case where the artifact is and what you want to do, and then it simply contains in this one full block the whole DMIS measurement file, or whatever the format might be, and then I think on the level higher that will really depend on what you want to do. I think it's difficult at this point to take that into account, what you want to do with the data.

MR. CALLAHAN: But how different is it really from laser data? You take a step gauge and you measure it with a Renishaw probe and in the description of the data you just say, "we used this instrument, which is the machine tool scale, and the Renishaw probe, and we used this artifact and it's aligned along a certain vector in the machine."

MR. SOONS: It's going to be difficult because once you start measuring artifacts you will have a whole host of new things, like feature definitions and you'll have to start defining spheres and circles and all those kind of things. I think it's a different kind of thing. In my opinion, DMIS is an excellent standard to handle that kind of thing because it was built for that purpose.

MR. DONMEZ: Yes. If you have a one-dimensional measurement like you described by the step gauge, it may be easy to correlate step gauge to laser, but if you have a two or three-dimensional measurement, like an artifact, cylindricity, or squareness, and all these things, then you might encounter a problem of correlating that with the laser data.

MR. CALLAHAN: Yes, but shouldn't the interim check just be a subset of that information? If you're properly designing the artifact, it should really be a subset of what you're getting.

MR. BISHOP: The NIST interim test artifact should reveal the errors that you see when you run the parametric error measurements.

MR. DONMEZ: But not that tower test that you were talking about?

MR. BISHOP: No, not the tower test and not the step gauge. When we use the NIST interim test artifact on the bridge-type machines then we should be seeing what we're seeing when we perform the parametric tests.

MR. CALLAHAN: I don't think it's that difficult to design the interim artifact so it's very similar to the more complete test.

MR. SOONS: I think it would be not-- I think you're right on simple artifacts, like the NIST artifact, which is basically two spheres, but should you then think about more complicated artifacts? Now where are we going to set the limit?

MR. CALLAHAN: What did Zeiss do with their three-dimensional artifact? They had a couple of them. They had a plate artifact and they also had one which was a cute kind of geodesic thing following stuff all over in space.

MR. SOONS: I think it might be possible to perhaps take some nice things from DMIS and incorporate it into the standard.

MR. CHANDRASEKHARAN: Maybe this would be a means for people to get their artifact certified, if they come up with something, whether it matches the data fields that you've assigned for the parametric errors? Is it a subset of it, or a combination that they're measuring by artifact?

The other issue is that it may not be an interim measurement of these errors, but the data we collect from the factory process capability information. I don't know where you would classify that, whether that's interim data or it's just company-specific data, but that is data that we definitely plan on collecting periodically and tracking and that gives a good indicator of performance.

MR. DONMEZ: But that test you're talking about includes cutting tests, right?

MR. CHANDRASEKHARAN: Yes. Capability of features and metrics that we're measuring.

MR. DONMEZ: We have a classification as "Cutting Tests," and that type of information would go into it.

MR. CALLAHAN: On your interim test data, can't you handle it exactly the same as you handle your hardware reporting? I have no difficulty at all with my interim part. I've got my squareness of the machine, alignments, cross-over errors, thermal distortions, and it gets passed up with the reporting of the hardware dimension. I already have that in my DNC system and can pull it down and chart it.

MR. CHANDRASEKHARAN: Are you talking about artifacts, interim measurements or complete parametric characterizations?

MR. CALLAHAN: Not the complete. The complete is the one I had difficulty with. The artifact, and most of the times the artifact is my actual hardware, to determine my machine squareness, cross-over errors, so that I have no difficulty in communicating. It's only when I go into non-workpiece, or non-hardware that I have a difficulty in communicating it.

MR. CHANDRASEKHARAN: But do we have assigned fields in the structure that is being defined was how the question started out?

MR. CALLAHAN: No.

MR. CHANDRASEKHARAN: That's how we started the whole issue, whether we have room in the database, as it is designed right now, or as we are planning on going with it, to accommodate data of this sort, because it's very useful data. Just like you said, you can plot it out and you can keep track of it, but will the database that we're proposing support it?

MR. CALLAGHAN: Now what you're saying there, Dave, is you are uploading this information coming from the machine tool through your DNC link, whereas the characterization data is coming from a different source?

MR. CALLAHAN: Yes.

MR. SOONS: Just to go back, I think it's an important distinction that is being made. If we are talking about artifacts which are specifically designed for testing like a straightedge and a square block, and perhaps even things like a step gauge, it is relatively easy to handle them in a format like we were discussing. However, once you start talking about artifacts that resemble the part that you want to manufacture and you're going to probe that artifact on your machine, then I think it's better to rely on formats that were specifically designed for that purpose like DMIS.

MR. CALLAHAN: Hans, in your specification here, you have basically raw data and then various higher level analysis. Is the goal to provide a lot of raw data into the repository. Is somebody going to try to consolidate this in some sense and parameterize it, or is it just going to sit there in raw data form?

MR. DONMEZ: I think the idea is, if the data is well defined, anybody can start doing the parameterization. UNCC should be able to take that data and start parameterizing it, or Caterpillar should take that data for parameterizing, and we will do the parameterization because we are interesting in modeling those machines. So, as long as data is unambiguous and is well defined, then I think we can get there.

QUESTION: Can we back up to the interim test artifact for just one moment? I plead ignorance in the whole machine characterization. I've never been involved with it and this is probably my first experience, even with much of the terminology. But I have worked in the characterization of CMMs and, in fact, I helped develop the interim testing artifact. I believe what I heard was that we were able to, through using the interim test artifact, look at the characterization and determine the error parameters of a coded measuring machine. Well, the interim testing artifact actually doesn't have that flexibility. Actually we identified with CMMs three primary sources of error, and that is 3 errors in terms of geometrical sources of error, which this is designed to check. One is the squareness. Another source of error is the ability of the machine probe, or the measurement probe, to lock up in a unique position and each and every time it repeats that position. So when we measure the ballbar and we look at the form error of each bar and we use a different index probe. So, if we see that a form is bad and we used a different index probe we know that we may have a problem in the repeatability of our lock-up. So we're not actually looking at the characterization of a CMM during the measuring; we're actually trying to delineate the source of error. So it may not be the kind of information you want to include because it's very specific. It gives you no real information about the error itself, but just a kind of general information that you can run the machine so when your technician comes in he can say, "I seem to be having a problem with my probe indexing," instead of "I have a problem; fix it." So, I think maybe they were misunderstood that we might be able to get more out of the interim testing artifact than we actually are.

MR. BISHOP: It's a nice baseline tool also.

QUESTION: Yes. Absolutely.

MR. BISHOP: Just like running the telescoping ballbar, if you look at degradation of the machine tool over time it's an excellent tool for that, so there is a lot of things you can deduct from the NIST interim test artifact, and one of them also being linear accuracy. I mean you can definitely look at linear accuracy.

MR. CALLAGHAN: Hans, have you started a data dictionary yet?

MR. SOONS: No. That will be the next step, to build a strawman document on that one and then distribute it.

MR. DONMEZ: Do you have any dictionary at all at Boeing?

MS. McMILLAN: We have a validated dictionary on other stuff, but not on this. But we do have the beginning of one, yes, because of our data modeling stuff, not that I could tell you anything about it, but we are beginning.

MR. BISHOP: But we are going to check to see if we can tell you and still maintain it at a proprietary level.

MR. SOONS: That's an action item for the next meeting?

MR. BISHOP: Sure.

MS. McMILLAN: Sure. I'll take that as an action item.

MR. MA: If you have two data sets from the same machine in your database, how will you treat them, just based on the time you saved them? Like where you put in one set of data and then you get another set of data they send to you, the same machine, the same measurement, just different date.

MR. SOONS: Probably the date.

MR. MA: The other thing is how long you would keep the data for a certain machine? Is it one year or two years, or whatever?

MR. SOONS: I think that very much depends on the users. Some people will want to keep it forever.

MR. MA: So, the user will give you a code saying, "I want this one to be kept for a while," or you haven't thought of that?

MR. SOONS: I don't think that would be a hard task at all.

MR. CALLAGHAN: I think typically we'd like to keep it all because when we get a brand new machine in I want to see what is right then and there and see what the degradation is over time, and when they retrofit it, I want to go back and compare this retrofit information back to the original and see if we can improve it.

MR. MA: So do you archive them to a floppy disk?

MR. CALLAGHAN: I back-up on floppy, as well as on the hard drive, and we're looking at a system for porting that into a Unix database that we've been talking about, and actually we're working on an Access database to parallel it, so we've kind of got quite a bit of action going on there.

MR. MA: Do you back up all the machines at once, or do you back it up machine-by-machine?

MR. CALLAGHAN: Right now, we are doing through the method that each machine has got a subdirectory, which is a somewhat painful way to do it, and we index the file name and increment the file name each time. So you get a date stamp and an X-Y axis test and then date stamp and a Y-Z axis test, and we keep it in the order you do the testing. It's kind of a clumsy way of doing it, that's why we want to use the databases.

MR. DONMEZ: One of the things that I pointed out in the morning as part of the discussions in the last workshop is to identify as well as weed out the bad data, and I think that's going to be a very difficult issue. Does anybody have any ideas on that?

MR. BISHOP: I don't think we need to, Alkan. I think the majority of the data is going to be good data and it's going to average out over the long run. I've been thinking a lot about what Steve said at the last meeting and I agree with what he said, but the majority of the data that we put into this should be good data.

MS. McMILLAN: And, if you do have something that's really odd, there are ways of highlighting that and commenting.

MR. CALLAGHAN: One of the easiest ways we do that is to look at the history. If it doesn't match the history, and I immediately run the test and I say, "Hey, here is what it's supposed to look like; why is it so far off?" The first thing I do is to check the setup. Setup is 95 percent of the primary problem. And they may go back and find something loose, or something wrong with a fixture. So, I think the biggest check we've got is history. If it's not within certain bandwidths of the previous performance then a flag goes up.

MR. HEMERLE: When you do your measurement for linear positioning accuracy using laser interferometer, do you measure on even grids to determine your cyclic error, or do you split the cyclic error two times over the run? How do you handle cyclic error? That's what I call bad data. The guy has measured the machine, didn't tell me what the grid spacing was and therefore I've included my cyclic error in there.

MR. DONMEZ: But B5 recommends that you include that into your data. In other words, if you have a metric machine, you measure it in English so that you don't separate the cyclic errors.

MR. CALLAHAN: To determine the manufacturing capability of the machine that's okay, but you wouldn't want to do that for your compensation evaluation tests.

MR. DONMEZ: Right. If you want to know the periodicity, then you have to use different ways.

MR. CALLAHAN: When you have your data put in, you would need to know that, would you not? Otherwise, I would say I don't know whether that's good data or bad data.

MR. DONMEZ: Right.

MR. CALLAHAN: But, again, that's just another piece of information about the machine performance, like periodic errors, just like bolt error effect on squareness. The periodic error affects your accuracy, so you have to have that information so you really know what the overall performance of the machine is.

MR. CALLAGHAN: Yes, but what I'm looking at, if I sent you one set of data and said, "Here I measured a machine and here I measured a machine," if one of those I have done on the grid, I'm showing you the accuracy, and if another one I split it so I see the sine error four times in it. If all you're seeing is my results, you won't know what the source of the difference is.

MR. BISHOP: The standard tells us to not measure it as we compensate it when we evaluate it.

MR. CALLAHAN: It also tells you to run periodic error. So you'd have to see both. I would never report squareness without reporting all the pitch errors, because it has no meaning without reporting those other errors.

MR. CALLAGHAN: It gives you some indication of what's going on. I know with a simple ballbar I can't do a lot, but I can at least have some idea of what my actual squareness is. I realize that the roll and pitch would have an effect on it, but it's not the whole story, though it's a piece of the information I didn't have otherwise, isn't it?

MR. CALLAHAN: Yes. The point I'm making is that you need the whole data set to make a meaningful evaluation. With the interim checks, you take a subset of that and that's where you're looking to see what has changed, but you have to have the whole data set to make any kind of reasonable assessment of the machine tool.

MR. CALLAGHAN: But it tells me something.

DISCUSSIONS ON SIMULATION TOOLS

MR. ESTERLING: Chris Deforge and I seem to be the "Lone Rangers" here, and maybe together we could do some things. However, I just wanted to respond to a question asked yesterday about what, from a software perspective, might be helpful.

The first issue is in terms of replicating; you might want to distinguish between replicating hardware versus software. If Steve Patterson wants to replicate what Loyd Bishop did, for example, he would want to have the same make, the same model, go on down the list, including the same maintenance records. He's not really ever going to really replicate what's happening in a different place, but you want to be able to at least replicate the experiment so you can see sort of what variations are within the experiment.

What I would suggest as a goal for the software is we, in fact, replicate the actual machine tool as it actually is. That's different from replicating the experiment. It's actually saying, "Here is what this machine with these characteristics can actually do." So, there is a subtle difference there in terms of replication. In one case you're just trying to replicate the environment, and in the other case you're actually trying to replicate the machine as if it's a virtual CNC with those characteristics.

The question is, what are the requirements you would want for this simulation? I think that leaves a lot to be discussed. The first issue is accuracy. If you're worrying about the sort of errors that are being presented here you're going to need to have a very accurate modeling system. But, at the same time, you don't want to pay a price in speed. If you wanted something that's practical on a shop floor, it's going to have to be something which is going to be reasonably fast. I can tell you from my own company's perspective what fast means. Back when we sold our software we were machining in a virtual CNC at roughly the same speed as the CNC and we did okay, but our real sales took off when we were actually able to machine in a virtual CNC environment by anywhere from a factor of 10 to 100 times faster than a physical CNC. I think it's those sorts of numbers that will make things useful. If you're running at roughly the same speed, or even slower than the CNC, then the tendency is, "Well, I'll just check it out on my machine tool itself, machine in wax or something like that." So you need to have accuracy to model the very small errors, but speed in order to maintain some sort of a practically useful tool.

To get down to what is needed, the answer yesterday was, "Well, what do you guys need?" and that should be correct. I mean, if we're talking about a virtual CNC, then we're supposed to be just like the Loyd Bishop-Steve Patterson axis; we should be able to take whatever information that Loyd gives Steve and go away and model that CNC.

The more practical answer, though certainly speaking from my company's perspective and in terms of cost, in terms of practicality, is that the higher the level of information to be communicated, the easier it's going to be for us. The notion of working with lots of different sorts of raw data is not something I would view with great pleasure. I would rather look at error functions as a standard way of communicating the errors that are in that system.

There is a second advantage beside the cost advantage, which is the issue of practicality of standardization. If, in fact, all these different machine tools, and their characteristics represented by the raw data are codified in some kind of standard way, it'll make both the development of the product easier and also make it be portable across vendors. Different vendors will have the same kind of input to work in. So I think standardization here will be very important in terms of the input.

The last comment I wanted to make was in terms of the kind of high level model you might have. There are various parametric types of modeling. I would like to know the extent that these linear Taylor series type models are really adequate for what, for example, we saw from Boeing, and other people yesterday. I saw some very interesting non-linear behavior yesterday. If, in fact, the errors in the machine tool are the errors that are important to you, then I would expect non-linearities. If you see non-linearities to the effect of anywhere from 1 to 10 of the area you're trying to model, then I would think those non-linearities might be important.

I saw a couple of non-linearities among data presented yesterday. One example was that at the various extremes of the machine tool motion you saw some spikes. That may or may not be important. The Boeing data indicated that there was relatively good data over a certain range, and it then began to take off. That kind of information might be important to model. By just doing a straight-line fit you may be missing some very important sort of information here.

MR. DEFORGE: I have a couple of comments. I think two questions had to be asked: what is it that we want to do with virtual manufacturing in the future; but first we need to ask the question, what is it that we're capable of doing today. It's important to ask both questions so that we make sure that simulation companies, such as ours, keep our eyes on the horizon and understand the needs of our customers.

Currently, we have methods of taking into consideration some of the inaccuracies of a particular machine, as were discussed yesterday, although there is no quick fix, there's no menu selection and say, "Let's fill in the blanks," and we're done with it. That's not where we're at yet. Hopefully, someday we will be there.

As far as what we're doing today, we're seeing simulations being used to prove out machines prior to purchase, to make sure we're getting the right equipment for the right job, kind of take a look at what kind of capacities are going to be available with that new machine tool, prove out post-processors prior to equipment being delivered, and continually using the simulation models to prove out those proposals, to take a look at cycle time issues at a relatively micro level on a tool-by-tool basis or workpiece by work piece basis, or the overall cycle time by looking for collisions, doing collision avoidance, looking for near misses.

So what kind of information do we need to make those kinds of models more available to companies other than, the big ones, to the small or medium-sized businesses, to make it a reality so that they can function in this highly competitive global market that we're constantly hearing about.

What I look at is information. I'm going to reiterate what I said yesterday about Hans' presentation. Information like that can help me make a model a reality quicker today. The information we discussed, as far as some of the inaccuracies, are the kinds of information I'm going to need in the future. So I think what we have to keep our eye on is what we need today for virtual manufacturing and where are we headed in the future.

As far as CAD data goes, we're just pretty much interested in the outer skins of a machine tool and most of the time we can get that information relatively easily. We need the position of each individual axis. We're not interested in knowing where every bolt is, we're not interested in knowing where every nut is, and things of that nature. That type of information bogs down a simulation.

Since we are also simulating the controller of the machine tool where we get bogged down is understanding how this particular controller is configured for this machine tool.

When we talk about accuracy we have two accuracies that we need to look at. One is the accuracy of the process. If we're looking at the machine tool itself, is it going to behave in the way that we would expect it to behave on the factory floor? For instance, if we're in rapid motion, do we see slow motion, or are we just dealing with point-to-point simulation?

Accuracy also has to do with what you were talking about earlier. How is this particular machine tool going to behave? We really need to know from our customers if that is how they intend to use the simulation. Do they want to have a simulation that is "the" machine tool on an engineer's desk? I don't know that answer yet. But to date, that really hasn't been the big push for us; we've been using the simulation more as a macro investigative tool, not a micro-analysis type tool.

The other accuracy has to do with the CAD geometry itself. I mean, if we're talking about looking at machine tools as precisely as was being discussed yesterday, we have to make sure that we get good CAD geometry for the machine tool up front. It's not going to matter if I have an axis that's off by 100 thousandths of an inch if my CAD geometry is bad going in. So I don't know how we plan on dealing with that; if we're going to try to make CAD geometry available to everybody through some type of repository, or just information about "These are the dimensions, now make it yourself." But I think it's really important to say what can we do today and what information do you need to make that happen and what are we going to need tomorrow.

MR. DONMEZ: From the perspective of what we need for tomorrow, the example that you gave, like a computer in front of an engineer to analyze what he or she can do, given a part geometry, would be a very useful tool.

MR. CALLAGHAN: Alkan, I think I disagree with you on that. I think the first step is to provide tools for the shop floor maintenance people so they can visualize what's wrong with the machine.

MR. DEFORGE: I can understand why you'd be interested in that, but I'm telling you that it's not where the thrust of our business is right now. I know that simulations are currently being used in a design phase to understand the overall process and to get a macro look at the process. Is it possible for this machine tool to make this particular item? What are the quality issues if we decide to use this machine tool is not the question being addressed in our software currently. Can this machine tool even get into the configuration necessary to cut this part and, if so, how long is it going to take, what kind of program is going to be necessary, what kind of fixturing can we think of using? We're not even talking about the issues of looking at the flexing of the work piece due to fixturing. That's something we're not doing in our simulations and we're basically a rigid body simulation; we can't take that kind of information into account today. The main reason is that you have to keep an eye on how long it is going to take to run this simulation. What kind of hardware do we have available today? We would all like to walk in and say, "Computer, give me a machine tool, and let's run it." We're not there. Maybe someday we will be, but we're not there yet. So I think we have to keep our eye on what can we do now, but we can't ignore the kind of information that you're gathering.

MR. CALLAGHAN: I raised that issue because there are lots of machines that are over 25 years old in service every day. I would say the vast majority of parts made here in the States are made on machines over 25 years old, and those are the ones that need the highest level of maintenance. This is where there is the largest degree of interest in looking at machine capability and making corrections to these machines.

MR. HEMERLE: To simulate the machine you would need to know whether it's a primed axis or un-primed axis. Would you need to know the feedback system? Because I look for entirely different errors depending on the machine design and configuration. Where people list 21 parameters, I track 72 significant degrees of freedom and there are many more that I don't do because I'm not at that level of precision. I'm not involved with rigidity, and that's a whole area that is going to determine how fast I can cut and what is the resulting part going to be. I think it would be an extremely long way away before I would want virtual machining to tell me anything about the expected part. What I'm looking for is, from the error characteristics that I observe, what are the mechanical elements inside that machine responsible to contain those errors and how do I identify them and their condition. Not what is it now, but the trending. When I see changes in my bidirectional data, changes in the observed lost motions, how do I interpret what is happening to the condition of the machine?

So, to simulate a machine isn't like simulating one generic machine. My machine A is entirely different than my machine B and the serial numbers are one different. So how is the trending in that? I see modeling to help me understand why machine A is different than machine B and how to adjust to it.

MR. ESTERLING: Dave, I think you would also want to distinguish between different types of machines You're thinking a lot in terms of five axis machines, three axis machines, and then, turning lathes. There are different levels of complexity here and also different levels of interest. We've already done some work in turning for Alkan, and I think we have the sort of modeling that nowadays is required for turning to actually model a machine for it. I would suggest that 3-axis milling is within reach, is an achievable goal, within this year. 5-axis is yet another ball game. We have a little more standardization with 3-axis machines.

There is another aspect. Are you trying to model the macro model, the overall machine tool characteristics? Are you worrying about the kinematics? Are you concerned about the low level material rules for the process? Which of these things? Different companies have different strengths in that area in terms of being able to deliver different kinds of products there. An issue here is where do we, as vendors, need to focus in order to meet your needs? Is it modeling, the overall sort of machine tool fixturing tool change environment? Is it modeling the material removal process? Those are the issues which I think we need some direction.

MR. CALLAGHAN: I think what Dave was trying to say was that we'd like to be able to present to the maintenance people, primarily, illustrations of what the physical errors are, in a machine and be able to track that over a period of time to say, "Okay, today we corrected this machine to take the bend out of it, and we came back three months later and the thing is still bent. Why is it still bent?"

MR. DEFORGE: That's a whole new focus. That's a whole new focus from what we've used simulation for and yesterday is the first time I entered into that kind of discussion for simulation to be used in that manner. So, just from a company perspective, we would have to take a look at the marketability of that kind of technology and if that's something we can invest a whole lot of time in.

MR. CALLAGHAN: The reason why I raise this issue is Dave and I do it every day. We do it with little cartoons that we draw for the fellows at work saying-- "Okay, this is the way the machine is going. We have to go to that corner right there and you have to raise it up to take that error out."

MR. DEFORGE: I think that's easily attainable. I know that, for instance, in our package for each degree of freedom we can control the motion, the kinematics, of that particular motion with a mathematical equation. So, if you can hand me an equation that describes that type of motion, we can make it happen.

MR. DONMEZ: But the problem is the scale. You have nominal motion that you're simulating and then Buzz gives you an error which is about one-thousandth of an inch. To be able to show what's happening to the machine in those two different scales is, I think, a bit of a challenge.

MR. CALLAGHAN: No. What I relate it to is mold analysis. They do the same thing with mold analysis, except that the moving structures are static, vibrating in space, and I would visualize something similar.

MR. ESTERLING: That gets back to what I mentioned about the speed and accuracy being important here. You can always exaggerate. You can scale-up the error in some way, but in order to be able to scale it up properly you'd still need to be able to model it down at the micro level in terms of what is happening.

MR. DONMEZ: I think what we're hearing is three different types of approach to the simulation. One is what is happening to the part, just from the point of view of tool-work interface. Chris is talking about the whole machine moving and then adding the errors to look at the part eventually. But Buzz is saying just look at the machine only and show what the convolution of all these different types of errors produce. They're somewhat related, but are three different directions.

MR. HEMERLE: Looking at the part, to me, is somewhat analogous to being an industrial paleontologist. You're looking at a footprint of a dinosaur, trying to describe the dinosaur. Asset preservation is what is the quality of that machine tool. The part is a by-product. If you can describe the machine tool, you know what is coming out, but you can describe a part and not have any insight into what is going on in that machine. You might be able to tie it back to your model.

MR. DEFORGE: Technology is not there to be able to deal with that yet. It's not there. But I think we have to be positioned to take advantage of that technology when it becomes available.

MR. HEMERLE: The errors and conditions are there--people are dealing with it--and technology is merely to assist them in doing it better today than yesterday.

MR. DEFORGE: When I refer to technology, I'm referring specifically to my technology, to simulation models. That's why I said yesterday that we see bits and pieces of this throughout the computer information industry; that company A is able to handle this kind of information, company B is doing some finite element analysis, and we're doing some dynamic modeling. To bring all that together into one software package with today's technology would mean let's get a Cray computer on everybody's desk, and that's not realistic. So, let's focus in on specific tools for specific jobs. Currently we can't always bring them all together. That's why I say we don't have the whole deck yet, but we have parts of it.

MR. ESTERLING: Chris' company and our company take somewhat different approaches toward the marketplace. Chris' company has focused more on the high-end user, which is well represented here, and our company has focused on the low-end user. It's probably reflected on our pricing, as well as the number of seats sold. Our focus has been on what horsepower available on the small shop floor. Our focus is to deliver a product which will work on what today's computers have or maybe what tomorrow's computer will have within a year or so. It's a different modeling structure and, again, as you look at different vendors, there is a handful of vendors out there doing what we do and each of us has our niche. There are two issues to be concerned with here. One of them, as Chris has already pointed out, what are these different vendors doing today and what can they be doing tomorrow. I think the critical point is the marketability. None of us are there in terms of what you're asking for now and for any of us to make that move and start doing something, there will have to be some market signal. The market signal, among other things, would be a specification in terms of what you want. That's where this meeting has been very helpful for all of us in terms of what your specifications are.

MR. YUAN: In cooperation with University of Illinois and Northwestern University, we're developing a project also called the "Virtual Machine Tool." Our idea is that, if you have internal error components you already measured, then we have a model and we can transfer that to the volumetric error. If you have a machine, then you use what we call a topology model to describe this machine. You have work piece branch and you have a tool branch. For the work piece branch maybe you have X axis and Z axis, and for the tool branch you may have Y axis, then you input the topology model and then software can develop the volumetric model automatically. Then, you have to do error components as inputs and the output will be the volumetric error. If you are cutting a part, then you have a path, and from this path you can get the volume along this path so then you can know what is the form error along the path. That is a theoretical volumetric error from your individual error components. This is what we are supposed to do. We catalog all the data in the topology model and how to automatically formulate the volumetric sensitivity model according to the topology model. This part has been completed, and other parts are still ongoing and underway.

MR. ESTERLING: All these discussions reminded me of something that I think is important to be mentioned in terms of this database that NIST is putting together. There is a spin-off of this effort that is very important to our companies. We are hungry for data about different machine tools, the ideal machine tools. By creating this database you're going to be providing us information about how that machine is set up in terms of for a given manufacturer, a given model, irrespective of the error component there. In fact, information about the actual set-up of the machine tool is going to be very useful to us, particularly as you get into multi-axis type machine tools. So, it's not your agenda, but that data is going to be very helpful to us.

MS. KRULEWICH: As far as Buzz's requirement about displaying particular types of errors is concerned, it wouldn't be that far of a leap to take a particular machine and exaggerate the squareness of one axis for maintenance and repair purposes.

The other comment I want to make is related to the errors resulting on the part, if the concern is the part. If you have a particular type of machine with a particular type of error and you're going to machine a part with that machine, then in the design phase you can intelligently tolerance your part, especially if it's an assembly with multiple stacks of parts. You can intelligently tolerance your part based on the performance of your machine. I think that there is a use for knowing what the resulting errors on the part are, not necessarily for diagnostics purposes, but more for the purpose of the designing of the part. But it doesn't need to occur in real time with this simulation. Because you're not going to see the machine move with those errors. So, that could be something completely in the background and then you maybe form the figure of the part with exaggerated errors when it's done, but that wouldn't need to happen in a real-time simulation.

MR. DEFORGE: In our simulation, the creation of the part is the result of the machine tool's motion. So we're actually taking the tool through the work piece as would happen in reality and, depending on how that motion is defined is going to determine your work piece. So, we're not taking CL data and saying, "Let's look at the description of the part based on that, and here's your geometry." We're actually taking the G&M code and driving the virtual model and the finished part is the result of that motion.

MS. KRULEWICH: When you're talking about computation time, I guess what I'm thinking is that it doesn't have to be displayed on the screen, while the machine is moving.

MR. DEFORGE: That's absolutely true. Because of limitations in hardware technology, basically what we always do for our customers is we draw up this triangle and we say you have extent, accuracy and speed on this triangle, and for any simulation run we say, "Pick two." That's what you're going to get. Let's say, if you want speed and accuracy, you're going to have to sacrifice extent. If you want extent and speed, then you're going to have to sacrifice accuracy. That's simply because of where we're at with hardware technology, not with software technology. We're seeing some significant changes in hardware technology that are making those kinds of tools less and less necessary. Those are limitations that we live within in the computer industry. But, to duplicate squareness is completely doable. On the geometry, if you say, "Here is my base. I'm going to lay my X axis on top of this base right here," we're going to put a coordinate system right there where it's supposed to go. Now, I can adjust that coordinate system anyway you want. I could attach two coordinate systems to that same place, one could be used along the X axis and the other could be used along the Y axis. So, I have the ability then to move those coordinate systems about. That's completely doable and very accurately, within a micrometer.

QUESTION: Can you simply take the inspection data and feed that in though?

MR. DEFORGE: No. That's what I said earlier; I don't have a button that I can push today and say, "Let's make those adjustments."

QUESTION: But do you think it's doable?

MR. DEFORGE: Absolutely. I know that, for instance, I could write a macro right now. I have the tools to make that happen. I could write what we call a GSL, a graphic simulation language macro, so that you could press a button and ask for the parameters and adjust each one of these tag points, or each one of these coordinate systems.

MR. DONMEZ: If you have a simulation of a slide, for example, can you put all six degrees of freedom errors on the slide and show that?

MR. DEFORGE: Yes, because with the way that we handle each axis motion, the system says, based on the menu selected, that this axis moves along X, this one moves along Y. But I can go in and make a more detailed definition of how that is supposed to move based on a programming language which you would actually walk in and lay out the mathematical equations. So, if it moves along more than one axis, as long as we can describe that with a mathematical equation, then we can duplicate the motion.

MR. CALLAGHAN: Alkan, I'd like to take a minute and try to put all this stuff in perspective since I've been messing around with this stuff for almost 15 years. To have this work, there are several stages that have to be accomplished before we even start to talk about what Debbie talked about with simulations. I think the first phase was to get the instrumentation commercially available with systems that will gather the data and get it in a format where it's usable. I think we're pretty well along that right now. You know, there is a number of products out there right now, there is a lot of things you can do to gather this data.

The second step is to apply that correctly to the machines, to get the machines stabilized mechanically, thermally, and so forth. We're not even close there yet. We have scratched the surface. I would guess that less than one percent of the machines in this country could use what Debbie is suggesting as a model because we don't know enough about the geometries of these machines are from day to day. There are a few machines that are in controlled environments that are using these tools, that have the measuring instruments. Users stabilize these machines on a regular basis and they measure them periodically, but, for the most part we don't have the stabilized conditions in the machines where we get a lot of value out of doing a simulation. You can do it in the laboratory but you're not going to do it in the shops right now. We're fighting continually with management over other techniques to stabilize the machines so, when I come back and measure the next time, I get reproducible results.

MR. DONMEZ: I think you're absolutely right in that respect but, this is reality. If this is reality, we need to have a representation of that reality, and the best representation of reality, I believe, is to introduce some of these terms into our models.

MR. CALLAGHAN: The problem is that most of these are outside the tolerance limits of the parts you're trying to produce. Dave Hemmerle has coined some words that are kind of interesting. Right now most manufacturing is done in what is known as "gauged base," and that's Dave's term. That means that they take a trial cut on the part and they come in and apply a gauge to that part and make a correction to the tool offset and then finish the part. Now, that gauge space application is the way they're able to produce these close tolerances. There is operator intervention. It is correcting for the changes that we can measure. The management's position is that the process is working, let's not mess with it.

There are a few places, like Dave's company, that are successful in developing what we call "machine space applications." This is the case where you can do a simulation and you can come up with some reasonable numbers. But I would venture to say that less than one percent of all the machines in this country are truly running machine space applications. A lot of people think they have that, and a lot of systems have failed. We would like to have something that we could present to management, a picture that says, "Okay, you just paid a half a million dollars for this machine to go in a straight line within ten-thousandths. It's installed and it's going at a tenth of a thousandth. You come back a week later the environment has changed and this machine that you just paid a half a million dollars for is now five ten-thousandths of an inch bowed up."

This is my reality. I'm living with this every day and trying to get people to stabilize the machines enough so that we could do some predictive analysis on them. We can't do it yet. We need that first step. We need to be able to provide to the maintenance mechanics, and to their supervisors, a real simplistic representation of the errors within the machine. That's the first step.

MR. ESTERLING: I agree. My point is that you really need both. For example, the nice thing about software is you can play the "what if" scenario. That's a lot harder to do on the shop floor. If you wanted to make a presentation to management and say, "Now here is what's going to happen. You've got a machine tool whose errors you can't see. But let's make a part. Let's do a 'what if' sort of part that you're going to run on that thing. Now let me show you in some way that's fairly dramatic to that manufacturer that this part is out of tolerance." Then you're not just talking about the artifact, but you're talking about the part this guy wants to deliver off to someone else. So I suggest both aspects are needed. You need to go in both directions. The advantage of software is that you have this ability to play and explain things to the maintenance engineer at one level, to management at another level, and it all ties together. That's really what hopefully we offer in terms of value-added here.

MR. DEFORGE: We're going to create this database of information, now who is going to be able to use that? How useful is this information? You know, you're willing to give your database and all this information to me, but what does that really mean to me, in my business? You say, "I have machine A and I have machine B sitting side-by-side. They're the same make, the same model number. They are one digit different in their serial number, yet they both act uniquely." So now, what does a national repository of that kind of information do for me?

MR. ESTERLING: But doesn't it give you some kind of statistical data so you know what kind of variation you've got for a given class of machine tool across the country and across environments of what you have? Now, is that useful or not?

MR. CALLAGHAN: I don't think so, because you're going to have different levels of maintenance.

MR. DONMEZ: I think the issue is, if you have machine A and machine B that are behaving differently, you know they are behaving differently because you have data on them. If you have data on them, you can use that data to predict what's going to happen using machine A or machine B.

MR. DEFORGE: Suppose, if we're using this data to help understand the problem and to help vendors such as my company understand where we're going with this information in the future and how we need to tailor our software to accept this information, then that is of value. Basically, let's look at the kind of information that's being collected and the kind of information that's needed to bridge this gap between virtual reality and reality, and what kinds of things do we need to look at to do that. That does become of value. But I'm looking for something that's even more basic than that, more standard than that, that Fanuc has this many controllers, and this is the kind of information, the kind of syntax, that they're expecting on their G&M code.

MR. CALLAGHAN: You want generic average readouts.

MR. DEFORGE: Absolutely.

MR. CALLAGHAN: What I am looking at, and what he is looking at, I believe, are very specific applications, and so my maintenance people may maintain the machine, the same machine, totally different than his configuration, or his accuracies, so I really see that specifics in the data base would be of very little value because there would be wide ranges between those and you wouldn't say, "Well, what is the specific machine I've got to deal with." But you're looking for more of an average generic call-out for the machine and I don't know if that should maybe come from manufacturers or the people that build them and get them on board with this kind of information and the methods of reporting the information, get them to do that, but it's still going to be wildly varied, depending on where you're at.

MR. HEMERLE: They already do that, don't they? They error budget by characteristics when they make up the machine?

MR. CALLAHAN: Not all of the parameters, I don't believe. They don't publish them.

MR. HEMERLE: They don't publish them but, let me tell you, that's where they make their money and could be why they're not here.

MR. JOHNSON: It seems to me that what we're talking about doing here could be useful information over a whole spectrum of activities, from a production floor all the way back to the customer for some product that is describing what the requirements are to some company that's going to design and produce that for him. Our environment, where I work at Texas Instruments (TI), for instance, our customer may want a laser range-finder for one of their tanks, or something like that, and to just take one requirement, they might want, a detection range of 3 km, or they might want a detection range of 10 km, and if they want one for 10 km that's going to turn into, eventually, a lot tighter tolerances on the piece parts that go into that and the electronics that go into that. So, they hand those requirements off to our systems engineers and the systems engineers determine what kinds of components need to go in here, which drive the manufacturing processes that are going to be used to build those types of components, and then they allocate those tolerances down into the sub-components and give those to the lead engineers, and then they sub-allocate those tolerances down to the individual features in those components. And then, that's how, that one and a half inch diameter ends up with a plus or minus a tenth of a mm tolerance on it. Those systems engineers can use the information that we're talking about generating here at a higher level of abstraction, of course, they don't care about feeds and speeds and depth of the cut, but they need to have manufacturing information to make the right decisions about the right types of components if they have alternatives that they can pick from that are going to be less costly to manufacture because of the manufacturing costs and the tolerances involved. So, it seems to me that we probably need to get a broader spectrum of people involved that perform different functions in putting together a road map for what needs to be developed first. Obviously, some things, the modeling, needs to be done. We need to collect some data, we need to validate the way we model these machine tools and what they're capable of before we can move up to the next level of abstraction and start embedding that into CAD tools so that the design engineers can understand what they're doing. Then we need to move up to the next level of abstraction so that the systems engineers know what the impact of the decisions that they're making are. It may be 10 to 12 years down the road by the time we get to the point where we really have good information for them to use. But, as we move upstream in higher levels of abstraction in modeling this capability, I think that the design engineers are going to get some level of use out of just being able to go to the manufacturing facility and understand the model for manufacturing certain types of parts. There is a certain amount of information that's going to come out of this pretty early that could be embedded in analysis tools that are being developed right now for design engineers.

So, we need a road map for future, may be for 3 to 5 years or 2 to 3 years into the future, then say, "Okay, now we have visibility for 5 to 10 years out." We need to get the right people involved so that we can at least all have an input for where we are in that whole product life cycle and what's important to us. A joint development of a road map like that is a real good tool for getting--if it's facilitated properly--a lot of information out on the table so that it can be sorted out, categorized and then put in some chronological order. From this roadman, we can generate plans for how we're going to develop this and then put some dates and times that are reasonable on when to expect to achieve those.

MR. ESTERLING: The market is driving that already. The major CAD vendors are talking to even little guys like us, and Deneb to do this integration of manufacturing into the CAD environment. There is lots of hurdles to get past, not the least of which is the whole sort of outlook that the designer has. But at least by making a clean environment inside a Personal Computer, let's hope the designer might actually get a little dirtier in terms of what's happening on the shop floor. That's the goal, but there a lot of market push in that direction already.

MR. MA: One obligation for the simulation, for the rating of machines, is to see how good the machine can be, what kind of part it can make. In some situations I understand the companies are trying to relate the manufacturing data to the sales. They have a bunch of machines and they want to put all this inspection data and then form a model so that when the sales or marketing are trying to get some business they are putting in the problems and see which machine is available and then whether they have capability or not. If the simulation can create a model showing a part, say a basic dimension, how to do it, and then that would help them make a better decision.

MR. CHANDRASEKHARAN: I've been sitting very quietly because we've gone through something very similar like this before when we talked at Caterpillar of why we wanted to get into something like this, and I clearly hear that. Everybody tends to gravitate toward where the problem is focused more at. For instance, Buzz and Dave are talking about looking at the machine and how it is moving, and somebody else is talking about the part, and somebody is not talking about variability saying that's not important. What we heard is all these issues are very important to us because we take a part, if it's in a cell, a cell controller, it could send it to any of the machines depending on what is available, so you have variability in your product coming in right there, and different machines are behaving differently and we need to capture that. We want to send it up to the design stage in a manner that they were talking at TI, but the core of the problem is lack of data, and I think that's why yesterday I was trying to show that we need to de-emphasize some of the simulation aspects because different people here want to use it differently. The core, again, is the data, how do we store the data, the completeness of the data to perform each of these functions, and I can see that as being a very useful outcome of this project, and that's how we're getting involved in this. Now that we're collecting this machine characterization data, if that's truly a characterization of the machine, it should be able to support all of these functions, not just one or the other, and we see that clearly happening. The variability across these machines might give us indicators of our C_{pk} (Capability index) not necessarily take it and drive it through each part, drive it several times, or run multiple simulations and then compute C_{pk} numbers, the brute force method, but we may be able to get other metrics out of it and do quicker simulations and estimates of how capable is this cell in making parts, use it to simulate things for maintenance folks. That was something that came up earlier about showing how do you physically show the machine move, and we said, "Well, if you can show the tool tip move, along with the ways, or show something on a bed, the way it's moving, to characterize an error, would that help the maintenance guys?" How do you show it? Where does that reside? Should it be on the same laptop that they're collecting data out in the shop, or would it have to be off-line on a workstation?

We're trying to develop tools that will help different areas. That's our role at the Tech Center. But the data has to come in from somewhere, data has to be stored in a unique way and just one place. We don't want different sets of data for all of this. That's why I'd like to reiterate that let's work with the data, modeling the data, let's figure out how to store it, and to test the completeness I think we need to ask people like we have here on the simulation side taking that and running simulations to see if we're meeting requirements like what we have to simulate a part, what they might have to simulate the way a machine moves, and can we get indices like what they were talking at TI and help designers better. And I think that's what some of the companies participating in this should bring to the table and maybe the software vendors can help provide things like that.

MR. JOHNSON: Yes. I think there probably is a very logical sequence for how this capability needs to be developed and put in place, and, if we can think of a way of, I guess, joint application of a plan for what should happen first and second and third, I think that's probably what we need, a road map with definable milestones, and say, you know, "This is the capability. This is what needs to be done first. This is what needs to be done second. And maybe there are some things that need to be done in parallel," but setting out a logical plan for getting this capability developed and deployed.

MR. DONMEZ: Yes, probably for an action item for us, I mean for the next meeting, we would present to you some sort of, as you say, 3 to 5 year's road map of what we see as important steps in the application.

MR. JOHNSON: I would suggest that you might also request inputs from people that represent all those functions across that full spectrum of the product life cycle also. Some people may be waiting for 10 years before they have the capability they want, but at least, you know, they'll have an input as this goes along. Hopefully it won't take that long.

MS. KRULEWICH: I just want to make one comment about the need to understand the repeatable versus the non-repeatable components and understand the type of error distributions again, because it keeps on getting brought up. It's not going to be useful to do this simulation for one particular machine because every machine is different. Even within one machine, it's not necessarily repeatable. But I think the power of having this database is the statistics, and if you have all of this data for a particular machine, maybe it's even for a particular machine through the time period of that machine, plus other machines of the same family, then you can understand the distribution of those errors. I think that's a really powerful tool that we definitely don't have now. I don't have as much experience going out and measuring all the thousands of machines, but I'm assuming that for a given family of machines you could do some type of error distribution of that one particular machine for a given factory floor.

MR. CALLAGHAN: No. The problem goes back to what I mentioned earlier. There are not a lot of factories in this country that are using machine space applications.

MS. KRULEWICH: That doesn't matter though.

MR. CALLAHAN: Yes it does, because the operators intervene. The operator is correcting for the real-time errors, he's correcting for the geometry errors.

MS. KRULEWICH: That's still okay though because, let's just say for a particular factory floor, the distribution of the errors from one machine to another on a factory floor is a uniform distribution. It could be anywhere from -20 to +20 micrometers of error, and it's a uniform distribution and that is a useful piece of information.

MR. CALLAGHAN: Not without knowing what the skill levels of the operators are. You won't have enough data to make that assessment.

MS. KRULEWICH: You need enough data. I mean, you can't make that assessment successfully if you have three pieces of data. But, if you have a lot of data, over a long period of time-- Say you have five years of data on this factory floor--they've had operators come in and out and you have enough statistical data--you can statistically make some conclusion about the distribution of errors on that particular machine and, knowing the distribution, you can put confidence intervals around the final accuracy of a part. I'm still thinking of the part, not from a maintenance point of view, but from the point of view of the part you can put accuracy limits around. In this factory you believe that this type of machine can make parts with plus or minus this accuracy based on all the statistical information. We need to know the distribution of the errors and the whole range. I think that an historical database, whether it's at one company or it's a national repository, would be very useful for that purpose.

MR. BISHOP: I agree with you fully. That's the direction we're trying to go because, if I've got 17 machines and one of them, or two, or three of them, are performing way out of their range we know we can't get in there and physically alter those machines. But, I also tend to believe that some of that would be competitively sensitive information and I'm pretty sure our company would not be willing to divulge that, or other companies as well. But the idea is very sound. I agree with that. And that's what we're trying to do.

MR. ESTERLING: From the statistics point of view, I suggest we have a relatively skewed audience here in terms of people who are paying attention to B5.54 and using the services of IQL and API and all the others. All our companies aren't. If you went to a given company and said, "Okay, you don't know what your machine tool characteristics are, but here, on average, is how that machine might be behaving, and here is how it's going to behave in your shop," should you, in fact, be concerned about standards? Should you be concerned about calibrating this machine tool and whatever? That's, again, the "what if" scenario that you can play with software, again to drive home to management just the importance of the kind of calibration that you guys are doing at Boeing and you're doing at GE, that a whole lot of other companies maybe aren't doing.

MR. CHANDRASEKHARAN: Buzz, you bring up a good point about the operator being that important. You can sell that to management, saying that you're taking the operator out of the loop. For a company like ours, what we've gone through in the last three years, and what Boeing has probably been through, you can be more consistent without the operator. Machines have helped us do that recently. When I set a machine up in the south, when I set it up out of the country, anywhere, if I can show that it's purely a characterization of the machine that is going to affect what I'm making out, it would mean a big sale. That's really useful stuff for us and we don't know how to do that yet because there is a lot of operator intervention. We keep hearing from our cutting tool suppliers that what they do in Japan is, once they put the process out, the controller is not accessible to the operator. They cannot change feeds and speeds; the overrides are completely locked. You go to our plants, that's where the operators' hands are, on the override. We cannot get our specs because we don't know how far down or up he has tweaked the controllers. A lot of it is good because a lot of our operators are very good, very well trained, and they put good parts out. I'm not saying that it's all bad stuff. But that's a problem because the new guys coming in don't have that training and they don't have the ramp-up time. So, it's very useful if we can take them out of the loop and know truly what is the capability of that machine in making the kind of parts that we have to make.

MR. CALLAGHAN: It would work if we can substitute, somehow, that knowledge base that they've acquired, for that particular machine into the configuration of the controller some way. But, when you can't do that, in the absence of that, I'll take a good operator any day because we've got a machine that you can't afford the maintenance necessarily. So the operator is the next link that enables us to produce good parts off a machine that might be necessary for full retrofit or something and would cost a lot of time, down-time, and money.

MR. HEMERLE: We will not make another automated factory.

MR. ESTERLING: Replacement of good operators just is not going to happen. I think what you might want to do is to put more power in the hands of the operators themselves, give them more flexibility in terms of what they can do, and that's certainly what the controller people are trying to do is put more intelligence down on the shop floor and take advantage of what these guys already have and leverage that.

MR. MA: You have software that can compute the error? If I give you the error, can you plot, like a volumetric error, like a 3-D, just purely the error?

MR. ESTERLING: We've done that for turning, for his NIST folks, but Chris, I don't think any of our companies have addressed this in terms of the general sort of situation. It's a different niche. Our niche has been CNC programmers, to sort of find geometric errors for an ideal machine tool. This business of now modeling errors and talking about it is something that is going to require some rethinking in terms of our plans.

MR. DEFORGE: There is no button on the screen right now that says, "Import Error Function Now Displayed." That doesn't exist yet.

MR. ESTERLING: Basically, we got the ideal part program, we also got the error characteristics of the turning machine error and integrated it in. We then displayed the part in the machine with various amplifications so you could see the actual error, sort of the tool would be jumping up and down, but also some ways to be able to measure the deviation of the ideal part from the truly machined part. But that's only been done for turning.

MR. DONMEZ: Any other thoughts on simulation activities? We should wrap it up for now. So if I summarize what we've all discussed, we need to look at, again, three different directions of the simulation needs. One is machine, one is machine overall with part, and one is only part and the tool. Those are the three different approaches. Even though, as Vivek said, simulation may not be the critical factor at this stage, what we should be looking at are the needs from those software components. We may need to modify our formats and the structure of data depending on what type of inputs those software tools would require. So, I suggest we should keep those in mind.

MR. CHANDRASEKHARAN: Definitely. I didn't mean to say we shouldn't be doing simulation, but what I'm saying is we should do it to define the completeness of the data and make sure our definitions are correct and we have adequate information, and I agree with you completely on that.

DISCUSSIONS ON HOW TO USE A WEB REPOSITORY

MR. DONMEZ: We talked about the repository yesterday. We showed some examples and we talked about what type of data that we would put in it. Basically we dwell on the very raw part of the information. Now, the reason I put this item here is to talk about what other needs that we have, what analytical tools or analyses that we need to do in the repository itself, if any.

As you saw yesterday, Larry ran a MATLAB program in the background and produced some information based on the raw data provided by the instrument. How much of that kind of activity we foresee that we need in the repository? That's what I'd like to discuss a little before we go too much further in the development.

MR. CALLAGHAN: I have a suggestion. Maybe as minimum, we should have the algorithms that are necessary to analyze the data according to the existing standards, like the new ISO standards, new B5, B89 methods of analyzing the data.

MR. DONMEZ: One extreme position would be, for example, if Don Esterling would require a functional representation of the error, do we need to do all the fits in the repository and provide that mathematical representation of that particular error component or not? I think that's an extreme case.

MR. CALLAGHAN: It makes sense though. If you look at the history of the CMM algorithms, there was a whole host of different ones out there for describing different forms and shapes, most of which didn't work, and it took like almost a ten year period developing a standard algorithm and I think NIST is a repository for those right now. I think that makes a lot of sense to have that done in one place, do it once, rather than have all the different vendors develop those fitting methods.

MR. DONMEZ: But, on the other hand, people may have better solutions.

MR. CALLAGHAN: Yes, they might, but again, they went through an extensive testing program on the algorithms for fitting the forms for the CMM. Maybe that's the same sort of thing that is necessary here, to fit certain functions to certain kinds of errors that we see in the data. To me, with the size of the community we have, and the resources we have, it doesn't make sense to have everybody trying to do the same thing, reinvent the wheel.

MR. DONMEZ: So, the sample that you saw, the MATLAB kind of mathematical tools, would be useful in your opinion to be able to do all these fittings and mathematical manipulations of the raw data that is input into the repository?

MR. MA: There are mathematical tools in the area of technical support. Different machines have different data patterns and someone will probably have to dedicate a lot of their time to solve all these kind of real problems and respond to them.

MR. DONMEZ: Those are sticky issues from the licencing point of view. I'm not too eager to put more mathematical tools into it. For example, the licensing issue for MATLAB came up during our own discussions. We just used it as a prototyping tool but, if you open it up as a tool that comes with the repository, then what happens to the licensing?

MR. CHANDRASEKHARAN: I'm a little confused here. Are we trying to, at the end, have a complete set of tools, of software and things like that, that somebody can use to make profit, or is it just going to be something to validate the concept on an experimental basis for what we are doing now? My understanding is the latter, so I don't think this licensing issue should be a big thing because it's sort of research at this point. All we are trying at this point is to show that we can take this data, define it in a certain format, store the data in a certain format, and prove that you can generate error functions, prove that you can use it to do simulation, prove that you can generate the kinematic motions of the machine.

MR. DONMEZ: Yes. That's certainly our view.

MR. MA: If you already set out rules, and then later you find that some of the elements are going to be very costly, then the rules will probably have to change. You said there is a potential licensing problem. You need to think about that earlier so you can make use of that later on.

MR. DONMEZ: The other alternative would be, as server managers, we could do the calculations in the background and provide the results and not do the calculations in real-time, and therefore the users of the repository don't use the tool.

MR. CHANDRASEKHARAN: Right. In fact, I don't think I'll be using that. For the data we're collecting on the floor we won't be using the repository and the tools you provide to analyze the data. We won't be doing that. We have our own tools the way we do it today, and we'll stick with that. What we'll probably test is, if we are developing simulation capability, can the models that they are generating feed something like that. So it'll be a trial basis or an experimental basis, and so you're absolutely right. If it does mean that Larry is the only person that will finally send for the calculations and put the results back up the next day, that's fine. We want to test the completeness of the data, so we probably should be okay. I don't know about the rest of the folks here, but we won't be using it for doing our regular calculations or regular analyses.

MR. DONMEZ: The other use from the simulation developer's point of view, is to be able to get access to the layers depending on their own complexities and be automatically generating the form that they want to put the data in, but maybe it's too early at this stage, based on the discussions earlier, that we don't know yet what simulation tools will require.

MR. DEFORGE: I think what I need to do is to communicate to Larry and others what we need today, to build a model today, and instead of doing that here, I'll send you the information that I require in order to build a mill or to build a lathe. Then at some point I think it would be valuable to take a look at these simulation tools and see the kinds of information we're able to get from them? I'm wondering if that would be an appropriate step at the next meeting

MR. DONMEZ: Should we allocate some time to do some sort of demonstration, like your system as of now, what can it provide, and what in the near future can it provide? We can provide you some data and then you can play with it and come up with some ideas.

MR. DEFORGE: Absolutely. We'd be willing to do that. I kind of envision, if this is where we're going, I'd like to be able to call up the database and say, I've got this particular machine tool and it's got its fundamental description which comes down to this document here, and, like any other machine tool, you can't do anything else. We can't look at some of these other issues until we have the basics. How is this machine supposed to be assembled? How does it move? So, until we get that information we can't even deal with any of these other issues. I think that's the first step. If we were to look at a web screen that says, "Basic Machine Components," and you click on that button and it gives you all that fundamental type of information to help us build a model quickly. If you had another button that says, "Now Let's Calibrate This Machine Tool," we could try to bring the virtual world and the reality world a little bit closer together. What kind of information do we need to do that and what can we use today and what can't we use today? I think that has to be defined so that we get back not just what we need, but what we're capable of dealing with. That then becomes of value to us and, I think, to our customers as well.

MR. ESTERLING: Chris' company looks at things on different levels than we do. They deal with more of an overall sort of machine tool process modeling, as well as the micro sort of modeling, whereas we're more myopic and look more at the material removal level, and that's our focus, our specialty. So our needs are quite different in terms of the overall sort of machine tool set-up, not where all the bolts are but what we really want to know is what is the cutter doing, what is the spindle doing, what is the holder doing, and, where is it going. Those are the sorts of things that we need within our modeling sort of structure.

MS. KRULEWICH: I have a question. Maybe this should be focused towards Boeing too to see what industry's interest in this is. Is the purpose of the repository just to create a place to store this data so that all these other packages can easily store to and retrieve, or is it more of even a larger vision, that you would actually put software tools in there also?

One software tool is the statistical analysis of errors, but that's the one tool that does not exist and can only exist on a system that has this large amount of data which doesn't exist now. But it seems to me it would be useful for it to have the ability to take this group of data and do some statistical analysis on. I don't know if it would be on a particular parametric error or on the whole volumetric error, but to do something like that could be useful. But it seems like now there are all these other packages that people are pretty set on using and the main thing for the database would be to have the ability to access, retrieve and store to the database.

MR. DONMEZ: If you remember from my earlier presentation yesterday, our ultimate goal is to be able to enable this virtual machining/virtual inspection environment. But, in order to get there, this repository is an essential tool because of two reasons: one, in immediate industrial use those companies need to get the information from their capacities and capabilities; and the other important thing is from the research perspective, as you mentioned, to do analysis on these healthy data and come up with more robust models than we have today, and that includes some statistical analysis into the variation of machine-to-machine behavior. So, all these things will be possible if we have a repository which has unambiguous, healthy data on a variety of different machine tools.

MR. CALLAGHAN: Alkan, I thought we agreed yesterday that this is strictly an experimental testbed and Boeing is probably not going to contribute any data to that. I probably will, because I want to see how it works. Cat is not going to contribute.

MR. CHANDRASEKHARAN: We will contribute sample data. One or two. We're not going to keep putting data into the repository.

MS. McMILLAN: We'd certainly like to give guidance, input, be able to ask questions.

MR. CHANDRASEKHARAN: For instance, if we think the data definitions may not work on a certain type of machine data that we collected, we'll probably test it by putting that data in and maybe take it back out, or put it back in and let somebody else use it. So, if you have some questions in testing the completeness or doing a statistical fit on different kinds of machines you can probably work with the group and see if there is similar data that you can get and do analysis on, or something like that. But it's not a repository where we're going to keep feeding in data. We're not committing to that.

MR. DONMEZ: That is absolutely true, but we also have to keep in mind that the power of this type of repository is the amount of data that we can put in and get information from that. So, one or two machines is not going to be enough; we have to have a lot of machines, not necessarily from only one company, but from all over the country we need to have lots of different types of machines.

MS. McMILLAN: Maybe if we called it a "Test" repository, so that people didn't think this thing was going to start growing and keep growing. I see it as a good test repository. If we could, in industry, start talking at least the same language, which gets back to your data dictionary, that's a start for being able to transfer data back and forth. If I've got the same machines that Caterpillar has got and I do want to do some comparison on a particular type of machine, I can talk to that person and possibly exchange data at some point, because we talk the same language. And maybe with that data structure I could compare it against the data structure that I currently have and see what I'm missing and see what I'm not. That's what I would want to use that for.

MR. CALLAGHAN: Back to your statistical analysis, I agree with that and we plan on doing that also.

MS. KRULEWICH: But that's a later step.

MR. CALLAGHAN: Right. We need to get the database in place and the fixturing in place and then analysis.

MS. KRULEWICH: Will the analysis reside on the same, or will it be a completely separate system? Will it reside on the same system?

MS. McMILLAN: In ours it would probably reside within it.

MS. KRULEWICH: Yes, because I was just thinking back to the question that you raised of whether you should be providing software tools or not. It sounds like most of the people that want to use this database, the main interest is just to see if they could access and retrieve, not necessarily do analysis.

MR. CALLAGHAN: My hope is, too, that we learn as we go. Let's say we have a database in place and we've decided what all the dictionary definitions are, we've got some data, we've tested it, the next phase is analysis, and I'd like to know what Caterpillar does with it. How do I statistically handle my data and how does he handle his? So you can communicate back and forth.

MR. CHANDRASEKHARAN: Yes. We will do that.

MR. CALLAGHAN: It's more than the actual specifics, how do you do it and how much do you do. I have an experimental question for that. Once you get the data, how are you going to use the data most effectively?

MR. CHANDRASEKHARAN: And we'll contribute as much data as required to meet their needs and our needs and do analysis of that type to keep the momentum going. That's our goal. We have a few priorities on how we want to analyze the data. Some of it is statistical analysis, some of it is just to have access and retrieval and use it for simulations of different types, and feedback information to designers. But, we need some place to test it. If we start trying to define this thing ourselves, and try and put some data in, we find our limitations in our resources in defining the data, limitations on the amount of data we had. If you can leverage things like this and call it "machine A, B, C, from Company DEF," that's all we need.

MR. MA: The problem is that we're not measuring a machine like you're measuring the part. You measure the part may be thousands a day. You're measuring a machine may be every month. Actually your machine bed probably already has changed, so your model now will be quite different.

On the other hand, when we send out data to this database, do you want the clean data, or do you want us just dump whatever format we have. Because, that's quite a lot of data entry work.

MR. DONMEZ: Yesterday Larry promised that as long as you provide the full format of your data he will take it.

MR. WELSCH: We need the specification though. That is absolutely clear. Now, obviously, if you're taking it from the same types of data that I've seen, then I think it's reasonably straightforward, but the data dictionary, as we keep saying, is a major issue,.

MS. McMILLAN: And it's a really good first step, don't you think?

MR. WELSCH: Yes.

MR. CALLAGHAN: I hope too that when you get this data dictionary in place and we can come to some agreement, that would start influencing the providers of software to move in that direction. We don't want to create little programs to search and parse the data individually. I'd like for us to somehow come up some standard methodologies and some standard representations for data where we have easier access to it than we currently do.

MR. WELSCH: That's where we want to head.

MR. CALLAGHAN: You can do that job and we can do that job, but I don't like doing that if I don't have to. If that's one of the outcomes of this meeting, I would hope that we could come to that eventually.

MR. WELSCH: Initially, we're going to set up a web page with a proposed data dictionary and start collecting everybody's comments on that. That will also be probably one of the early discussion topics on our mailing list that we'll be sending out in the very near future and trying to solicit everybody's comments.

At this point in time, for data similar to the types of data that I have seen, similar to the types of specification, where there is a --and I'm going to use a computer science expression-- well defined regular grammar to it, or a very well defined format, getting it into some type of form is reasonably straightforward in the sense of writing a program that will parse it. Now, as you write more of these, keeping track of all the different things starts to become a tremendous issue.

MR. CALLAGHAN: All the versions that you have to keep track of?

MR. WELSCH: Yes. But that gets us started, and hopefully, once the usefulness of the repository becomes clear, we'll be able to draw those things that are simplest, or most straightforward, or that comes closest to what people actually have, and start encouraging people to then deliver it in a limited set of forms. But, right now we want to just get started, so, we'll take it on ourselves to take some of these specifications and get the data and get it in. I don't know another way to really get it started because, in a sense, if we define a very complex format and give it to everybody and say, "Here, this is the only way we'll accept it," nobody will build to it. The problem I'm faced with is how robust can we make these things.

MR. CHANDRASEKHARAN: Debbie, you talked about something else. You talked about sign conventions and the way we store data and things like that. If, indeed, the way Hans Soons is defining the data is complete, no matter how you submit the data, it should be able to have enough information. You can parse it and store it uniquely, so anybody else can go and recreate it. By different people submitting data--obviously Boeing is probably collecting it and storing it differently, you're doing it differently, we're probably doing it somewhat differently and different vendors of the hardware are doing it differently--that, in itself, is a test for communicating correctly. Then, you can look at the more difficult stuff of trying to get statistical metrics out, trying to get other things out, all the other stuff that we talked about.

MR. MA: I think you need quite a model of a machine, what type of machine, what kind you have, so that you have the same program, the same language.

MR. CALLAGHAN: Just starting up with two, I don't think, would be necessarily meaningful at this time until we define what those rules are and what that data dictionary looks like. I don't know that it would be beneficial until that has been established.

MR. WELSCH: I think it's a chicken and egg problem. In a sense, the development of the data dictionary, in my mind, is partly driven by what's in the data today. Top-down design is great when you know what the end product is going to be. Bottom-up design is great when you don't have any idea what you're going to build. Usually most designs are from the inside out. You do a little bit here, you do a little bit there, and eventually you develop a very nice solid design from the top to the bottom as long as you are willing to be flexible.

MR. SOONS: I think there might be a slight problem with that approach. Although I would very much like to receive samples of data, part of the information that we are really interested in is in Loyd Bishop's notebook. What extra information does he write down about a test besides, just say, the data file. To test the completeness of the data dictionary that information is essential, and I'm wondering if you are willing to part with that information or that you want to wait before there is a dictionary and see if you can translate it into that dictionary.

MR. BISHOP: Either way, from an experimental standpoint I don't think there is any problem with that. That's nothing proprietary at all.

MR. CALLAGHAN: Larry, you're saying, almost, that if we give you the data, then you'll figure out the dictionary for us, based on the inputs. Is that what I understand?

MR. WELSCH: We'll try. We'll take a stab at it. And it'll probably be wrong, but it might be very close.

MR. CALLAGHAN: I think Hans has already got a really good start here. We've already done the actual field structures and everything is based on the software that we've been using currently. We know what the size of the fields are, the number of characters and everything, for all the different fields that we're using. We have some of that information and I don't think any of that is proprietary; so we could share any of that we've already accumulated if that would be of value. That would help it go little faster, a little easier, than you having to read and decide how many characters are in each data set.

MR. WELSCH: That's exactly the type of information that would make it go very fast.

MR. CALLAGHAN: For the kind of data that Hans was discussing, we built tables. I hate the keyboard entry of anything. So, what we're trying to do is categorize all the different kinds of inputs and make them in pull-down lists. But, you can't sort on text very well. When they just put a paragraph in there it's really hard to know, from a computer standpoint, what that means. So we've taken some effort to do the other direction where we actually have fields and we categorize those elements.

MR. WELSCH: I think sharing that with this group and with us is extremely helpful in the sense of accelerating this process.

MR. CALLAGHAN: We have it conceptualized. We haven't yet taken the data on the tool. We have to get out to Loyd and people like him to do that.

MR. BISHOP: Do you have the front ends yet?

MR. CALLAGHAN: We've got the table out there. We don't have the data input screens. They're in the process of being developed. They're not quite that far along yet. But we know element-wise what we need to do. We need to test it and verify it. A lot of things have to happen.

MR. WELSCH: One of the possible ways of us working with you is to take that element data, put some screens on it through an HTML basis, through the web, and broaden your test to a larger community of people so we can get a more accurate evaluation.

MR. CALLAGHAN: We probably need to. We have discussed it, but whether or not this is going to be an open-ended web page or a restricted application, we're just wondering what the participation level would be based on that.

MR. WELSCH: I don't think we could stand open-ended web page.

MR. CALLAGHAN: So you're saying it's going to be limited, hopefully?

MR. BLOMQUIST: That's what we decided yesterday, it was going to be a limited number.

MR. CALLAGHAN: Limited to people who have records to give. We have to verify that we can do that, but I don't see a problem.

MR. DONMEZ: I suggest that we would iron out the details of this type of thing later on, but it's clearly necessary that we need to start on the data dictionary, and one of the things that we can use as a starting point is the existing standards. B5.54 has a glossary and definitions, ISO 230-1 has definitions. I was just talking to Ray McClure earlier, we may be able to put them on the web site if we can get some proper permission from ANSI. Ray indicated that if you download it you pay, but if you don't download it, you look at it, you don't have to pay, so that might be the way to get around that problem. I will investigate it. If possible, will put those on the web site.

DISCUSSIONS ON REPRESENTATIONS OF MACHINED PART GEOMETRY

MR. DONMEZ: Our last item on the agenda is the discussion on representation of machined part geometry, which is related to the simulation tools as well as virtual inspection programs. We haven't talked about virtual inspection in this meeting but, as I mentioned yesterday, our long term goal includes virtual inspection as well as virtual machining. So, we need to start thinking about how we are going to represent the machined parts in the computer domain. For now, the best thing would be to measure as much datapoints as possible on the part and then keep all this information as raw data. But there are other alternatives. We can have B splines, we can have polynomial fits, we can have all sorts of other mathematical tools to represent features on the part. There are pros and cons in all aspects of representation, so I'd like to initiate a discussion, so that we can think about it after we go back. We'll have more detailed discussions in the next meeting.

MR. ESTERLING: I'd suggest that if you tried to maintain splined data you'll be overwhelmed. Each of the companies that does a simulation has their own internal modeling system and each has its own individual strengths and weaknesses. Chris Deforge and I both have a solid modeling format underlying our structure, rather different in terms of our approach. The advantage of a solid model system is it's complete, robust, and it's got what you need. The disadvantages will be the kind of accuracy you need to maintain the model. Your ideal part may have B splines, but your actual part has all kinds of funky features in it which aren't amenable to a standard sort of CAD type modeling structure. That's why, for example, our company developed a proprietary internal modeling system to handle that.

But I think, if you try to go to point data, you're going to have several problems. One is an overwhelming amount of data, much of which is not really required. You are also going to have a problem of accuracy. If you try to trade off that point set with a sparser set because you don't want to have all that data, then you lose accuracy between the sparse points. The third problem you have with point data is feature formation. Depending upon the kind of modeling structure you're using, if you could maintain feature data, and by "feature" I mean relatively simple features--pockets, holes, edges, corners--that's the information that you might want to look into and have available in your system. But if you have only point data you don't have that information.

MR. DONMEZ: You have an internal representation which is proprietary. If we are going to provide the information on the part to another module, which will do the virtual inspection, that a company like ICAM is developing, how are you going to give that information to the other module?

MR. ESTERLING: We are market driven, like everybody else in this, and we developed a tool kit which lets folks get in and out of our model to access different parts of our system. We started out with a traditional CAD type solid modeling systems. We went to a proprietary system because traditional CAD for solid modeling didn't work in this kind of environment, at least it didn't work for us. But that still means that we needed to talk to the rest of the world, so we needed a way to export our system into a more traditional type CAD environment and this is something which we sort of have now and it's under development and will be available very shortly as part of this tool kit.

So we're not closed in the sense of communicating with other modules, but it's closed because we had to develop our own. But we still have to talk to the rest of the world, both import and export. We need to import CAD type data for stock, as design data, and we need to export in terms to be able to say, "Okay, what's the next step? Do you want to use this for inspection? Do you want to use it for assembly, or whatever?"

MR. DEFORGE: We basically have the same type of approach, where we have direct CAD interfaces, as well as standard CAD translators for exporting part geometry and importing part geometry as well. Our machining process does work with a proprietary CAD system, for lack of a better term, and that really goes to the core of the software. So I don't see us changing that. The best we could do is make sure that we do make available these CAD interfaces and CAD translators.

MR. DONMEZ: When you export your data, are your models basically nominal part models?

MR. DEFORGE: That's correct.

MR. DONMEZ: But when you have this type of simulation capability you will have non-uniformities in these surfaces. Are you currently capable of exporting such geometries?

MR. DEFORGE: Yes, within reason. You have to look at issues of accuracy and extent. If you want a simulation that takes a process that would normally take, let's say, 8 hours on a machine tool and make it happen in a few minutes, which seems to be the desire, in essence, you're going to sacrifice accuracy in the rendering of the part in today's technology.

MR. DONMEZ: As a user of the output can I specify the spatial frequency of the data when you export the data, for example?

MR. ESTERLING: Again, Chris and I come from different modeling methods and different sort of spectra. In fact, we're doing today something that takes 8 hours in a machine tool in a few minutes on a Pentium at the accuracy that you need at a shop floor for the nominal part. That's where we are right now. You know, there are things that we need to do to our product to be able to sort of handle the kind of waviness, the error analysis, that we discussed here, but it's within the same sort of modeling structure we have right now. It's an achievable goal.

I suspect Chris and I look at the same perspective in the sense that when you give us a tool pack with errors in it, we consider the desire to know what the tool sweep is , where it’s going and we then model it. We have to model it in different ways and different methods, each with their individual strengths and weaknesses.

MR. DONMEZ: Yes that's true, but, in the end, what I'm interested in is getting that information out from your module and putting it into another module where I can test my inspection algorithms. In order to do that, sometimes I may need very finely spaced points, though sometimes not. I need to be able to specify that kind of spatial frequency to you.

MR. ESTERLING: It leads back to the point I made at the start regarding speed, accuracy and the size of the part. But for a nominal sized part and with a reasonable horsepower in a reasonable period of time you're putting very heavy demands on the accuracy of the model. That's this triangle that Chris was talking about, and I'm saying for nominal parts, without the errors involved, we're there today.

MR. MA: Do you have any CMM simulation software?

MR. DEFORGE: Virtual inspection is something that I don't think puts us in a position to claim we can do, to create a part that we can say, from a model, that these are your quality control issues. We're not there yet.

MR. ESTERLING: We cannot. It's a product we'd like to manufacture. I mean, there are two aspects here. One aspect is to model the CMM process itself. And we don't do that. I have to tell you on my top 10 list of things to do it's probably not in that top 10 because we have lots of other things we still need to do within the CNC environment, as opposed to the CMM environment. But to be able to import, to get back to what Alkan was asking about, to import a CAD model, a CAD surface, as Deneb does, I believe as well, and then be able to give you a profile as to how the as-machine part deviates in terms of gouges, in terms of excess material, is something that several vendors offer. If that's what you mean by CMM, yes. We also offer--and by "we," I mean, generically across the industry--ways to do something like a CMM probe, you can point to a given spot on the part and given the CAD data, get back your coordinates of the point as well as all the surface normal deviation for the CAD data as well. You know, that's available in the industry today. It's in several packages.

MR. MA: How accurate can the data display of the profile of the errors be?

MR. DEFORGE: Basically we take the position that is user-definable.

MR. MA: I guess that goes with digital limitation, right?

MR. DEFORGE: Absolutely. For instance, if you want to look at a circular interpolated move in the motion, we all know that it's broken down as a series of linear moves. That's user-definable in our software. How many segments do you want to divide this particular move into? What is the size of that segment? You can go with a very small setting, just like the machine tool, but you're going to bog the system down. The same thing goes with the rendering. We have the capability of setting tolerance levels for the Boolean operations for combining different features. It's user definable. You could set them to zero, meaning you want to represent every single math subtraction, or we could combine some of those that don't make a difference. It depends on what kind of accuracies you want to get out of the system at any given time.

With respect to CMM technology, that's being market driven. We have to look at other types of measuring technologies that are currently being used, and is CMM actually the most effective, especially when you look at non-contact type measuring devices that are out there. That's going to be completely market driven from our point.

MR. ESTERLING: I want to give you a sense of the differences between what is available out there. One of the really good things that Deneb does very well, is modeling a whole machine tool environment. But there is, perhaps, a price to be paid by modeling the whole complex. When you get down to the micro level of material removal, I would argue that we do things faster, cheaper, better than ever. But our corporate philosophy is what is happening at the tool tip itself. That's really where we have focused. In the same sense of setting tolerances, we don't let the user set tolerances. We require that our software deliver the kind of machine tool tolerance we expect at the shop floor which are a few micron type tolerances. We start out with that by saying, "This is what's required," and typically it's not so much processing time; in our model it's more RAM dependent. If you don't have enough available RAM you're going to start going off from the hard disk and then all hell breaks loose in terms of processing. But, as long as you're staying within the RAM environment, our processing time is not affected due to (1) our modeling system and (2) our avoidance of the traditional CAD type systems.

MR. JOHNSON: How do you characterize the non-uniformity of the surface? Do you do that?

MR. ESTERLING: Yes.

MR. JOHNSON: What kind of specification do you use for that?

MR. ESTERLING: We don't use a polyhedral system. One of the problems of the polyhedral systems and why we abandoned it is because of the problem of speed and accuracy and the trade-off from that. We could pull some really horrendous parts together. We just went through a benchmark with a fairly large part with roughly a tenth or two-tenths of a millimeter in depth and a one meter size. That's our job, to deliver a virtual CNC. How we do it isn't our job to tell you; it's our job to simply say we're doing it.

MR. JOHNSON: It's all internal, so you wouldn't export that data to a customer?

MR. ESTERLING: No. What we were talking about with Alkan here, is that we also need to provide hooks so that we can export it. No one would want to fool with our model. I mean, it's not a CAD-like model. It's only useful for a CAM type environment where you work in great large numbers of Booleans, tens, hundreds, millions of Booleans, at very high accuracy. That's what it's tuned for. What we need to do is to take that model we have and export it a more traditional sort of CAD type format. Deneb is ahead of us there. They provide several hooks already. This is something which we are developing and fairly shortly will have it out.

QUESTION: Is there any accuracy loss in doing that translation to export?

MR. DEFORGE: If you're doing translations there is the potential for accuracy loss, because just in setting up parameters for both IGES and STL export translations. If you're looking at direct interfaces, that potential is minimized.

MR. ESTERLING: If, for example, the first type of format we would export to is Stereo Lithography (STL) format, which is basically just a huge number of triangles floating in space. The advantage of it is it's an incredibly brain-dead way to sort of describe a solid system. It's also one which is used. I mean IGES like standards have never really come along and developed a universal standard for a solid system. Whereas STL has come in and it's basically one that's used by everyone for its simplicity. But there is a trade-off with STL. If you're doing that kind of a format, the file size you're dealing with, is strictly related to the accuracy you're imposing. But it's simple, so we love it. The export to that is real simple.

MR. DONMEZ: I'd like to move onto other topics now. I'd like talk briefly about what are our future needs. I marked up some of the action items for us. One of them is starting the data dictionary, as we talked about earlier and starting a web site to do the communication and the comment exchange. We will put the proposed data formats that Hans presented yesterday on that web site so that we can get more detailed comments from you all.

We haven't really finalized the sign convention, which is a very important issue. I was hoping that we would have more discussions into it, but we didn't get that much discussion. But I'd like everybody to think very seriously about the pros and cons of different types of sign conventions basically, part coordinate frame versus machine coordinate frame, and how to use them properly.

Another action item for us is to provide some data to Deneb so that they can start playing with the type of simulation that we were talking about earlier.

We will also ask for comments about the road map and then, based on that, we will compile and present a road map for the next time.

MR. CHANDRASEKHARAN: Are we going to have the time to submit the data? Is that something we want to decide now, or do we want to wait for the data definitions and the data dictionary to go through? Should we be doing them in parallel?

MR. DONMEZ: The earlier we start submitting data, the better.

MR. BLOMQUIST: One of the things we talked about yesterday was forming a consortium to do this so that we don't get inundated with 10,000 participants. I think we should do that. The best way for us to do that is through a Cooperative Research and Development Agreement (CRADA). It acts as a filter for serious people only. I don't think that we should have a requirement of being a member of the consortium to participate in these meetings. We'll just have that wide open. But actually to log on to the web site, collaborate with us, I think we ought to limit that to the members of the consortium. So we'll do that.

MR. DONMEZ: So, as an action item then, we will develop a generic CRADA and send it out to people for them to review and finalize.

QUESTION: What's the status of involving the automotive manufacturers in this?

MR. DONMEZ: We have sent out invitations to automotive manufacturers for this meeting. We didn't get any positive response. As I mentioned earlier, one of the comments from our last workshop was that we need to involve small manufacturers, machine tool builders, and automotive industry. Those were the lacking components. We visited NTMA, the National Tooling and Manufacturing Association, and presented our views and plans and we were basically told that we need to talk to individual small companies, and one of the advanced small companies, in order for them to get some excitement and participate. And we haven't been able to reach them yet.

As far as the machine tool builders, we constantly send them information and invitations and so far we haven't gotten much response.

If any of you can help us bring more of those companies on board that would be very appreciated.

MR. CHANDRASEKHARAN: Do you think the auto companies are not jumping on board because they're still more focused on transfer lines, and is that an issue?

MR. DONMEZ: I believe it's somewhat of an issue. Yes. But I would have thought that their tech center people would be looking at it more closely.

MR. DEFORGE: We have some contacts that we'll make a few phone calls.

MR. BLOMQUIST: I think a more realistic contact with the automobile industry is the tier suppliers. If anybody has good contact with the tier suppliers; previous work with the big three on other issues has led me to believe it's highly likely you could get them to participate a lot more than the big three.

WORKSHOP SUMMARY
R. McClure

Our economic future depends on our ability to create a manufacturing complex that has the characteristics of competitiveness and rapid response. The first thing I think we need to understand is the process by which anything is bought and sold, particularly something like a machine tool.

The key components in such a transaction are a customer and a vendor. As recently as two decades ago, the process was straightforward; Joe, at Boeing, called Sam, at Cincinnati Milacron, and ordered a bunch. In the late '60s Lawrence Livermore National Laboratory ordered a Sundstrand OM-3, one of the first, and we were required that it should be done according to a detailed specification. However, we did not know what the capability of the OM-3 was. The Atomic Energy Commission had another OM-3 at one of its other facilities. So, a team was sent there and they measured it extensively and discovered that it was pretty good. Sundstrand built fine machines in that period.

There were a couple of things that didn't fit our needs, like the spindle growth on the trunnion-carried spindle, so in our order for a new machine we asked for some special adaptations such as putting a water-jacket around the spindle. Of course, they charged us extra for that. But what was interesting was that they also charged us about ten percent of the cost of the machine just to work to the specification.

Eight years ago I went to work for a machine tool company and now I understand why Sunstrand asked for so much extra money. They were scared of that kind of specification. And, as it turned out, our specification caused them a lot of trouble, time and money. The machine sat on Sundstrand's floor for 14 months while LLNL's people tested it. During this time Sundstrand had to make modifications in order to meet the specification. They even had to make modifications to the modifications they had previously made since they had built the machine that LLNL had previously tested. Between these two machines, modifications had been made that had changed the machine's characteristics in the wrong direction. For example, someone had decided that a motor would be better inside the casting than outside. It took us four months to find out that it was the reason for the changes in thermal characteristics from those of the first machine. The fix was easy but took a long time to find it.

During that time, Boeing bought an OM-3 approximately every month. At least 15 were sold while we were still trying to make our machine meet our specifications. But, at no time was there any interest in sharing data or experiences between LLNL and Boeing. In fact, I don't think Sundstrand was particularly interested in anything but getting our machine off their floor and collecting their money. I don't know what the Boeing machines are doing now but LLNL no longer has its machine. It would have been interesting to compare all of those machines at the beginning.

You've got the vendor and the customer trying to talk to each other by means of Joe and Sam. Joe and Sam have a very difficult problem to solve. Joe has a part drawing and he didn't care less about what the machine was like. He has to make the part and what he would like to do is send Sam the part drawing and have him guarantee that the first part, and every part, made on the machine will be within spec as called out on the drawing.

The vendor, on the other hand, has a model number. He'd love to have a purchase order that says, "Send me one each Model No. X"--like a SIP 6A--or something like that. That's the way we used to buy and in most cases still buy. That's the vendor's zero risk position. The customer's zero risk position is the part drawing. Resolving the problem of two possibly mutually exclusive zero risk positions is the purpose of a specification.

There are some other people, though, who can't be ignored who are involved in the process of developing a specification. First, there are civil authorities. These are the guys who tell you that you can't use Freon in your manufacturing. Civil authorities now have significant influence on the buying and selling process. And there are technical authorities. These are the guys who write the standards upon which a specification is based. National and international standards prescribe how to measure the characteristics that are required in the specification. Without standardized language and procedures, the customer and vendor are unable to talk to each other except with part drawings and model numbers.

Somewhere in the buyer's chain is a product manager. This is a guy who has the responsibility for bringing a product into being, like the guy who brought the 777 into being. I don't know what happened to him, he got transferred the day of the first flight.

But he was the product manager and he had to bring that machine, that airplane, onto the market at a specified time within a certain budget and it had to perform a certain way.

There is a product manager behind all of these chains and we've got to take him into account more and more as we get into virtual enterprises and, as you all know, we've been talking here about the things that are necessary to make such enterprises work.

By the way, my definition of a specification is a finite set of administrable requirements. A lot of specs go out that can't be administered. There are plenty of things on a drawing. A drawing is a specification. But how many things on a drawing actually get measured? If it's not administrable, you have to bluff. But manufacturing is a series of bluffs, isn't it?

We make the assumption that the drawing conveys all the information necessary to make a part, but the truth is that it doesn't. A drawing is the second stage of a series of bluffs that occur between the conception of a product and its manufacture. The guy who conceives the part, and what it's supposed to do, goes to the draftsman and bluffs him into believing that he knows what he wants. He probably doesn't, completely. The draftsman takes incomplete information and transforms that into a drawing, takes it to a shop and tries to convince the machinist he knows what he's doing. The machinist makes the part and he presents it to an inspector and tries to convince him he knew what he was doing. And then the inspector inspects it and tries to convince his management that he knew what he was doing. If you look at any of those processes very carefully you find it isn't true. We somehow get along, but how? By human intervention?

Let me talk for a moment about this product manager. He's got some questions that he has to answer. He's got a new product--let's change industries--let's say it's a new contact lens. And this is a contact lens that not only gives support to an older person who needs bifocals, but also has astigmatism. When you look at the Zernike coefficients of something like that you find that it is really difficult to make. But isn't that typical of a new product--it may have never been made before--that's why it's a new product

So, can it be made? That's the first question. Then, how can it be made? Then, how can it be made at a cost that's acceptable and competitive? Finally, an important question to a product manager, once all these questions are answered and we are in production, how can we keep the production system from deviating or breaking down? Maybe that's what the former 777 product manager is doing now, making sure the system he set up doesn't get out of control.

I'd like to carry this theme one step further, and I labeled this "Goal". In the last meeting we talked about our basic challenge which is to cope with the development of a new manufacturing paradigm. Whether you call it "agile" or "virtual" or something else, the facts are that people don't want to own factories and they don't want to employ people. There is too much bother with harassment lawsuits and benefits and such. So, the product manager will minimize all that by contracting work out. But, he has still to make sure that any vendor produces on schedule and delivers a satisfactory product--all of his vendors--and they could be in Europe, the U.S., China or, soon, anywhere in the world. At the same time, he has to arrange for somebody--maybe he owns a factory, maybe he doesn't--to assemble all of this and package it and ship it to customers. And he has to depend on certain functional resources, some of which we've been discussing in these meetings.

This is not an exhaustive list, but:

Data. He has to have data with which you can make decisions about how to make something. That data has to conform to some models and his models are pretty crude at this stage. The kind of models you are talking about in these meetings are a lot more sophisticated than the ones that managers now use to make decisions.

And, you need the hardware--the computers--the people and the natural resources.

We haven't talked about the issue of people much, but you can't ignore it. One of the biggest problems we have is that the number of people who are competent to even be here and have this conversation is pretty small and this whole enterprise won't go anywhere until that population increases.

Finally, natural resources. You've got to have a source of stuff.

Talking about specifications, we have been talking about "data" in two ways: data with which to assess how good a product is and data with which to write a specification. In the process of writing a specification you have to take into account all possible characteristics. We could list all kinds of characteristics. Hans [Soons] has done that in the work he's described and his list is probably not exhaustive. It's scary when you look at Hans' list. But, how many parameters have to be controlled and optimized?

In writing a specification it is necessary to take the set of all possible characteristics and pass it through a functional filter to obtain a list that must be included in a given specification. This filter, in the past, was provided primarily by skilled people who could tell you, for example, what a good grinder could do. You can still go out into the shop and ask someone "How round can you grind something?" and you'll get the reply "Fifty millionths." Skill and experience were used and are still used to do this filtering with very little hard data. Very few people go out and actually measure something, like LLNL did in the case of the purchase of the Sundstrand OM-3, and try to create a specification on that basis.

We're encouraging people now to develop error budgets as a better means of filtering. But there is no one way of developing an error budget. Oak Ridge doesn't talk about an error budget in the same way that

LLNL does. However, differences are mostly method, not the basic idea. Perhaps we can use simulation as a filter. Indeed, that seems to be one of the important applications of the simulation work that has been discussed in these meetings.

If you're going to establish a total system you need a process model, and I think I heard you say that it's where you are headed. I believe you want to include everything up to and including the assembly. That might give the product managers a way of making decisions and of controlling the process.

A discussion took place yesterday about corporate policy, and I saw a lot of horns being pulled in when the question was asked, "Will your company do this [share data]?" I've run into that before, in many forms, and I suggest that it needs to be addressed and your management has to be sold. You need to go back to your companies and explain to them why it's good for them to "do this". Or the group here or someone else needs to do the selling of these ideas. You ought to point out that there are some good things that can happen. This data base--through some kind of pooling--could help to validate procedures.

For example, instead of being ignorant of what the other knew, today it should be possible for LLNL and Boeing to share data about the OM-3s they were each buying instead of being studiously ignorant of each other as they were 30 years ago. With such exchanges you would not only be able to validate data, you would able to validate procedures.

The Web is clearly the way to expedite the exchange of data and procedures. Creation of such a Web page should be one of the highest priorities of this project. The Website could have links to other sites where people could, perhaps for a fee, use your software to perform their own analyses, compare with other people's, and certainly validate the procedures related to buying equipment. This could help avoid the pitfalls that would result when people get the wrong data and perform the wrong analyses. There are a lot of neat things being offered in the metrology area, more every day. But you have to be careful because instruments don't always produce the same results. A good example is the experience of surface finish instruments. We went through 50 years of evaluation to get to a place where we could actually control the output of these instruments so that they would be consistent with each other and I don't think we're perfectly satisfied with the status yet.

With such exchanges, we are bound to improve our procurements. In Europe, value engineering has been used in conjunction with other procurement procedures to improve selection processes. Data exchange could add substance to such value engineering.

As we all know, vendor control is key to the successful implementation of the new paradigm of manufacturing. ISO 9000 and similar procedures are becoming increasingly necessary. But ISO simply says what should be in place not how it works. Technical procedures are still needed and they need to be continuously developed and improved. The existence of data bases like that discussed in these meetings is the best means of validating data and procedures and most expeditiously improving the means of controlling virtual enterprises.

There was an article in Manufacturing Engineering about 10 years ago, entitled "Machine Tool Accuracies aren't the same. It showed that data collected under a DIN standard, the NMTBA standard or the Japanese standard would give different results. That's certainly something that would be forced to improve if some collaboration was formed.

I have some advice to give to you. Don't mix your problems. One person here pointed out that the designer looks at this subject in an entirely different way and has different needs. Another pointed out that going to operate a plant also has unique needs. What's the maintainability and reliability? What's the up time? What's the through put? Please try to concentrate on one set of problems at a time, otherwise you will try to solve all problems simultaneously and progress will be slow.

Having raised the maintenance issue, I am reminded of NIST's work on "interim testing" of coordinate measuring machines. An artifact is used as a quick way of assessing whether something has changed or not. This kind of testing does not provide detailed accuracy and performance characteristics but just enough data to determine that something has changed. This kind of information is valuable in system maintenance.

Interim testing is a form of an old method of metrology that is, I believe, being revived and brought up to date and now is called "Comparative Metrology". Artifacts are used in comparators to validate parts in process. Let's ask the Boeing people how many parts are examined by comparison?

BOEING PERSON: Not many.

MR. MCCLURE: I disagree, I would guess around 90 percent. You must look closely at what is actually happening. I will give you an example. Grinders are difficult things to support in the field because the grit in the wheels give different surface patterns, depending on a lot of conditions. Everyone who makes a grinder runs into a customer who calls him up and says, "I've got a new machine standing right next to my old machine and the parts look different. What's wrong with the new machine?" I've gone through this situation where I have showed them numerically and scientifically, according to all the standard ways of measuring, that, if anything, the new part is better than the old one. He won't accept that. "It's different, so it's wrong". He's applying a comparative form of go-no go inspection.

Comparative metrology is used now and will become more important to effective process control in the future. It will especially be important to the role of coordinate measuring machines, 40 percent of which are now underutilized (according to John Bosch, formerly with Sheffield). These machines did not live up to someone's expectation which typically was that they were absolute gages. But because of environmental and other effects they are not absolute gages. But I suggest to you that they make magnificent comparators. They can collect and process a large amount of data in a short time and fit nicely into comparative metrology schemes. Comparative Metrology, briefly, uses standard or certified artifacts. The artifacts are certified by some agency like NIST. Comparative metrology was virtually the only way of inspecting before there were standards and people the likes of Eli Whitney. The artisan made a part that he used to compare with all subsequent parts.

Comparative metrology needs to be developed, especially in the application of coordinate measuring machines as process controllers.

Finally, some conclusions. The best thing I've heard about in the past two days is the discussion about a Website. I think this answers the question about how to get started. And, to get started, it would be appropriate to address some issues that can be easily defined.

There is the question of standards. A glossary is a standard. ISO 230-1 is a pre-existing set of definitions that is supposed to be applied to the inspection of machine tools. You could start with that. By the way, some of those words need to be redefined. The old glossary contains words that are no longer valid. You could also include the Sign Convention which obviously should be applied to all machine tool accuracy standards.

We need more competent people.

We need data. I don't know any other product that we know less about than machine tools. Builders don't test them thoroughly, they depend mostly on process control.

I present the word "taxonomy" here because we tend to get bogged down in language difficulties and prior fixed notions and, I believe, we are over-concentrating on machine tools. Personally, I'm not convinced that there is a machine tool product anymore. I'm not sure that there is a valid machine tool industry. Most of the machines being built today in the U.S. are "specials". Standard products are being made in other countries because of cheap labor. In our new distributed manufacturing process there are probably going to be processes ranging from glass-blowing to machining and that's why I believe we need a taxonomy.

There was a fellow at Brigham Young University who, in the late '70s, early '80s, who came up with a taxonomy for manufacturing. It would be worthwhile to revisit this issue.

For a machine tool database, you need storage and retrieval, and we've spent a lot of time in these meetings on that subject. Someone has to maintain it once it exists and maintenance doesn't mean just stocking. Someone has to be dedicated to polishing the knobs, grease it and change it if we want to make improvements.

Economic issues cannot be ignored. The ultimate purpose of any collection of information is to allow someone to make judgements on how to make thousands of parts.

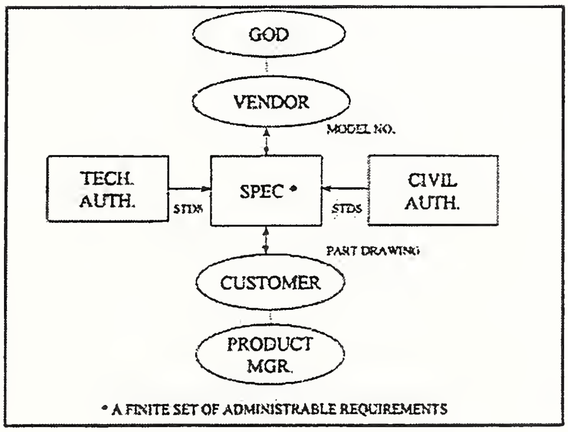
There was a discussion that seemed to fizzle because of embarrassment or shyness, I don't know which. The issue was who was going to own and operate this database, particularly what is the role of the government. Of course, if you're in free enterprise you don't like the idea of the government owning and operating it. However, there are some examples of past successes private as well as government. There are also some examples of failures. Some of the relatively good past examples are the Department of Agriculture, the Bureau of Mines and the National Advisory Committee on Aeronautics (NACA). Without the Bureau of Mines the Materials Handbook would not exist.

Pardon me for referring to NIST as the National Bureau of Standards or NBS, but I want to emphasize its original role as keeper and supplier of standards.

NACA was established around 1915 as a spin-off from the Navy as a means of collecting and disseminating data. As a young engineer at Boeing, I worked on a problem involving landing gear spring-back. The only data I had I found in old NACA Technical Notes.

NACA became NASA with a different mission and I think the value of NASA as a source of information suffered. The primary intent of NACA was to provide data to a fledgling industry. In the 20's and 30's companies like Boeing and Wright were too weak to build the kinds of wind tunnels that were needed, so NACA built them and the industry used them. The elliptical wing and laminar flow airfoils were developed this way and were used by the industry. Now, computer simulations have largely replaced the wind tunnels. These are the good examples of government support. With that, I'll finish my summary.

Slide 1



Slide 2

PRODUCT MANAGER

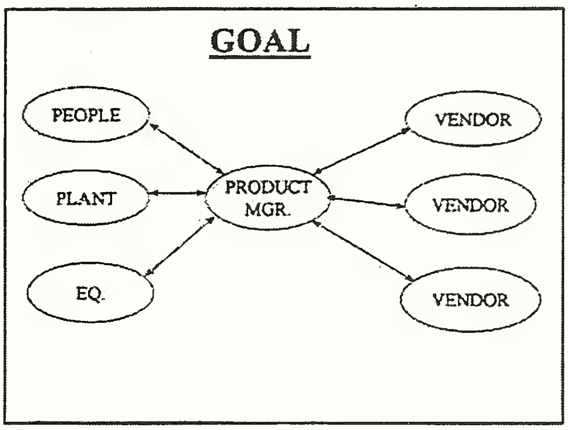
"Can it be made?"

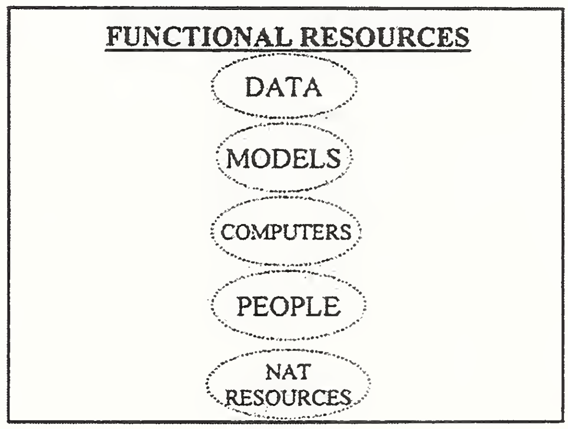
How can it be made?

How can it be made competitive?

How can it be kept that way?

Slide 3





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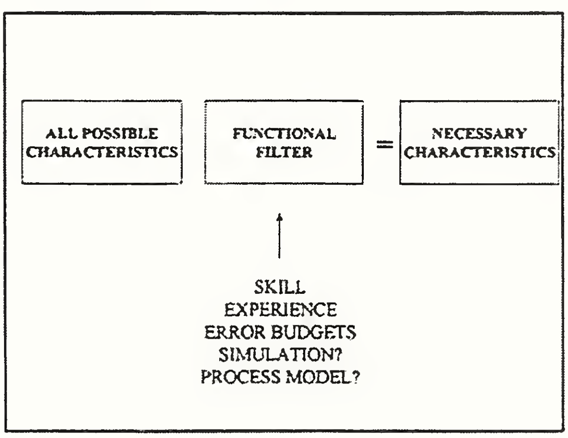


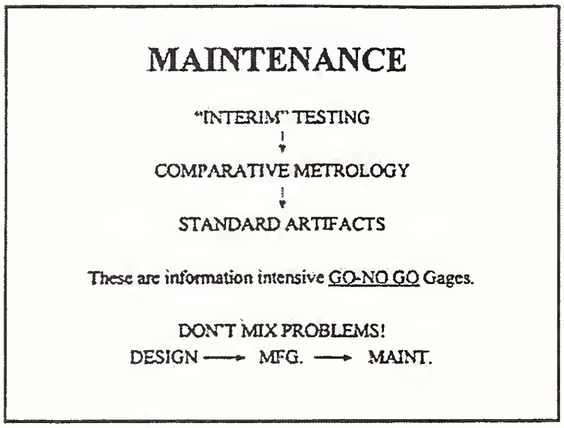
Slide 5

CORPORATE POLICY

- Validate Procedures (& Data, Equipment)
- Improve Procurements
- Vendor Control (Quant., Uncert.)
  "Accuracies aren't the same" Mfg. Eng.
- Improved Operations

  .
  .
  ISO 9000
- Minimize Risk... Virtual Mfg.

Slide 6



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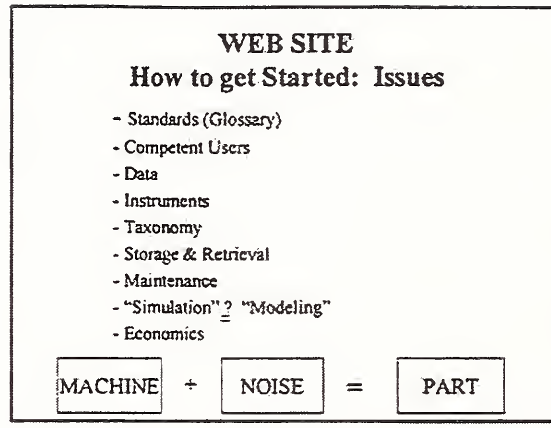

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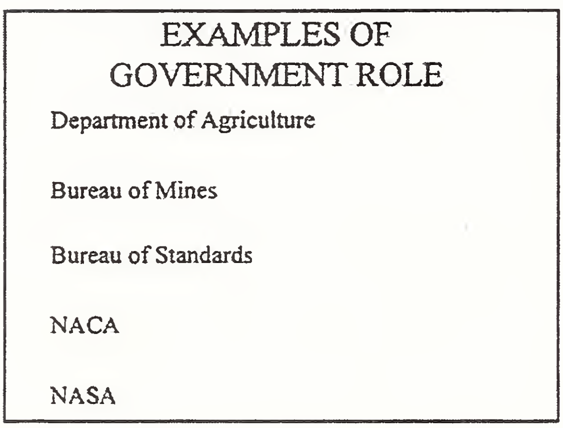

APPENDIX A
WORKSHOP PARTICIPANTS

Mr. Donald Blomquist, Co-Chair, National Institute of Standards & Technology
Mr. Alkan Donmez, Co-Chair, National Institute of Standards & Technology

Mr. Herb Bandy	National Institute of Standards & Technology
Mr. Loyd Bishop	Boeing Company
Mr. Robert Callaghan	Independent Quality Labs Corp
Mr. David Callahan	U.S. Army - Watervliet Arsenal
Mr. Vivek Chandrasekharan	Caterpillar, Inc.
Mr. Jim Covington	Boeing Company
Mr. Chris Deforge	Deneb Robotics
Mr. Donald Esterling	N-See Software
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Mr. Hans Soons	National Institute of Standards & Technology
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