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Third NIST Workshop
on

THE DEVELOPMENT OF MACHINE TOOL PERFORMANCE MODELS AND DATA REPOSITORY

November 20-21, 1997
Pleasanton, California

Edited by:
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NIST
National Institute of
Standards and Technology
Technology Administration
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Foreword

This document is a transcription of an audio recording of presentations and discussions from the Third NIST Workshop on the Development of Machine Tool Performance Models and Data Repository. The purpose of this workshop is to present and discuss the progress in NIST work as well as industrial and academic collaborators' work focused on the development of machine tool performance models and data repository. Extensive discussions were held to review the current and future needs of industry in using such data repositories and associated analysis tools to estimate performance capabilities. The results of discussions are a prioritization of tasks and establishment of a timetable to satisfy the needs of the collaborators. The primary focus of the document was to capture major points from presentations and discussions rather than a word for word account of the meeting. The presentations with corresponding discussions are summarized and given in the main body of this document, with slides from most of the presentations provided in the Appendix. The discussion of the road map of the program is also summarized and given in the main body of this document, with slides and a Gantt Chart resulting from the discussion presented in the Appendix.

Introduction

Alkan Donmez
National Institute of Standards & Technology

To reduce costs and respond rapidly to changing customer needs, large companies are relying increasingly on a network of suppliers and outsourcing a significant percentage of their manufacturing needs. This type of geographically; and organizationally; distributed manufacturing requires better communication and improved coordination and utilization of internal and external manufacturing resources by all the participants.

The goal of this project is to develop tools that enable design and manufacturing engineers to predict machine tool performance and ensure that parts can be machined to specification with a minimum of prototyping. [Slide 1-2]. These tools include data structures and low order machine models that represent actual machine behavior, mathematical representation of actual part geometry, including dimension and form errors; virtual machining algorithms; virtual inspection algorithms; standardized data formats; and remotely accessible machine data repositories.

This project aims to replace actual machining and inspection of parts during prototyping with virtual machining and virtual inspection modules incorporated into a Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) system. The virtual machining module will simulate the movement of the cutting tool when making a part. In this simulation, the effects of error motions, predicted from machine-tool characterization data will be reflected in the tool path. Virtual machining will result in an electronic approximation of the part that can be inspected by the virtual inspection module. The virtual inspection module will determine the uncertainties associated with the selected inspection plans and equipment. These uncertainties will be checked against the specified design tolerances of the part. This virtual environment will make it possible to optimize the manufacturing process by trying different machines and making changes to the process plans or part designs.

There are various needs that we are addressing in this effort. [Slide 1-3]. Machine and process capability evaluation, machine performance tracking, capacity planning, maintenance planning, inspection planning and algorithm evaluation are among these needs.

A major challenge in creating a virtual manufacturing environment is the representation of the performance and capabilities of various machine tools. [Slide 1-4]. Currently, there are no provisions in machine tool or Coordinate Measuring Machine (CMM) standards to store the performance information in any electronic media. The lack of standard representation prevents the creation of machine data repositories that are needed to test different simulation algorithms and to compare the performance of a given machine against many other machines within a similar category. In order to overcome this problem, with your help, we are developing a data dictionary along with a standard format for representing meaningful machine performance data. We have developed an experimental web-based repository to accommodate this data format. The other challenges are to develop virtual machining and inspection models, to communicate these models throughout various companies and to interface these models to different software packages.

The first of the two previous workshops (September 1996) concentrated on the identification of the above-mentioned needs. At the second workshop (February 1997), the aim was to evaluate the status of the program and identify the future directions. [Slide 1-5]. The main topics at the second workshop were machine tool metrology and information modeling, data requirements and formats for machine performance evaluation, prototype web-based repository development at the

National Institute of Standards & Technology (NIST), interim machine check (importance and storage/communication of information), simulation tools (current/future capabilities and needs), and representation of the machined part. Sign conventions were also discussed but no conclusions have been reached so far. [Slide 1-6]. Frequency content (spatial and time domain) of performance data and how to use this information for error budgeting was discussed. Machine and process interactions and tools to address these issues were discussed. Machine and environment interaction and how to capture this information in repository were discussed at length. The need for including the physical description of machine in the repository was identified. [Slide 1-7]. Economic performance information to aid with capacity and process planning to include scrap rates for the estimation of cost of using a particular machine was discussed. Storage and structure of data and models in the repository were discussed. The use of data models in repository to visualize machine behavior for maintenance issues of machine was also discussed. In addition to detailed data and information models, we need tools to translate the information to simple and concise results such that management and decision makers can be briefed of the machine issues. Performance tracking by part probing was discussed but no conclusions were reached. Graphical representation of machined part was discussed. [Slide 1-8]. High level information extracted from repository for simulation tools was a requirement from the software developers since raw data needs processing prior to interfacing with software packages. Three different types of simulation approaches were discussed: (1) only part (design issues), (2) part and machine interaction (process planning issues), or (3) machine only (for diagnostic purposes). Accuracy versus speed compromise in simulation tools was addressed. Finally, information storage requirements in three categories were discussed: (1) machine only, (2) instrument used to measure machine, (3) measurement related issues.

The consensus of the previous two workshops is that virtual manufacturing is needed. [Slide 1-9]. It is a big goal. As for the immediate tasks, we need to concentrate on machine errors, how those errors relate to part errors, information model, and file formats. Once these features are captured in the repository, we can go to the next steps of virtual manufacturing. A road map will be discussed at the conclusion of this workshop.

Some action items were identified at the last meeting. In order to capture and properly use any information in the repository, we need to have a data dictionary. [Slide 1-10]. We demonstrated an experimental repository (tools and procedures), the next step was to import data and test the repository. Another action item was to establish a consortium so that people can start accessing the repository prior to public access and to establish a more effective means of communication between participants. In addition, the need for a road map was emphasized.

In this meeting, we will present a draft data dictionary that we have developed since our last meeting. [Slide 1-11]. Comments, modifications, and additions to this data dictionary are needed. We have started importing data into the repository. Boeing and Caterpillar have uploaded data. Storage and analysis are performed on the data. Three Cooperative Research and Development Agreement (CRADA) agreements have been completed and five are still pending. In this workshop, we will review what each of us has been doing since the last meeting. Data dictionary, repository and analysis tools, simulation tools, and a draft road map will be discussed.

Factory Computing Architecture:
A Key Component of Boeing's 2016 Vision
Martin Kitna
Boeing, Seattle

Several weeks ago, there was a "Factory Computing Architecture Users' Conference" that brought a large number of people together to discuss technical matters as they relate to Boeing factories. This presentation is a collection of charts and graphs from several presentations. They were prepared by the Factory Computing Architecture (FCA) Program, myself, and what we in the Measurement Domain--which includes machine tool accuracy, coordinate measurement machines, on machine probing, numerical control machines, statistical process control, hardware variability control (decisions made in your engineering areas before you actually know what to measure in terms of statistical process control and other similar things).

What is Factory Computing Architecture? First of all it is a strategic effort that will take at least a few years to accomplish. It is essentially a set of computing-based strategies, which enable factories to implement our company's initiatives. [Slide 2-2]. Our executives might say "go make significant improvements in a particular area", but when you look at the underlying computing technology that is in our factories, we are finding that it is very challenging to implement the initiatives that we are trying to achieve due to variation in computing technologies and applications in use around Boeing. In short, some standardization needs to be defined and implemented for computing technology used in Boeing factories. This is a guiding principle of Boeing's Factory Computing Architecture Program. An integrated Factory Computing Architecture will enable our factories to be more flexible and better able to change as business needs dictate so that when initiatives or needs for improvement arise in the future, we are able to react in a more responsive manner. We want to assure connectivity to upstream and downstream data, and functionality for future integration.

How do we capture all of this? We've developed some computing architecture frameworks to "forecast the future" of factory technological needs. As we document technical standards and product standards, we then develop transition plans for what we call domains and technology pictorial representations. We are also doing some use-case modeling of certain factory business processes that have been identified as candidates for computing architecture improvements. The use of CASE modeling is an object oriented method of identifying all of the actions that a particular business process possesses and all of the relevant types of information that flow into and out of that process. That is important for reuse down the stream. When we develop applications, we like to be able to develop ones that we can reuse many times. We also have a notion of a factory upgrade process. Right now, we have silos of activity that are involved when we upgrade our factory when we respond to production increases. There needs to be integration among those processes. What you get is one group coming in with a new machine, they do their job while not necessarily being cognizant of how they're affecting other groups that need to also be involved. So the notion of a factory upgrade process is to work that situation out and to make it more efficient.

Integrated Factory Computing Architecture is going to change the way we do business with our supplier community. [Slide 2-3]. Right now, in our factory information systems, there is a lot of proprietors in machine controllers that makes it difficult to develop broad-based applications that get information from many different machines because developing individual machine interfaces is costly and time consuming. It is our goal to change that by advocating the use of Open Architecture Controllers, we'll be able to begin to turn the proprietary situation around. One of the key messages to our supplier community is to incorporate products in their business strategies supporting open architecture controllers and our transition efforts.

This is a chart showing visions for the year 2016. [Slide 2-4]. There are some starred items on it of interest to the FCA program. The notion of being a global, international enterprise; design anywhere, build anywhere is something that we're interested in. Our management's role is to support inter-team communications. Boeing is organized to include special, small business units and process-oriented organizations, which ensure process commonality across the company. In addition, the FCA program staff, is a small central organization, which provides technology integration services to many different organizations supporting Boeing factories.

I'll go ahead and show this chart again. [Slide 2-5]. I just talked about this on the other chart. It is basically global enterprise, lean efficient design and production, small business units, small central organization for integration, people and culture integration.

Cross-functional integration. [Slide 2-6]. This is very important; where we talk about moving away from "silo activity" that you get from large company activities and more towards cellular and getting many different organizations working together. At the top we have what our company invests in--specialty disciplines. We have specialists in tool design, manufacturing engineering, manufacturing research & development, quality assurance, facilities and information systems. Those are all silos; they have different roles to play in what we call the factory upgrade process. The wording underlying the factory upgrade process are processes that we know of that have an impact on upgrading our factories. Those are the processes (lean manufacturing assessment, capacity analysis, new equipment introduction, etc.) that need to be integrated. From there, we want to develop some tools that will enable coordinated delivery of technical standards, specifications and rules, into our integrated product teams which bring all of these different areas together and focus on upgrading our factories.

This is another way of looking at Integrated Product Teams (IPTs). [Slide 2-7]. We have the discipline owners cutting across several different business units (machine parts, sheet metal, assembly areas for 727 and 757, and larger airplanes, etc.). This chart is dynamic.

This chart shows the scope of the Factory Computing Architecture Program. [Slide 2-8]. The portion above the center line is what our enterprise level initiatives are, besides manufacturing, which involves product definition, build materials and process planning and asset management which involves the management of factory machine tools, the actual buildings that they're in, even down to the air conditioning of the factory. Below the line is the factory specific stuff, where we have the machine controllers and cell controllers. There's a feed for digital manufacturing data sets. Those come in and are then executed on the machine. There's the measure and analyze quality, which is my area. Monitoring machine performance, I am involved with that and performing maintenance operations. One of the key things that had to happen was, at Boeing because of the mentality which exists in certain parts of the company, we had to bring the facilities people into this effort. The reason why is that they have the money and expertise of the factory machines, maintaining and upgrading them. That's the scope.

This is one of the types of frameworks that we have been developing. [Slide 2-9]. We have a notion of information level, which is the top layer. We have our factory workstations, data collection and applications, things like wireless networking and things like that, upstream computing systems. We have a high level, which goes up into our main business system. At the control level, we have our cell control workstations. At the device level is where we get down to the nitty gritty; we have our machine tools, machine controllers, data collection devices of our machines and sensors. We also have this notion of non-real-time at the top, near real-time and hard real-time. I think there is only two categories. Hard real-time is when you are making something, you're getting data, and you are able to interact with the controller.

Focus of factory computing architecture. [Slide 2-10]. An existing factory situation with benefits to our program, we have emerging business processes, then we have strategies. "Existing factory situation" is where we build a consistent factory upgrade processes. [Slide 2-11]. As I said before, we have people coming in, in a disjointed fashion to upgrade our factories. We have variation in factory sub-component functionality, split responsibilities for the factory computing architecture, undocumented standards, which is changing as the program is developed. If the cycle time for change is too lengthy, we're aren't able to reap benefits projected by our initiatives.

We want to simplify our manufacturing process before automation. [Slide 2-12]. We want quality control to occur via process acceptance. We want to get away from single item inspection, we want to work towards accepting our products based upon process information. As part of that, we need reliable machines for production. Digitally controlled manufacturing. It would be nice to go from our design process, push a button, and then have our parts produced. We have a lot of overhead between our design system and our production system.

Emerging business processes. [Slide 2-13]. We want reliable and repeatable factory upgrade processes. Where we can deploy our technical product standards, we want modular, integrated products, pulled by customers, we want to move from proprietary systems and evolve to open, modular architecture, and we want more up-front consideration of software requirements.

This chart is our current factory upgrade process. [Slide 2-14]. We have engineering design and build up here at the top. When our software step starts to happen products are already starting to be produced. The software activity occurs too late in the process. The preferred way is to move the software design, building and integration much more forward in the process so that the software that comes out is of higher quality.

Benefits of the program. [Slide 2-15]. Categorized as follows: unit cost, cycle time, defects, and customer satisfaction.

Domains. [Slide 2-16]. We have factory domains, which include the creation of (Numerical Control) NC programs, verification, simulation, and execution. We have measurement, which includes machine tool accuracy, statistical process control, and hardware variability control. The items at the center, manufacturing process control, cell control, machine control, adaptive control, are specific to machines. Machine controllers with modular architecture. Adaptive control, to be able to adjust manufacturing in real-time (e.g., while products are being made). The next one is related to the facilities. We have machine tool and equipment effectiveness. That's not really a domain that has a management body, where the others do. Right now we are rolling this area under Measurement, until this area can stand on its own.

Tooling. When we had our users' conference, we only had manufacturing process control, measurement, and numerical control and computing services. Computing services, think of that as your underlying support infrastructure of your network and people who keep your PCs running, and those types of issues.

Other framework standards. [Slide 2-17]. By and large for machine controllers. We also introduce enterprise standards and delivery system standards. I'm just giving you a flavor for the work that we're doing.

CHANDRASEKHARAN: I noticed that you had 64-bit computing listed, would you explain that.

KITNA: It's a direction. This particular chart came out of a target/conceptual direction for machine controller standardization. Under the enterprise area, it shows 64-bit computing.

ESTERLING: Until you can get NT, a real-time operating system, then there are kluges being implemented. The market seems to be strongly going towards standard PC Windows applications, because it's cheaper.

KITNA: In some ways. In other ways, Microsoft's back office strategy for the enterprise is costly. Information Week had some interesting articles. Windows NT is a preference, UNIX is still in the picture. We are not satisfied with real-time NT capabilities as of yet. There is a place for it, and the Factory Computing Architecture Program will determine where NT is most gainfully implemented; in addition to UNIX's place in the factory computing architecture.

WELSCH: Share your experiences with ODBC.[1]

KITNA: We use it for connectivity with databases (i.e., Oracle or SQL Server) in the PC environment. I have heard of some performance problems, but I don't have first hand knowledge.

I had mentioned we used some different types of modeling (i.e., global) in various domain areas that I described. [Slide 2-18]. As an example, we have a use-case diagram for one of our business areas, the automated spar assembly tool which is numerically controlled. Things that happen there are order management, job management, machine tool data set management, process control (which includes measurement and statistical process control, machine part programs, etc.). Then you get some interesting-looking process communication diagrams. These types of things can be, for example, 50 pages per area that you model. This is just to give you a flavor of what type of object modeling that we're doing.

To quote my manager, "It's all in the infrastructure". [Slide 2-19]. One of the things after Boeing started downsizing in '95, where they had some early retirement options being offered. From my manager's perspective, that had an impact on the underlying management infrastructure. It has taken creative efforts to put back in place what was once there. Our initial authorization came from the Boeing Commercial Aircraft Group (BCAG) Produce Process Management Board, which is populated out of discipline boards or specialist areas such as quality assurance and facilities, etc. We have a program steering committee, which is cross-functional, including information systems. The program lists many projects under the main areas of the discipline boards. Then we have an area where we have subject matter experts where we can draw upon their knowledge to create this architecture.

Expectations for this year and next year, we want to establish an integrated architecture and related management infrastructure. [Slide 2-20]. The integrated architecture is technical, infrastructure is the management. Our team is our user community. We are also partnering with the automotive companies (i.e., Chrysler, General Motors (GM), Ford; we've also talked to Saturn). The automotive companies buy more machine tools. We want to leverage their voice with ours to influence machine tool vendors to support our factory computing architecture directions. We want to develop a multi-year architecture deployment plan for each of the

[1] Open Database Connectivity (OBDC) is Microsoft's application programming interface that enables applications to access data from a variety of existing data sources.

domains. We want to convey our computing strategies and direction for technical and product standards to our suppliers. As a part of that, we will be having a suppliers conference next year in the May time frame. We want to work with suppliers to implement our strategies.

Another piece of the infrastructure that I'd like to discuss is that we have what we refer to as a domain architect and a domain captain. The domain captain is typically a management person, who works in concert with the domain architect to develop/identify the necessary technical product standards for that given area of business activity. The domain captain will be more the customer with the non-information systems representative and the architect is more the information systems representative. I mentioned that we had a Users' Conference several weeks ago. Our expectations for that conference were to communicate factory-computing architecture as an enabler to implement BCAG strategies in production. [Slide 2-21]. We want to establish a level-set of all of our initiatives in the various ongoing programs. As you may know, we absorbed a few companies this year. Several representatives from Rockwell were present at the conference and it was very important to get the communication flowing. In addition to the agreements, issues, and action items identification, we are going to converge toward our factory computing vision. The conference also served to initiate communications with the new members of our team; to build synergy in the various areas. We want to understand how technical data will be delivered to our business units and cross-functional teams, which are called IPTs. As part of the factory upgrade process, we started some process integration in this area. We want an awareness of the necessity to empower these steering committees in the various boxes that I showed in the infrastructure chart associated with the FCA program. It's always a struggle, particularly for Boeing when you have large production increases and you are still trying to do things the same way. In the information systems world, we are all competing for the same resources. Production wants everyone to worry about, of course, production, yet we still have to worry about the future and this architecture. By working with the infrastructure that management is putting into place, we are able to keep the momentum going. At the Users' Conference we had executives come and give us their perspectives on the program.

Another key element, in addition to getting the communication at the Users' Conference, we want to gather all of these different areas together to understand the strategy, vision, and to set up a forum for the items that I mentioned. We want to be able to have one voice for Boeing to communicate effectively with our suppliers. We want our suppliers to be able to call anyone within Boeing and get the same answer, no matter who is called.

By bringing together all of the process-oriented folks and technology folks, we want to get all of the process and computing elements necessary for production together in one place. [Slide 2-22]. On the left, we have the various initiatives coming into the factory area.

We have our factory execution process, which is drawn from several sub-processes. [Slide 2-24]. Our domains specify what is within their framework. The notion of the factory upgrade process is included, where we have a clear understanding of the component processes and their inter-relationships. We are able to get the tools in place such that the technical and product standards, etc., can be used in the notion of the cost model; nothing is free.

This is the highest level of the Factory Computing Architecture Framework where we have various domains along the top, the utilities layer, a set of standard application interfaces and the delivery system hardware down at the bottom. [Slide 2-25]. An example of this is shown in the slide. We have domain business activity identified at the top. Specific utilities, whether we are buying them or creating them ourselves. The bronze colored blocks are where we start to specify the standard access methods per Boeing standards, lists them out like Standard Query Language

(SQL), ODBC, Data Objects, etc.. You can see we become very specific for the standards we want to apply.

WELSCH: Did you consider other frameworks such as Enterprise Management?

KITNA: It was created by the people who work in the area. I asked one of our consultants, and she had an example that basically validated what we produced. The types of frameworks that I showed were developed along the way, and I'm not aware of other types.

These are the major architecture design steps of the development of the Factory Computing Architecture Program. [Slide 2-26]. We are in Step 1, where we are defining the 2-D architecture, which I have already described. The next step is to prepare the domain transition plans that measure the numerical control, the manufacturing process control, and computing services, etc.. The domain transition plans will incorporate the moves to new technologies that we are forecasting. That could be 64-bit computing, where NT and UNIX lie in the architecture, etc.. The upgraded factory, that is deploying or supporting the integrated product teams throughout the next few years to go forward to upgrade our factories. People like me who support those efforts. Business unit implementation plans; to make sure they stay tightly linked to those activities.

This is my last chart, which is a high level view of what we've done and where we are going into the second quarter of next year. [Slide 2-27]. We had our Users' Conference in October. We had a couple of white papers. At the conference, we had a survey where we asked what types of technology, which were of interest; since they were all users, it was all valuable information. We had an initial list and we asked them to multi-order them, then we wrote a white paper on the results. In addition, we had a white paper for infrastructure. That was the management organization, which was put into place to make this program grow into fruition. We made project plans. Those essentially provided the visibility to essential projects, which can be used at more than one site. We had four domain project plans: (1) numerical control, (2) manufacturing process control, (3) measurement, and (4) computing services. I already talked about the transition plans and how we're implementing the technologies to transition over time. Then the second quarter, I've already talked about the Suppliers' Conference. The bottom bar is the Factory Upgrade Process, there should be progress on that line since we're moving forward with the factory upgrade process integration, infrastructure, white paper, teams that are looking at the upgrade factories. I want to iterate that through as we learn how that process is working. I've given an overview of the Factory Upgrade Process, FCA Program Development, an overview of what we've accomplished, what we've accomplished at the Users' Conference and what is planned for the future. Are there any questions?

DONMEZ: When is the framework going to be actually ready for implementation?

KITNA: I'd say in the April/May time frame of next year. Just because we want to have a transition plan well understood before we begin implementation.

KATTER: The asset management, will that be controlled by a central unit or a business unit?

KITNA: We have an organization called FAMO (Facilities Asset Management Organization). It is the Boeing organization responsible for our facilities. It is a central organization in the sense that it reports directly to our Group President, but it is regional. We have FAMO-North, which would include Washington. We have FAMO-South, which would include Wichita. How FAMO relates to our new acquisitions, that has not been determined. It is going to take a few years to fully integrate Rockwell and McDonnell Douglas. Therefore, there are separate facilities management organizations that handle these types of issues.

Machine Capability Diagnosis and Recovery System
Angel Dahilig and Jim Covington
Boeing, Wichita

COVINGTON: We're having a tag team today. Angel Dahilig is my project manager. She will talk for the first half of our talk on the computing aspects.

DAHILIG: We've got a project going on in Wichita that is being considered as a candidate for an enterprise level project. It is the Machine Capability Diagnosis and Recovery System and we call it MCDRS. I am the project manager on the technology side and Jim Covington is the Systems Manager.

KITNA: What is the difference between a project manager and a systems manager?

DAHILIG: We're following the P+ methodology and they call a project manager the person who is managing the actual product building and delivery, which is like the software engineering team. The systems manager is the person who is leading the (functional) process side of the project (user representative).

DAHILIG: This is the agenda. We will talk about: what is MCDRS, we'll go over some process and data definition strategies, the MCDRS web site, and machine data.

What is MCDRS? It supports some of our Boeing initiatives. Supports reduction and variability of numerical control machine parts by identifying and monitoring sources of machine error. It will provide for active corrective-action planning and tracking.

The objectives of MCDRS are to reduce part variability related to machine performance errors. Reduce unscheduled machine down time, specifically breakdown times. Establish reliable methods and processes for machine performance tracking, and increasing the accountability and visibility of machine performance.

The scope of MCDRS is being considered for enterprise wide implementation for Computer Numerically Controlled (CNC) machines and a baseline for periodic machine inspection such as ballbar, laser diagnostics of linear axes, and analysis.

What will MCDRS do? MCDRS will define standard machine measurements, plans and schedules. Capture machine measurement data, document and manage data. Provide automatic notification when one of two exception type situations occur such as (1) when there is an out of control condition that has been detected for your expected machine parameters and (2) when scheduled measurement events occur. This addresses accountability of actually performing and sticking to your plan of machine assessments.

MCDRS will analyze the data to determine the machine capability performance against planned parameters, predict out-of-control machine performance deterioration, analyze part family compatibility or incompatibility for a particular machine or machine class.

This system will rank machines by performance, provide root cause error analyses, and provide recovery recommendations and documentation. These last two bullets, we plan to use knowledge-based processing.

Our Implementation Plan. We are using P+ development methodology. I'm not sure how many of you have ever heard of P+. We are currently a SEI/CMM site at level 3. Boeing, Wichita information systems (IS) is the largest IS site to have that level 3.

WELSCH: How did you determine the level?

DAHILIG: We are using P+ as our methodology for SEI/CMM. SEI people came in and interviewed all of the projects, project managers. We're official. Before they did that, Boeing tried to analyze where we were at to make sure we were on track for the deployment of this. CMM means Capability Maturity Model and the whole idea behind that is that you have a standard and repeatable process for software engineering. The preliminary analysis phase: We were originally scheduled to be completed the 1st of December with the preliminary analysis review which is the steering committee buy off. That will provide conceptual functional data and process models for the system.

Define business and technical requirements: Technical trend analysis, additionally potential cost benefit analysis and implications, is scheduled for the rest of the project. That is all provided by the Preliminary Analysis (PA) phase. Because we're planning on becoming an enterprise application, teaming is very important and that is a cornerstone of our philosophy of MCDRS. Teaming, with other Boeing locations, we have a Boeing MCDRS Intranet site, which we're using as a communication tool. Teaming also with our suppliers. This is one of the reasons we are here now with the NAMT program, and NIST in particular, may help us see where our project fits. Our software engineering team is co-located with our system manager. That is to help facilitate the team inter-communication. We plan to move on to this phase with system construction.

Data Subject (P+ 150). This is just to give you an idea of the types of data. We call it data facets, groupings of data that we will be handling with our system. Everything within this interior rectangle is actually MCDRS "owned". When we say "owned", that actually means MCDRS is responsible for the creation of the application. Of course, other systems can read it. Everything interior to the exterior rectangle is data that we may have created with other facets. This is manufacturing equipment, and that describes our machines and machine tools. Machine test facets: describes our machine tests that are to be performed (i.e., the frequency of the tests, type of tests, parameters expected from that test). Test equipment: that defines our equipment that we're using to gather the measurements (configuration). Machine test results: after they perform the assessment test, what they got, and how we're actually performing.

HEMMERLE: Your expected machine capability, is that based on type of machine or on the product being produced?

DAHILIG: The machine.

HEMMERLE: If I need a certain quality within my work zone that is based upon type of machine as opposed to the product, which is going across the machine?

COVINGTON: In this particular situation we are talking about expected values in terms from historical data. We are getting a set of outputs and this set of outputs is within expected limits for a family of parts.

HEMMERLE: So the accuracy requirement of the machine tool is based upon the product going across it?

COVINGTON: Yes it is. If you don't have enough accuracy, then you can't produce the part. We always want to monitor when the machine starts deteriorating. Once these values have been established for a particular part type, then we want the performance to remain within the limits that we set. If the machine exceeds these values, then we investigate what is happening (workloads, etc.).

DAHILIG: System external data facets are the things that we need from the system that we don't control: people associated with the shops, associated with the machine. Product data: eventually we are going to integrate all of this with our product measurement Statistical Process Control (SPC) data.

DONMEZ: What do you mean by data/machine tool structures?

COVINGTON: Defining our machines: configuration, primary axes.

DONMEZ: Does Boeing define the classification? That is one of the things that I mentioned before that NIST has previously done some work in this area.

COVINGTON: Boeing-defined classification means that the machine should conform to parameters in machine tool industry.

DAHILIG: This data diagram is a little bit incomplete. There are additional one or two facets, possibly more. The one that I definitely know, which is not included in here yet is the portion that takes care of the diagnosis recovery information. Also, we are talking about integrating with maintenance system.

KATTER: Has this already been implemented?

DAHILIG: No, we are in the process of implementation.

COVINGTON: We recently acquired the resources to manage this implementation.

DAHILIG: System Definition P+ 200: This is at a high conceptual level of what all is involved with the system. These are subsystems and they are usually identified by SS1, SS2, etc.. Everything within the interior rectangle is what MCDRS is responsible for. Everything external is what effects MCDRS: what it reads or writes, from groups of people or external systems. These rectangles are called external actors. Quality assurance is involved here, machine operators, management, shop management, maintenance, etc. Sub-system 1 is where we manage the machine information. Someone has to identify what machines are going to be statistically analyzed. We put a performance track on it. Then the data goes into the system. Of course, there is always visibility of this information. This block here called subject is called the data repository. There are arrows going into and coming out of the data repository. The information that goes in is the manufacturing equipment. Sub-system 2, manage assessments: that's the process associated with setting up your assessment plans, parameters, expected acceptable tolerance ranges for those assessment plans and frequencies, the administration of those plans. Sub-system 3 up in the corner, manage machine measurements: that is definitely bigger than the other two subsystems. That has to do with actually running the assessment, getting the data, getting the parameter values, getting into the data repository, performing quick analysis on the data, and also more detailed analysis is available. There is some immediate feedback between the person that is running the tests and then uploading to the data repository. Also, if there is a problem detected with the tests, then that will trigger the problem diagnosis and automatic notification to the appropriate management or person who should have visibility if there is a problem with the machine. Facilities are also involved for maintenance issues. Sub-system 5, manage the problem diagnosis: that handle the problems coming into the system, diagnosis are based upon knowledge or past experience. If we don't have that experience then we can build it. Maintenance can have input to the diagnosis of the problem. Recovery will also have a knowledge-based portion, based upon past experience and knowledge where we can determine the recovery for a particular type of problem. We can also build that experience base by obtaining input from maintenance or the machine operator.

DONMEZ: What is the time frame to implement these sub-systems?

DAHILIG: That is still to be determined. Because we are considering this system for an enterprise-level effort, we are still setting up a steering committee, not only with our maintenance people, but we are trying to identify those people who should be involved. Also, we are basing our development on a concept on what I'm calling distributed teaming; distributing our software engineering. We are also doing many things with commercial off-the-shelf software (COTS), bringing in software from outside and trying not to develop as many projects inside. There is always the need to customize to our particular process. We're expanding not only to external suppliers, but also interior to Boeing. Boeing is so large and we have so many regions. Like Marty mentioned we have brought in McDonnell Douglas and Rockwell and with all of their regions. Across Boeing, we have many pockets of activities. The issues with machine maintainability and machine performance and how do we use our machine tools optimally. It is not a problem that only Boeing faces. Everyone in manufacturing experiences these issues (Factory Computing Architecture that Boeing has) and is something we are all trying to solve. All of these pockets internal to Boeing are all trying to grasp and come to terms with this. Based upon their focus or expertise, maybe they created small systems that perform something, maybe for their particular types of machines or tests that they perform. There aren't any systems presently available that integrate everything at a Boeing-wide level. That is what MCDRS is trying to accomplish at an enterprise level. As part of that philosophy, the distributed software engineering, we are trying to identify what pockets activity are out there, what are they doing and at what level. We anticipate finding several small systems and plan for their integration, but we want development to be the least amount of resources required as possible. One of the reasons I am here is that I am interested in what you at NIST have to offer. I can see two areas where you can help us: (1) analysis tools and (2) the data repository. We already have a data model, it is currently at the physical level. We would like to standardize with industry and we think we can help you as much as you can help us. One of the main things that I definitely see that you can help us with is the analysis tools.

HEMMERLE: How is this all funded? Is this indirect manufacturing expense? Do you have separate costing for your time and your time to know what this is costing to determine the payback?

DAHILIG: Yes.

HEMMERLE: What type of annual budget is that?

COVINGTON: I can't get too specific on that, because I also don't know too many details. However, I can give you a generalization from my interpretation. In all of our different regions, as Angel has indicated, we perceive the same kinds of needs. We have many isolated groups utilizing their own overhead money, their own resources to provide solutions. We have duplication of effort in many areas throughout the company and even throughout divisions. We're trying to bring together solutions that will solve these types of problems. A handful of people from each region came together to integrate the individual systems, and to build upon each resource. We have some other track work to be done yet to make sure that we are getting the type of management support we need to succeed. This project has been around for a couple of years, conceptually. The main thing that we are trying to do is bring together and facilitate a partnership to develop mutually beneficial packaged applications. We don't have a large set of resources, we have to use the existing resources and learn how to interact more efficiently with our peers.

HEMMERLE: What I was looking for is, are you able to get internal teaming: your key maintenance specialist that understands the variance within the hardware, how it came about within the machine, or what the variance within the machine track looks like on the hardware. Are you able to get those types of people many hours per week to help you? Alternatively, are you going to outside people to help you? Do you have enough internal people who support current operations and are willing to team? I have a perfect barrier there.

COVINGTON: Yes we can. In my experience, when you show what benefit can be expected, they see what you need and will respond. With limited resources we need a high level of support.

HEMMERLE: You can get high level support, but I'm talking about the guy on the ground only has so many hours per week and this is equipment to them. How do you balance what is important to the manager and product importance?

COVINGTON: We have the same problem.

KITNA: We are also using Factory Computing Architecture Program as a vehicle for getting more support and combining resources.

COVINGTON: I've been at Boeing for nearly 20 years. I've seen a lot of change in attitude within the last 3 to 10 years. I have seen redirection toward the motion for common processes as opposed to the variance that has occurred in the years past, where people didn't talk with anyone else. We are in a "better world" for cooperation, to share information due to common requirements that we all have. We have to work together now.

DAHILIG: Production has had "big brother" looking over their shoulder in the past for reduced productivity. But during the process of talking with them, we realized that they haven't had the data to document what was going on with the machines. Talking with the different pockets of production within Boeing helps with the realization that others could use this system to their benefit to help them to do their job better. Upper level management sees the potential benefit and the provides buy in, but doesn't force the system on anybody. When management sees a benefit to their own organizations, as well as the overall company, then it really helps to get the needed support. That has been my experience.

Architecture Strategies for MCDRS: As I have said, MCDRS is on the Boeing Intranet web. Because it may become an enterprise system, visibility and access to the system development and data is really important. Some of the reasons for putting it on the web are because of the Boeing-wide computing interface process; to lessen the importance of hardware and geographical constraints and the advantage is local data across regional or across the enterprise.

Our current progress as I mentioned is that we're in the preliminary analysis phase, to be completed sometime towards the end of this year. One of the reasons that our schedule is sliding a little is because of our increased emphasis on the "Boeing-wide" coordination. We currently have a conceptual, functional and physical data model. We have a conceptual process model. We're working on our functional, and what that means is we're breaking down the sub-systems into functions. The technical and functional alternative analysis for our recommendations is in progress.

We have our intranet site established and we're still working on it and trying to get more input from other people within the company for communication. As I mentioned earlier, we're at level 3 status. Jim will take over now.

CHANDRASEKHARAN: You mentioned before that you have an enterprise level issue. Are you making your data accessible across the business units and facilities as well?

COVINGTON: Typically regional. There are some types of analysis that can be used over a wider range. However, regionally, there is some need to contain that information to some extent. Technically, you could share that information with other geographical areas.

DAHILIG: Our plan is that people from other regions can access the information. We are still working on the security issues on the server, the speed, connection and related items.

CHANDRASEKHARAN: The issue is then not technical, but sharing too much information with your suppliers/customers.

COVINGTON: That issue is more internal. We're working hard to bridge the gaps, with all of our sub-business units if you will, our suppliers. Sometimes there are problems that arise between business units and we try to make that information available on request, but not necessarily in a forum where there is no control of the information. We don't want to have incorrect conclusions drawn from data that was acquired without understanding all of the parameters involved. There is a risk in making information totally available, that people may draw incorrect conclusions. That is one of the things that we're trying to manage with this regional concept. When we say regional, we want the same tools used throughout Boeing, Wichita, Seattle, that we're using the same clones, the same kinds of software, the same interfaces, the same kinds of data. The fields will all be the same Boeing-wide, there will be some differences and some amount of security of information. To manage the sensitive areas, some managers have had problems sharing certain types of information. We're still exploring these issues. I personally believe in wide-open information, where it is not competitive or sensitive, but at the same time, there are certain political aspects as well.

DAHILIG: There are some functional issues as well as technical that need to be worked out.

COVINGTON: We have a communications project, a graphical tool that we have just started. We put all the relevant information on the Intranet and made it available to anyone in Boeing. Essentially, the documentation, ballbar, our teaming efforts, project status, all of the different facets of what we're doing are being communicated with our team members within Boeing through this tool.

Right now, we have laptops out on the shop floors. We are running lasers and ballbars, all kinds of different tests and equipment. By and large we have a lot of different types of information that is taken on site and at the machine that is not being captured, contained, or compared to previous history. The laptop moves and we don't have a centralized database. We are collecting data and what I hope to have happen is that we establish configuration management, so when data is taken with a laptop or whatever system that they have, the set of information that is captured is consistent. This information is taken by a variety of people. The laser work that we have done is always performed by maintenance or Quality Assurance. We have some limited activity performed by the operator, (i.e., ballbar, certain types of spindle analysis, etc.) simple tests to get a quick feel of how that system is performing. From that information, we get a simple stoplight analysis chart that shows performance over time for any of these types of tests. The system responds with a "red", "yellow", or "green" light to inform the operator of the condition. This information is fed back into the database, compared to previous information and certain types of analysis are performed so that we can see any types of trends developing and any other things that are happening that we need to be alerted to. From that, we are using Microsoft Exchange to email out different kinds of messages (signals), for one thing, the schedule notification. We had a real problem with accountability. We have many systems, we don't run them as often as we say we're going to run them, therefore we need to manage the schedule so that we know whether or not certain tests were run. If a test comes back with errors associated with it, then we automatically send another signal that notifies management, Quality Assurance and others as required. Schedule notification in relation to maintenance: sometimes we have a difficult time performing the tests around the production schedules that we have set for ourselves and we need to be aware of those things. This is kind of an overall view, using messaging, to track the overall performance of the machines. This is just for machine capability and not for the measurements of production parts. You can, in parallel, compare the machine performance data with your part measurement data. Our ultimate goal is to be able to predict part performance by tracking machine performance, that you can control the resulting part by controlling the parameters of the machine process.

Capture database knowledge and make decisions: this is a teaming effort, operators, metrology, maintenance, all of the personnel necessary, including a group like this NAMT workshop to help us understand the problem, what the theory is and help us utilize it to make decisions. We are back to decisions; we need to make decisions that are based on solid information.

We put together a simple database. It consists of the actual reference information, type of machine, table size, location, travels and those types of things. For example, the 21 machine error parameters of a machine, roll, pitch, yaw, etc. What I'd like to do, we're not there yet, is to click on these error parameters and not just see the values, but the ability to see the charts. One of my goals, I'm sure we're going to see a little of it with the ballbar, is to see similar types of analysis for the other types of tests. I hope we would see these values for a certain machine and that we can compare different time intervals simultaneously to see the trends for machines. In one case you may have linear accuracy for an axis and can look at a chart to see what is going on at a particular location. We identify zones of the machine, some, which are acceptable, and others, which are not. We do that, but we want a system to allow for management of the information in a more systematic manner.

The ballbar is one test that is quick and dirty that gets our operators involved. It is a quick indicator and that is the only reason we use it. I caution everyone, if you really want to know what is going on, use a laser system. Some of the process controls we provide include pictures so that the operators will have a visual reference for the setup.

We can produce graphical outputs using DOS-based software, which doesn't lend itself to the working environments that we'd like.

We also have another analysis tool for the operators to look at. We created software around one of the Renishaw products. What Renishaw doesn't do very well is keep track of your machines, operators, and certain kinds structure that we need to monitor our business units. Ours is just a simple monitoring system. We did actually detect a problem that was occurring in all three planes of a machine with this system.

We generate charts trending across the three primary machine planes. All of these machines have different ages, histories, and those kinds of things. One of these machines has a serious problem in the XY plane.

CHANDRASEKHARAN: You mentioned having software that is wrapped around the Renishaw product. Is their package running in the background and you are just working around their package?

COVINGTON: Yes. We just built an interface to their package and didn't reinvent anything produced in their package.

CHANDRASEKHARAN: Do you take the Renishaw (.rtb) files stored and then analyze or is it a real time operation?

COVINGTON: We set up all of the parameters, manage the .rtb files and have template files, which we use over and over and always have the same set. We have configuration control over the setup this way, so that two different operators will collect the data the same way. We also manage to store the data associated with a particular machine with the time and data filenames; all of the data is managed. That is what I mean by a front end, not really a database, but manages information. We have one ballbar system per shop. Our system allows the operator to pick which machine to test; the software manages the files and places information in the right places for analysis. We also produce extra charts, for comparison.

DEFORGE: I visited some of the facilities at Boeing. They are using a simulation of job setup. In Seattle they are looking at modeling about 170 machine tools and I noticed that you had your links to try to show the machine tool itself. It would be interesting to draw on those resources of setup and modeling and bring them together on your web page so you can go to your machine, go through a step-by-step description of the job setup.

COVINGTON: I didn't show you that but it is a rather lengthy process to setup. We have setup instructions that are customized for a particular machine. You have an excellent idea to have the pictures available during the setup, and we do that with our system.

DEFORGE: A 3-D model for that type of situation is beneficial because you can pan to different views and angles of the setup. Talk with Joe Analy down in St. Louis, I can give you a name and number to do that. A window will come up with a 3-D view, which works similar to a tape machine in that you just hit play, and it is different in that once you start to play you can use your mouse to move around at will. Then a set of instructions comes up.

COVINGTON: We're working in some cases with 386 computers and I'm concerned about getting too high tech. That is an excellent suggestion for us to look at.

SOONS: To follow up on the second issue, an important component for the comparison of machines to work is that you also have to standardize setups, standardize ways to measure machines, and standardize what kind of tests you are going to do on the machines. Is that an important part of your overall scheme, to standardize these issues? My second question is, do you use tests during production?

COVINGTON: The answer to the first question is absolutely we need to have standard tests, like tests for like machines. If we use a machine for certain purposes and you know what its defining qualities are, then you should use the same tests on those machines, run in exactly the same way. Then we look at performance, how much deterioration do we see over time to determine at what frequency interval we should measure the machine. The answer to the second question is a qualified yes. One of the biggest problems in the maintenance world is that the shop often won't give up the machine, they'll run a machine into the ground. What we want to make sure happens is that when an agreement with the shop and the shop management is made about the methodology of performing a test, we want to make sure the agreements are fulfilled, and this messaging system helps us do that. Yes there are going to be problems, and yes we are not going to want to stop production to make measurements. In the past we've had unscheduled breakdowns and part scrappage that scheduled maintenance might have prevented. What we're working on is that these machine measurements become scheduled events.

HEMMERLE: My different machines have different mean accuracy work zones. Sometimes it may be 500 mm high; sometimes it may be 200 mm high. My systems people want me to run the same test in the same spot, yet my accuracy is in a different place. You can't really perform the test and get the comparison that you want. If we're in agreement, then you need to go talk to my quality people.

COVINGTON: You have to determine in what zones you are going to run your test. You may have to run multiple tests to get the information that you want. Where you make the test is part of your test definition. It varies from machine to machine. We would like to make it as similar as possible, but sometimes performance requirements and other issues make life complicated.

To recap, what we are trying to do is to control the resulting part by controlling the process. We want to assure our process is performing adequately. In the past, we just relied on faith until machines broke down. We are now monitoring the performance of machines to prevent breakdowns. We are trying to maintain performance data adequately. We are implementing accountability, machine performance report cards. We want to discover new ways of measuring machines, to understand and optimize the methodology and report on machine data.

DEFORGE: If you were to link this data that you are collecting on machine tools back to simulation models that you are doing on process prove out and things of that nature, would you primarily be looking to identify inaccurate zones on your machine, to flag the operator to not use certain work zones? Alternatively, are you looking for and actual reflection of the inaccuracies on the generation of the part?

COVINGTON: I don't think you ever want to change your model. The model needs to stay pure no matter what. One of the problems that we had until recently is that even if you knew the geometry of the machine, you didn't know on which machine a particular part was going to be manufactured. Now we can target our products for a particular machine for a particular accuracy.

Machine Tool Management and Machining Simulation

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Jim Katter is with me and we work on machine tool management and machining simulation. My presentation is focused more on the specifics of our project and not as much on the high level as what we've been hearing today.

Our focus continues to be in three main areas: (1) process planning, (2) machine performance data and asset management, and (3) simulation. [Slide 3-2]. I'm specifically going to talk about three or four areas of progress that we've made since we last met in February. We've had increased pressure from plant to implement "something". That is as much definition as you get from plant. "We want something and we want it now and it is your job to get it done". We've actually leveraged a lot from this community, from the work that NIST has been doing. Therefore, we really appreciate that. We did sign the NIST CRADA. I will talk more about some collaborative work that we've been doing there as well.

First, I would like to talk about machine classification. [Slide 3-3]. We leveraged the work of NIST published in the document - NISTIR 5707. We actually took that and implemented it by taking several machines and putting data into the classification. It worked really well and we're happy. There were a few changes the plants wanted. They wanted information on work area issues that are relevant to our planners such as the maximum capacity of a hoist or a lifting device etc. There was some information that was very specific to the way we do business, so we merged it with our internal "machine folders", which is a folder that process planners keep and it varies from one business unit to another. We combined some of that information with what NIST had and implemented "something". There are several issues with platform of implementation and layering that we talked about earlier that are yet to be addressed. We also want to make additional high level information accessible to the plants so managers can plan capacity related issues. There also has to be link to commercial databases for new machines such as the Machine Selector software. We have not got to those details yet. The good news is that the machine classification that NIST had and some of the things that Hans Soons presented at a previous meeting merged really well when we implemented them.

There are issues that have come up in the repository as to what kind of errors we store and how the errors are characterized. [Slide 3-4] We heard a lot about the ballbar and the laser, there is work that universities addressing, issues of thermal errors and ambient effects, repeatability and combining all these errors. We eventually want to know how all of these effect the part. As a start, we tried comparing laser data with ballbar. We tried to take quasi-static errors from laser data models and injected them to a circular path, to see if it compared with the ballbar data. It was not that close. We haven't had much success yet, because there are other errors that the ballbar picks up such as servo mismatches and backlash, etc. that you don't capture with the laser. Some of the differences could be in the way that we are simulating the system. We are still debugging that portion. It is very interesting to try to understand how these errors can actually combine.

There is internal work that we are doing in the simulation area in validating the data model for the machine classification. [Slide 3-5]. We have more experience with machine characterization using different tools such as the API 5-D laser. Standardization issues as you mentioned about the ballbar tests, how different people might do things and how to address those issues. We learned a lot more there and a lot more about how our work relates to the repository as well.

We've done some work in the quasi-static machine error measurement and simulation. We came up with a file format for machine errors that you get from tests, and we used a neutral file format to represent these errors. This is as an interim solution. We define the coordinates that are measured, minimum and maximum, and also what is the zone, how to store the variables, the coefficients of a polynomial fit, so we're not storing the raw data. This is something that has worked well, but it needs to be tested a lot more and validated with different kinds of errors that you might store. It is less data intensive.

Specific to the NIST repository, we were successful in submitting a ballbar data set. [Slide 3-6]. Larry Welsch walked me through one, and it worked great the first time. We took a Renishaw ballbar output and submitted the data. We did some comparative analysis with the reports that Hans Soons has generated. I believe he was using the ISO 230-5 format, I'll show you some of the plots. I used some of Hans' data definitions. We have been working with Larry on communication and demonstration issues as well. No major breakthroughs since the firewall is in the way.

At this time, I will show you the data we submitted to NIST. [Slide 3-7]. This was the ballbar data that we took for the machine and you are familiar with the Renishaw output so I will not show those. However, I will show you the ISO 230-5 output, you can see the min/max numbers that are output. This is the report that is generated in the NIST repository and these are the numbers. [Slide 3-8]. However, we need to move on and that will be the focus of my talk. We need to understand the algorithms to reduce the data, errors that are output from the Reshishaw, squareness and other types of errors. This may not be new to you, we came across some work at Tempre University of Technology at Finland, where they have developed algorithms and software that takes ballbar data from different instruments, Renishaw and some of the others, and computes errors similar to what Renishaw outputs. [Slide 3-9]. That could be something that we potentially look at to develop a standard.

CHANDRASEKHARAN: Someone mentioned how to go in and find acceptable limits of machines. [Slide 3-10]. You can go in and change the errors in each of the backlash, squareness, pitch, and scale errors and then the software will re-plot and show how the errors effect the test. [Slide 3-11]. I think it could help US industry to apply some of this and maybe standardize some of the algorithms for data reduction. What happens is, when we talk about measuring Machine A and Machine B with two different ballbars and all you track are the final numbers, then you are not going to be comparing the same two squareness numbers; you are not comparing the same two performance capabilities of the machines. We would be very interested in understanding the algorithms for correctness and how accurate they are. I don't know if it is public domain and accessible to us. I would like to move in that direction. It is a shareware right now and they gave it to us with a timed license. It is a windows-based program where they just gave us the executables and no source code; fairly user-friendly. I also compared the different errors. You can see that many of them are close to what Renishaw comes up with, it depends on the numbers. Renishaw tends to report the average numbers, you can see they report some in the clockwise and others in the counterclockwise directions, and some of the axes backlash numbers. But the numbers are very close, so the algorithms that they have developed appear to be the same as those, which are used by Renishaw and other programs. If this is public domain type of knowledge, then we would like to start working with it in the B5 or an appropriate committee to try to drive those to a standard, so we can at least make comparisons.

Now I'd like to address what we want to come out in the near future and what we'd like to contribute to the road map. [Slide 3-12]. First, standardizing the method of computing the errors, we can keep tracking that. In the ballbar area, we'd like to see in the repository is comparative analysis of machines. I think, talking with Hans and Larry that they intend to have the capability of overlaying plots and also trending data. We'd like to understand how this is performed. Another essential issue is that we want to work with our suppliers, whether it is machine builders, or suppliers of this technology, so that we can standardize formats. We've worked with the Renishaw format, but there are obviously others. We want to work on getting this technology transferred to us. We want to keep working in parallel in acquiring some of the code. We want to work on performing a demonstration of doing some corrective work. The laser area is what we think should be the next logical step. [Slide 3-13]. We've been working more with the 5-D laser, but I'm sure that other people have other types of data sets (i.e., HP, etc.). I don't know how we, as a group, are going to work collectively as far as writing interfaces and things like that. We've come up with a file format that we can use for simulation purposes, and we are developing some tools there. We can either change to whatever file format you come up with, or we can write interfaces to whatever the repository comes up with as a standard. Our goal is to take data that is in the repository and run simulations to see how the machine errors effect the part. Alternatively, if our manufacturing produces machine tool error data, we want to see the simulation of the resulting part. In that context, we are going to spend quite a bit of time on visualization tools. I have a plot to show what the machine errors do to a part. We plot both the ideal geometry of what you would like to create, and what the machine errors are doing to the part. You can see the amount of error on a part feature resulting from the machine errors. If you know that these are your high points, then you can start controlling your process. We don't perform any type of sensitivity analysis to figure out which of the machine errors are contributing to these part errors. That is something that we'd like to do. But you can play with the numbers. For example, you want to reduce your squareness from 20 arc-sec to 10 arc-sec, then you can see what this does to my flatness values. This gives you an idea of how to correct the machine. If I have to maintain a certain quality of part going out on this machine, I just need to bring the squareness down by X or bring the straightness errors down to Y. So we are trying to use simulation tools, and I think that is what Alkan Donmez has been trying to focus on. Trying to use simulation tools to drive how you want the machine capabilities defined and how to visualize data as well. We are very interested in this area. It was interesting to figure out how much error was coming from the machine. I am interested to see what Joe Falco has in his demonstration of the Deneb software visualization.

DONMEZ: Does this plot show all 21 errors?

CHANDRASEKHARAN: Yes. The machine was characterized with the 5-D laser. We took the output file and stored in our file format. We used MATLAB to make a 3-D plot of the data. We are developing capability to use other tools for visualization. I know that API is developing visualization tools and Joe has developed an interface with Deneb. We've shown limitations with the IntelliCad 3-D software engine. This is what we've come up with so far. It gives you a 3-D visualization of the errors and the opportunity to see which errors effect your part the most. I mentioned that we had a file format which we convert the 5-D laser data into, then that goes into the simulation. We currently do not store the raw data, just model coefficients. It is not a standardized model, but we can interface with any type of a model that you create with your 5-D laser. If the repository chooses to store the raw data, which seems to make sense for the longer term, we can adapt to that. If the repository chooses to store coefficients, then we need to standardize a model. We are not storing the goodness of fit. You may have outliers with the model that you use. The other issue is repeatability of the 5-D measurements, the forward and reverse data that is collected. We perform the measurement three times and then average the result. We need to address repeatability because that will effect the Cpk numbers.

The last area of recommendation that we are interested in for near term future work is the simulation area. [Slide 3-14]. We talked about the ballbar and the 5-D laser system. As I mentioned before we are trying to understand the different types of errors (i.e., spindle analyzer data, tool change repeatability data, quasi-static errors, and ballbar data) and combine them for simulation. If you want to simulate a circular path, then you can just use the ballbar measurements. We are simulating the quasi-static errors, but if there are machine motions that have backlash errors, that have scale mismatches, it is not necessarily captured with one test. We know that there are limitations to just simulating the quasi-static errors. We want to determine how to combine different types of errors. Then there is the issue of the internal representation, there is no standard on the CAD side. I think that we could get some assistance from this community on visualization tools. We are interested in sensitivity analysis for machine correction. We just have a brute force method where we change parameters and see the result on the part. I think a more elegant way is to do some sensitivity studies. I know Boeing mentioned that they wanted to use knowledge-based systems and methods to predict part errors.

Precision Metrology
Sean Olson
Automated Precision, Inc.

I will talk about two projects that API is currently working on. In case you don't know, API is a manufacturer of precision metrology, but is also involved with using this equipment in the field. We have 3 main systems: 5-D laser, ballbar, and spindle analysis systems. These systems acquire data, which reflect specific geometric, dynamic, and thermal characteristics of the machine tool. Feedback from customers have led us to determine that the users' in the field have become inundated with these types of measurements and they have a hard time of putting the data into a manageable form. To respond to this need, API has developed a Microsoft Access-based data management system that is specifically designed to organize data produced by our standard series of metrology systems. This database can handle measurement results from seven systems which include the autocollimator, telescopic ballbar, hysteresis system, 5-D laser, spindle thermal, spindle dynamic and electronic level systems. Next I'll show some data from the 5-D system.

What this slide is showing is a typical setup of what our 5-D laser system on a vertical-milling machine. [Slide 4-1]. What we're measuring here is the linear displacement accuracy, the horizontal and vertical straightness deviations and the yaw and pitch deviations.

This plot shows some results of the linear portion of the test. [Slide 4-2]. This is error vs. nominal position in terms of machine coordinates.

This plot shows some results of the straightness portion of the test. [Slide 4-3]. The top plot showing the relative horizontal straightness deviations and the bottom plot showing vertical deviations in terms of error vs. nominal position.

These are some results from the angular deviations. [Slide 4-4]. The top portion indicates yaw deviation, the bottom pitch deviations.

For a single axis test, the 5-D laser system produces 3 error files that, in effect, summarize those results from the 5 individual measurements that I just showed. [Slide 4-5]. These error files are just ASCII (American Standard Code for Information Interchange) text. Currently, we are just summarizing, so we are primarily interested in maximum error, maximum reversal error, bi-directional repeatability, and certain parameters that reflect the mission of the test: where you tested on the machine, the length of the test that was performed. This is the actual information that is read into the database management system.

The system is designed on a machine tool basis where every particular machine tool you have a variety of tests [Slide 4-6]. There are three basic sections. The first section deals with displaying and previewing certain types of report formats, specifically in summaries of a particular test or printout of a history of performance of a machine tool for a particular type of measurement. For example, you may be interested in certain performance characteristics over a period of time. The second part deals primarily with updating and adding machine tools and adding individual error files for each particular machine tool. The third section deals with some raw file management where you can add new machine tool specifications or delete a machine tool altogether.

This next slide is an example of the kind of generic report format that the system currently outputs where we are summarizing the test results of the 5-D laser system. [Slide 4-7]. Again, you have all the important numbers that you are interested in: the maximum errors, repeatability, and backlash types of errors for each test.

This is the database system as it currently stands. It allows the metrology technician to manage the large quantities of data that are being produced by just a few simple tools. It also allows other people to view the data as whole or just pieces of the data (i.e., people in maintenance, quality control, or production planning). The future enhancements of this software depend upon feedback from groups, such as this, and primarily from customers in the field. Currently the software is being tested at a beta site, where they have a whole series of our equipment. Feedback from them will help determine the specific formats that they would like to see in upcoming versions. Perhaps the addition of graphical numerical analysis tools will be made.

DONMEZ: Does the database management system currently only import API-generated data?

OLSON: Currently yes. Eventually we may be able to accommodate other instruments.
The second project that I will talk about is the ongoing development of a 3-D machine tool error modeling system. Again, because of the high volume and the complexity of the data collected for a single machine tool, more sophisticated means of displaying errors is required; more than just disconnected X-Y plots as I previously showed. Taking that approach a step further, we realized that the end user is ultimately interested in what part errors produced from the machine errors. API is currently working on a Small Business Innovation Research (SBIR) project to develop a 3-D machine tool error modeling system that simulates the machining process, account for the known measured errors. Eventually, displaying the actual part with its associated geometrical errors. The first model we developed was a 2-D model, based upon data collected from a CNC turning center. Using the 2-D model and assuming a simple nominal part and process definition, the actual tool path is then calculated. Using this information, software was developed with a solid modeling kernel to display the finished part with its associated errors. For the 2-D model, the nominal part was defined as a simple cylinder with a fixed radius and a simple tool path on the perimeter was assumed. This plot shows the errors for the measured lathe and the display is in error terms that were based loosely on geometric dimensioning and quality principles. [Slide 4-8]. For this particular case, we show the radial error and the axial error. This is an actual solid modeler, which gives us the capability to rotate and look at different directions. Further efforts will include the development of a 3-D model based upon collected data from a 3 axis CNC machining center and the addition to visualization software of the results of that model. This work will be done assuming a simple cube for the nominal part [Slide 4-9].

Based upon the data from the 3 axis-machining center, we would then display the distorted cube due to the machine tool errors. [Slide 4-10].

DONMEZ: What types of data are you using to do the modeling? And is the data in polynomial form?

OLSON: Right now, we are just using geometrical data, measured by the 5-D laser for modeling. The model is being developed in two sections. The section that actually crunches the data is very similar to what was shown in Vivek's presentation where all 21 errors were used to develop the model, which displayed the actual location of the tool tip as well as the nominal location. Assuming a linear relationship between points, then we can calculate an actual tool path. Eventually it will be combined with thermal models. Eventually the 3-D model will display a cube similar to the one shown here, but distorted due to the machine errors. This particular model is somewhat abstract because the process definition is not an actual part, it is a cube defined somewhere in the machine workspace. Currently we are not programming the capability of simulating an actual tool path. In the 2-D model we assume a simple tool path. For the 3-D simulation, it will correspond to a number of passes over a plane by an infinitely small end mill to generate that type of topology. Those types of capabilities where we will be able to simulate more complicated parts will eventually be incorporated.

Now with software such as this, we hope that we can give engineers a tool to implement the closed loop feedback control of a machining process. With this tool, simple corrective actions may be implemented such as linear compensation for a controller, or a simple mechanical adjustments, or simple mechanical repairs or even overhauls, or even simple real-time error compensation. Ultimately, the development of these types of error analysis software tools will enable the end user to fully utilize the data obtained from standard types of machine tool error measurements (i.e., the laser and the ballbar). These are the main two projects that API is working on that directly apply to the NAMT program.

DONMEZ: When do you expect to complete the 3-D visualization software?

OLSON: This is Phase I of an SBIR project. Currently we are writing a proposal for Phase II. We need to perform more analysis and don't expect a commercial product for another 2 years. Since it is not a trivial matter, it will require some analysis and an assessment will be made to determine exactly what crucial functions to include in such a software package.

DONMEZ: On which platforms will the software run?

OLSON: The underlying engine, which drives the software, is a solid modeling kernel called Parasol. That is what builds the solid models. We use Visual C and Microsoft C to program the User Interface.

KATTER: What does the Beta software consist of?

OLSON: The database management software is not currently delivered with the 5-D laser or ballbar. We reached an agreement with a user who bought the entire series of measurement devices. Since the customer had many types of machine tools, API thought that it was a good place to test the data management software. It has been out there for about 3 or 4 months now, we're looking to obtain feedback from the Beta site to better define the format for the data output. Feedback in terms of what type of analysis packages would be beneficial. We would be willing to work with other people as well and provide the software for evaluation.

COVINGTON: We are interested in getting a copy.

OLSON: I don't see a problem with getting a copy of the software to Boeing.

KATTER: How far away from commercialization is the 6-D laser system where roll is also measured?

OLSON: API is developing a 6-D laser system where roll is measured, but I am not certain of the specifics of when that will be available?

COVINGTON: Do you have any devices, which measure 4 axes?

OLSON: API does have a device, which we refer to as a "swivel check". We have an autocollimator, but doesn't work well on the rotary axis.

KRULEWICH: How accurate is your 5-axis system?

OLSON: For our standard system, linear accuracy is 1ppm. Our high accuracy system is 5 times more accurate. For other yaw and pitch it is 1 arc-sec. For straightness I would have to look it up. The resolution is 10 times smaller.

Loaded Machine Data
Steve Patterson
University of North Carolina at Charlotte

I want to talk about something a little different. I'm not going to talk about the database or computer models. Each time we've had these workshops, I've tried to talk about the data that will be used in the data repository. What I'm trying to do is come up with the type of data that is not easily encapsulated. I'm just going to give one example of that by talking about a class of data which is being discussed by the B5 committee, which is loaded machine data.

A lot of the geometry data that we've been discussing so far today have been using metrology methods to measure the machine tool essentially as if it were a CMM. Questions have been raised from time to time of what actually happens on a machine in the presence of loads that are there when the machine tool is actually plunged into metal. To look at that, we've built a setup using one iron disk and a couple of relatively strong magnets. By varying the gap between the disk and the magnets, we get a pretty smooth load, so I don't have to worry about varying rattle in the loading device. We can place about a hundred pounds or so of force on the spindle. I will give you one "characteristic" result. What we find is, of course, what you don't want to find when you go out and do this: that there is a definite difference between unloaded and loaded performance in the machine tool. What is even more interesting is that when you do this at different speeds, there is no simple model for a particular spindle. This particular measurement was made on a spindle which has a Timken, tapered roller bearing on the nose, hydraulically preloaded from a table based on spindle rpm. The pre-load changes as a function of rpm and results also change as a function of pre-loads, so it is a relatively complicated situation. The only real contribution that I was going to make today was to present some data. There is still some richness in the area of machine tool testing in terms of having a real understanding of what is going on. We heard earlier about questions of reconciling the difference of ballbar data with laser measurement data. What we ultimately want to do is reconcile our understanding of machine tools with the parts that we're getting off of them. This is another piece of the puzzle, which is going to have to be included sooner or later.

HEMMERLE: Did you axially pre-load there? Did you do any side pre-loading?

PATTERSON: This is an axial pre-load. I have not done any side pre-loading yet. You can only do so much with a Masters student before he escapes.

DONMEZ: What ranges of loads did you use?

PATTERSON: We varied a gap between the disk and the magnets, which yielded roughly 70-140 lbs. of axial load.

DONMEZ: It seems then that loading essentially creates an on/off effect.

PATTERSON: Some loading experiments yielded a binary response, and in others that is not the case between loaded and unloaded. At 1000 rpm, you don't see any difference between loaded and unloaded.

HEMMERLE: Where are you going with this? What is your next Ph.D. student going with that?

PATTERSON: These numbers are not huge, for some applications they are important. There is about 5 µm of difference there. For some of us, that is a big number, but for most of you it's sort of so-so. One of the other things that I'm interested in looking at is the error motion itself when you take a look at the asynchronous and the synchronous error motion and how that is changing with load. The idea being basically to get a handle on what is the boundary of changes between loaded and unloaded. After that, seeing if we can reproduce the difference in parts, which is the challenge.

DONMEZ: You mentioned 1000 rpm not having any difference. What is going on between 1000 and 1500 rpm? Is it again an on/off switch?

PATTERSON: At 500 rpm, it behaves like you would expect it to, with increasing pre-load causing increasing offset. There are two shifts in the hydraulic pre-load that occurs in the spindle assembly and every time you cross a boundary the behavior changes not only quantitatively but qualitatively as well.

DONMEZ: That means that we have to capture information about the loading; the loading types and the amount of loading in some of the data that we have. That should be another layer of our repository.

Techniques for Modeling CNC Machine Errors
Don Esterling
N-See Software

We are a company that has been in the verification business for about 15 years. Verification can be thought of as error modeling for a perfect machine -- error modeling the process (the part program) rather than error modeling the hardware. At the last meeting in New Orleans we discussed the utility of error modeling and the accuracy that is required. Often large and small shops each have a difficult time in understanding the value of hardware error modeling. There is a parallel. A few years ago, Computer-Aided Manufacturing (CAM) vendors were not really interested in process error modeling or verification. Now you can't find a CAM package that doesn't have some type of verification tool imbedded. The mindset changed for several reasons. The change came when error modeling/verification was recognized as reliable and cost effective, enabling part program mistakes to be discovered before they cause costly errors on the shop floor. It is also much more convenient, easier and you can do a lot more in simulation than you can do on the shop floor.

Today I will present ways of modeling error sources from my point of view. [Slide 5-2]. When I first spoke to Alkan Donmez about the project, I understood the project as starting with a collection of CNCs on the shop floor, error modeling data for these machines, and certain part programs, and then asking the question: which CNCs are the best choice to manufacture products within specified tolerances. That is what I considered as our challenge.

The verification industry has spent man-decades of time developing various engines to model process errors for a perfect CNC. The hardware errors that we are talking about with CNC machine tools can be in the tens of micron level range and so require very accurate modeling tools. What are the lessons to be drawn from modeling comparably sized process errors?

There are various ways to model errors on a perfect machine. I will describe three approaches.

Some verification systems use animation techniques, but these are accurate along the viewing direction. [Slide 5-3]. If you try to rotate to a new view, the verification system will have limitations in zooming and in reporting dimensional data. These are due to model inaccuracies in the screen X-Y direction, perpendicular to the viewing direction. Typically, the accuracy is one pixel in size, one part in 500 if you are using a 500 x 500-pixel error region. This translates to 2000 microns over a one-meter part. This approach is also relatively slow. The main issues here are speed and accuracy. Error modeling, of any sort, on the shop floor demands high accuracy within a reasonable time.

There have been various CAD modeling schemes for verification, which are very helpful in modeling large scale, complex work cells. [Slide 5-4]. For the metal removal process, this approach presents you with a choice. If you want a reasonable response time, then there is a sacrifice in accuracy as can be seen when you zoom in and find a smoothly varying surface approximated by flat polygons. Alternatively, if you want to have shop floor accuracy for material removal, then the response time for a complex part can be very long.

Another alternative and the path that we chose to take, is to develop our own internal modeling engines tuned to CAM, rather than CAD, applications. [Slide 5-5]. We started out with a CAD solid model system and realized that there is a brick wall there in terms of the type of technology needed to develop CAM-specific solid models; one which will handle very large part programs.

To give you a sense of what we've had to deal with, recently we were benchmarked by a vendor who was evaluating us against other products. They gave us ½ million lines of code with a very mild gouge somewhere and told us to find it. It took us 2.5 minutes on a Pentium Pro 200 to find the gouge. That is the type of response time we need to deliver. That is a lot faster than the CNC can process the part, which would be about several hours, and we are still able to maintain shop floor accuracy. A CAD-based solid modeler would take a lifetime, if ever, to process that number of Boolean operations (one per tool cut) at that level of accuracy.

I will now demonstrate our part verification product. [Slide 5-6]. This presentation will consist of 2-axis turning, 3-, 4-, and 5-axis milling. We provide pixel-based animation, which is very useful for seeing large errors or unexpected tool motion. We also have solid modeling for turning and milling where you can rotate to any view, zoom in for details and obtain accurate dimensional data anywhere on the part. [Slide 5-7 to 5-10]. The system allows you to even see scalloping effects, basically errors at any level of interest, particularly errors required for the NAMT objectives. [Slide 5-11].

When you have humans in the loop, things happen that sometimes you don't expect. The nice thing about our model is that it models the machine exactly as it behaves. If it goes wrong on the shop floor, you can see it in our software. Here is the surface of the benchmark part, and if you look carefully, you can see a small gouge. [Slide 5-12]. Here is the surface of the part as it compares with the CAD data. We can import a CAD model and superimpose the CAD model over the part. [Slide 5-13]. The different colors indicate where you have over cut and under cut the part. If I zoom in to the critical region where the gouge is, you can see how deep the gouge is. [Slide 5-14].

This is not a pixel model; it is a solid model. One of the characteristics of a true solid model is that you can zoom in to any point of view. That was just a short demonstration of our current capabilities.

What we did about a year ago in response to that NAMT request, was model a simple turned part, along with an error model that had been developed by Alkan's group. [Slide 5-18]. We demonstrated the feasibility, within a reasonable response time, to accurately model very small errors for a lathe. We simulated a simple step part for a particular CNC. The model provided in an automated way a means to visualize the errors on the part caused by the machine errors, similar to what API showed.

We are interested in developing a milling CNC error model, where the challenges are somewhat different than turning. [Slide 5-19]. Turning is a 2-D model with a 2-D error model superimposed on top of that. You don't really need solid modeling to do that sort of thing. When you get into milling, particularly if you want to model the entire process, not just the finishing process, and you have a part with significant lines of code, you want to have a model that will handle at least a perfect CNC system. How can you handle CNC hardware errors if you can't even model a perfect CNC? We have something that will exactly model the machine tool to the errors that you are introducing. We are interested, but first need to hear from some of you as well.

A Summary of Machine Tool Error Visualization
Using Deneb Robotics Simulation Software
Joe Falco
National Institute of Standards & Technology

The Intelligent Systems Division has developed an error visualization tool for displaying machine tool errors in the form of error vectors based on a set of polynomial equations for a given machine tool. The visualization tool also displays the machine tool and a "ghost" image of the machine tool to depict machine offsets do to the errors. The visualization tool was developed using Deneb Robotics Envision Software (formerly IGRIP and TGRIP). The Envision software plots, within its 3 dimensional environment, both a desired machine tool trajectory based on an NC program and the actual machine tool trajectory as predicted by a set of polynomial equations that model the machine's errors. The software user has the option of specifying an interpolation variable for finer position resolution, and can magnify the resulting error vector representations using a scaling factor. Vector entities are then drawn within the 3-dimensional environment between each trajectory point and the associated error-induced point. The scaled vectors are overlaid on a solid model of the ideally machined part and are color coded, red indicating the that the machines errors resulted in the removal of excess material and green the opposite. In addition to the scaled vector representation of the machine errors, the visualization tool also displays the machine tool during the generation of vectors. Two machines are displayed simultaneously, one being that of the actual machine tool which tracks the error induced NC trajectory, and the second, a transparent "ghost" machine tool which tracks the nominal NC program trajectory. The geometry of the modeled part is not changed based on the machine tool errors nor are the individual machine error components modeled onto the simulated machine tool. We used Deneb software to help us model errors in our machining process. Essentially, what we did was take Alkan Donmez's error model, which was a polynomial, and fed the error models into the Deneb software. This is just a visualization tool, which allowed us to model the Monarch Turning Center. [Slide 6-1 to 6-4]. We show the actual machine tool with the errors introduced, where there is a ghost image of where the nominal part should be. [Slide 6-5 to 6-8]. You can see the ghost image of the desired paths and show the actual path as it occurs, green indicates positive error and red indicates negative error. [Slide 6-9 to 6-11].

DEFORGE: Would you tell people what you are running on as far as the hardware platform.

FALCO: This is a Pentium 120 MHz laptop. We typically use Silicon Graphics and other higher end machines for normal use.

CHANDRASEKHARAN: How are you rendering the ghost image and the true path image?

FALCO: That is all written in the Deneb software. Essentially we have two machines, (1) the nominal, and (2) the machine with the error model, and we display them both at the same time. We had to perform some preprocessing since we are using the laptop for demonstration. On an SGI, the computations are fast. You can vary your resolution for computations, which will also vary the speed in which you obtain your result. We have also created a similar application using "Envision" for our Octahedral Hexapod where we are able to visualize the error characteristics of a five-axis machine.

DEFORGE: One of the things that you might want to explore, if you do any further work, is at each one of those locations you could actually lay out tag points that you are familiar with. Then you could fill the tag point with whatever quantified values you wanted. Then you could query the tag points.

FALCO: I am currently using tag points.

KRULEWICH: Can you model spindle errors? Can you see the surface finish caused by tool marks, does it take into consideration the shape of the tool?

FALCO: That would be a very detailed calculation.

DEFORGE: You might be able to do that if you turn on the material removal option. It depends on how large the errors are. The last meeting we brought out that some of these algorithms and functions of errors can be simulated, but may be computationally intensive. We are at a point in the technology where we in the software business come up against the hardware limitations. If you want to do this simulation at the same time you do material removal, at the same time that you are doing motion planning and things of that nature, what that means is you may be looking at two days of computation. However, if we can take parts of the problem and look at each one separately, the computation is manageable. Turning is simple.

ESTERLING: What you're saying, that with your technology the material removal process is relatively slow. Material removal is where our strength is. We are able to model machine tool errors fairly rapidly.

DONMEZ: An issue that was brought up at the last meeting was whether or not we were going to be concentrating on part only or machine only information or some combination of both. Machine only information could be provided to the maintenance people. If you have error information, you can show the machine behavior.

DEFORGE: From a technology point of view, what I am interested in hearing from this organization is what you think the end users are going to want as far as a visualization tool. The data collection is wonderful. However, how do you expect our software to tap into the data collected? How do you ultimately want to see the data represented? I think visualization is key, because there is so much information available that the guys on the shop floor are not going to look at numbers. However, if we can incorporate those numbers into a picture to show them where areas of concern are on the machine tool, that would be great. How are we going to take that approach? I think it would be nice to map out regions of a work envelope on a machine, which would be of concern. You can then fixture your workpiece within the work volume to maintain a tolerance on a part. That would be a useful tool for those on the shop floor. My other concern is implementation, how often do those zones change? These are answers that I need in order to give our developers a direction to proceed.

Activities at Lawrence Livermore National Laboratory:
Debbie Krulewich
Lawrence Livermore National Laboratory

I brought a couple of viewgraphs, (1) that talks about LLNL and where they are in terms of this workshop, and (2) talks about specific areas of concern that we're facing. I also brought outputs of our data acquisition. We are lucky to have Sam Thompson at this meeting who is the developer of most of the data acquisition of all of our metrology.

We actually don't do a good job of archiving the performance history of our machine tools. [Slide 7-2]. When a machine has a problem, we may partially characterize a machine. If we have a problem five years later with the same machine, we are lucky to find an old folder that someone has; we may find old strip chart recordings. We really don't have a good way of archiving information. I think it would be very useful if we, at Livermore, had a good way of recalling the history of characterization for a particular machine tool. The second goal is related to a project on which I am currently working. When you are error budgeting for a new machine, you need some type of general knowledge about certain errors. I don't have the historical experience. For example, Donaldson has the experience to tell you what types of errors to expect if you put an air-bearing spindle on your machine. There are so many people who measure machine tool errors that it seems like it would be very useful to have a database with error budgeting information. For example, if you had a machine with this type of spindle and this type of pre-load, etc., then here is a range of accuracy that this spindle will provide.

We are doing some work in cutting simulations. I would like to avoid performing experiments to obtain the cutting coefficients, which are dependent on the type of material, type of tool, the rake angle, etc.. Since so many people perform experiments to obtain those coefficients, the repository should contain the results such that experiments don't have to be replicated.

These are my concerns as we discuss the format of saving data vs. the sampled rate. [Slide 7-3]. It is a little confusing to try to figure out whether you are talking about spatial, temporal. When you are taking data point to point, it is hard to figure out what the spatial sampling frequency of the data that you are storing. The way that the data is represented is very dependent upon these things. I was able to sit in on a meeting pertaining to spindles. Analog filtering was a hot topic at that meeting. People have very strong opinions on both sides of whether or not you should filter your spindle data. The data is very different depending on whether or not you filter. How you know what types of preprocessing has been done to the data prior to storage in the repository.

I have brought up sign convention before. If you are trying to compensate or simulate errors, there is a lot of confusion on sign convention; especially if your part is on a moving axis.

What is the distribution of your apparent non-repeatable error terms of your machine.

I wanted to show you outputs from our data acquisition system that Sam Thompson wrote. Basically, this is a spreadsheet and acts as our history chart recorder. The software is fairly user friendly, it gives the user what the ranges are, it prompts the user for comments. This is one output of spindle growth tests.

This is a straightness measurement. [Slide 7-4 to 7-8]. The way Sam has the program written is that it asks the user for important information, for example, the software locates the measurement line based on the user input.

We are taking error measurements, typically taken in free space, where we try to find the actual errors on the part. Rather than taking measurements while the machine is loaded, we are taking the measurements that correspond to the motion of the tool in free space. We are trying to consider the machine process as a nonlinear-type of transfer function in the frequency domain. I am trying to develop an error budgeting tool that predicts the final errors on a part in a continuous spatial frequency sense. [Slide 7-9 to 7-12]. A conventional error budget may, for example, address waviness and surface finish. This continuous error budget will give you continuous amplitude vs. spatial frequency of a part. I'm running into measurement issues. What I need are errors that are characterized in the frequency domain. It is forcing me to take measurements on the fly. The data that I have been collecting is finely spaced. I am also interested in obtaining a probability distribution for the non-repeatable errors. Every time you measure errors, they may not be exactly the same.

I have been trying to work out a positioning error in spatial frequency domain. This data was taken on a lathe. The graph on the upper left is where I took data every 10 micro inches. I took data by hand over two revolutions of the ball screw. Two revs are the large pattern. There is a high frequency error that occurs 1600 times every inch. It was exactly every 320 times per revolution of the ball screw. It was very regular. This machine was being brought into production and I had a chance to look at the way that others took data on this machine. They were doing positioning tests with the values of the position in lookup tables. They took data every 5 mm (1/5 inch), which caused aliasing in the high frequency error. When they input their "corrected points" in the tables, the machine was worse than when they started.

HEMMERLE: Ray, can't you answer the question of what that cyclic feedback is?

KRULEWICH: I would like to know if that is a regular phenomena or is what I measured a fluke.

HEMMERLE: My major error loss in whole producing capability is cyclic error in inductosyns.

KRULEWICH: What is the frequency?

HEMMERLE: It can be pretty high, depending how you look at it. Linearly, if you have a metric feedback system and you are looking at an inch, look at every 3 inches and you'll get 10% of the maximum. That is how I determine the cyclic error on an inch measurement. On the rotary, I use an inclined surface plane, which is automatic.

KRULEWICH: I have an encoder. I didn't have the opportunity to take any time-based measurements. That is the next experiment that I will be performing. What I want to do is trigger off of position.

DONMEZ: Is this a regular type of ball screw with a regular plane-wave error?

KRULEWICH: Yes.

HEMMERLE: You always get a certain amount of ticking, no matter what your increment? High/Low, High/Low?

KRULEWICH: No. I did the test at many different sampling rates and I didn't just see a High/Low pattern. In addition, when I showed this to other colleagues who are interested in vibration data, they concluded that it was not time-based. It is spatial frequency. Because I was not taking data at regular time intervals, but spatial intervals.

SOONS: I had the exact thing happen to me when I was working with a ball screw experiment. I didn't take the standard approach of using randomized sampling intervals. I did use regular sampling and started zooming in, where my sampling got smaller and smaller. I ended up tracing the periodic error of the scale. Yours may be a similar problem.

KRULEWICH: The first two bullets that I raised, where I talk about the conventional error budget, and where the physical error source is identified, I'm thinking that the next step will be to take a Fourier Transform or FFT of the data. The next step will be to transform the errors into the frequency domain then sum them in the frequency domain, but I'd like to talk to you about that more. All of this is for an error budget that doesn't exist. The biggest thing for this work is that I need to get a better feel for classifying error components on machine tools to their corresponding frequency. I have one machine, which I will be fully characterizing, in the frequency domain. This project resulted from another project where we are manufacturing optics, the tolerance specifications on the optics is in the continuous frequency domain, or actually power spectral density, and somehow that relates to the transfer function of the optics. Therefore, the problem is continuous from form error to the high frequency errors. That project along with other projects is driving the need, at least at Livermore, perhaps in other industries as well. One other thing that is interesting is the material removal transfer function is different from the conventional approach. We are just starting to formulate a transfer function to relate the motion of the machine tool, which contains a superposition of sine waves in space, and it's resulting effect on the part. We are trying to work with Northwestern University on this problem. There are certain frequencies that the machine will filter out, which will not appear on the part. On the other hand, if you excite resonances on the machine, then you will see amplified effects on the part.

SOONS: How do you incorporate thermal errors with the power spectral density error budget.

KRULEWICH: There are two parts to that question. The first is the combinatorial rule. At the same time you obtain a conventional error budget, you account for correlated and non-correlated components. It ends up not being a Root Mean Square (RMS) type of position when you talk about adding up sine waves. I make a general assumption that all thermal errors are correlated, and all other errors are not correlated. The second thing is that I treat thermal errors as basically a very low frequency to DC component. So the plot that I showed had some thermal errors seen by the slope of the curve. I plan to remove the slope and then account for the slope using thermal errors in an additive manner.

Calculation of CMM Measurement Uncertainty via the Method of Simulation by Constraints

Dan Sawyer
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Steve Phillips requested that I give this talk in his absence. This is an exciting new concept in Coordinate Measuring Machine (CMM) measurement uncertainty that we've been working on at NIST. I will talk about the calculation of CMM uncertainty and more specifically, I will talk about the new method of CMM uncertainty calculation by use of constraints. Dr. Steve Phillips is the project leader, I've been working on the project for about 3 years, and I will do my best to describe what we have been doing.

First, I'll quickly overview measurement of CMM uncertainty, which may be an introduction to some of you. [Slide 8-2]. The characterization of geometry errors in CMMs has a lot of similarity on how you characterize geometrical errors in 3-axis machine tools. I'll talk about computational approaches to determine CMM measurement uncertainty, then I'll show the method by constraints.

The CMM measures parts [Slide 8-3]. More specifically the CMM determines part features. It may be determining the diameter of the cylinder, or may be inspecting the perpendicularity of the axis. The fundamental output of the CMM is not a feature, but a discrete point. We use a processor to take a collection of discrete points and generate substitute geometry (i.e., a cylinder). Associated with each one of those points, is a measurement error. Ways are not manufactured perfectly flat and we do have associated errors (i.e., angular) that aren't perfectly modeled and compensated. The measurement error is then propagated to the feature-fitting algorithm. Error in this respect is defined as the measured minus the true value. If we knew the true value, we wouldn't need to take any measurements. We have a concept of uncertainty to help express the "true" value.

This slide helps describe the error in the CMM measurement and its uncertainty. [Slide 8-4]. We have a sketch of a 3-D CMM work volume, where the ellipsoidal regions represent the CMM uncertainty. They change in size and orientation as you vary the work volume.

What factors effect the uncertainty in my measurement of features (i.e., a simple circle)? [Slide 8-5]. There are several such as algorithm selection and fitting and extrinsic factors such as contamination and fixturing. I will talk about those as well as part form errors. I will also talk about geometric modeling errors and probing errors, which we have a new model developed at NIST to characterize the systematic behavior of a touch trigger probe, not the analog probe but the TP2 type with a 3-prong, kinematics seat. We have preferential triggering directions. We have a model, which backs out errors associated with the orientation of the probe axes. I will also talk about sampling strategy and its relation to CMM measurement uncertainty. The goal of this project is to determine feature measurement uncertainty through simulation. We use a sampling strategy to propagate the CMM errors into the feature measurement. Sometimes people don't understand the relationship between sampling strategy and measurement uncertainty.

This viewgraph shows a circular feature inspected with three points. [Slide 8-6]. Associated with each of these points is a random radial uncertainty. In this case, the uncertainty is 1 μm. The problem with the vertical axis is the standard deviation of multiple measurements of that circular feature using the same sampling strategy. That is, at 120° (which refer to the angle between 2 and 3 measurement points) we see that the standard deviation of the measured points (I think we measured 100 points) is close to zero. That is, we measured symmetric sampling points around this feature, which resulted in a very small uncertainty of measurement of that radius. The point that I am trying to make is the intended angle of these three points is sufficiently close. The uncertainty is two orders of magnitude greater, 100 μm. The sampling strategy is a very important consideration in terms of our feature measurement uncertainty. We have a good analytical model that describes this behavior at least for three points. Once you increase the number of points, then the model breaks down, since the problem is more complex. I will show you some data that we've taken with multiple probes. People understand this problem but in the real world, simple circles are not the most complex features of interest.

There are often issues with relational measurements. [Slide 8-7]. In this figure, the feature of interest is the total radius, which is the perpendicular distance between the center of the circle defined by this partial arc and the axis of the bore. We can't sample the full range of the bore. The challenge is how to assign uncertainty to the radius. There is uncertainty in measured points, uncertainty in the substitute geometry due to the fitting, uncertainty associated with the axis and with the location of the center of the tool. There are two primary approaches to assigning uncertainty, or assessing the machine performance in these types of measurements. The first is to create a master part, which means every time I modify a part, I have to generate a master part. I have to gauge with another method that completely characterizes that part. I then measure that part on the CMM and know its geometry perfectly. In the real world, we measure the parts as they come off of the assembly line and to have to check the assembled part against a master part, that is extremely expensive and impractical. It is done in practice and perfectly viable, but not the best solution.

Another approach that is being used, is to simulate the measurement process. [Slide 8-8]. The goal of simulation is to capture task-specific measurement uncertainty from non-task-specific data. What is meant by task specific measurement is that we want to calculate the measurement uncertainty given the sampling strategy. I'm not trying to optimize anything. If the CMM operator wants to inspect four specific points, what is the most accurate result to expect from a specific machine? We don't want to measure a part with a sampling strategy that is associated with a high measurement uncertainty. There are apparently two approaches to this technique. The first is used by PTB (Physikalisch Technische Bundesanstalt) , and that is to fully characterize the primary source of errors, geometric errors, for a 21-degree of freedom model. [Slide 8-9]. PTB measures each of the 21 error parameters, then fit functions to the data and they use the kinematics equations that they derive from their sampled data to propagate errors into their measurement. The rigid body model then serves to characterize the machine. They use the kinematics equations and the sampling strategy to determine the part measurement error. The problem with this method is that there is an uncertainty with the determination with those errors. We can't measure those errors perfectly. PTB realizes that the errors aren't measured perfectly, so they slightly perturb the functions with some specified method. They have a criteria by which they perturb the functions. Then they measure a different kinematics state and generate a new set of errors. They perform this process several times to obtain errors for different kinematics states. The standard deviation of the part errors gives a measure of the feature measurement uncertainty. The perturbation analysis results a space of possible measurement errors, where they obtain a statistically significant number of samples to obtain the measurement standard deviation. This process is perfectly valid. We performed this process at NIST when a gentleman from PTB visited and worked with Bruce Borchard, a colleague from NIST. They performed measurements on an artifact for three days where they wrote a part program, measured 12 different positions of the CMM and several different probe offsets, and were able to back out a particular set of error metrics that described the geometric errors of the machine. This is a perfectly valid approach.

The second approach is what I am here to present to you, the simulation by constraint algorithm. [Slide 8-10]. What we are using is incomplete information. We look at performance evaluation data from a standard (i.e., ASME B89) and try to determine a possible population of kinematics states. The kinematics states that we generate may have completely different values for parametric errors. All of them, when used in simulation, reproduce the performance evaluation data, where the performance numbers in the simulation bound them and we discard any kinematics states that the machine cannot occupy. We obtain the performance numbers from ASME B89, "The Method of Performance Evaluation of Coordinate Measuring Machines". [Slide 8-11]. To implement this method on machine tools, you might use the ASME B5.54. The particular numbers that we use are repeatability, linear displacement accuracy and the volumetric performance. These six numbers, collectively, are sensitive to every possible geometric error. That is, if you think about the parametric model for a simple CMM, then assign the Z-axis to be the ram axis. If you measure every part with the vertical ram then you are insensitive to Z-axis roll; you never see any effects from Z-axis roll in any of your measurements. If you were to calculate these parametric states, you would be unable to confine the Z-axis roll terms. I will explain the model in further detail to illustrate my point. We use the B89 performance data to calculate the population of possible machine states. These machine states have a widely varying possibility of parametric functions. However, when we use each one of these machine states in simulation to produce tests, we get the performance data for all possible machine states. If I don't have the information to fully characterize the machine, then this is a valid approach to discard the states that are not possible. We then take each possible state, and we measure our part given a sampling strategy, which gives us a population of measurement uncertainty (standard deviation).

The interface for this approach looks like the following. [Slide 8-12]. Dr. Phillips developed the model for this method while in parallel we have had ICAMP Company work on the interface with the model. This interface doesn't have the full functionality of the model, but this will give you an idea of what it looks like. Part geometry, you can select a feature of interest (i.e., a circle or cylinder). The number of simulations is the number of virtual states that you want to calculate. You can then determine where significant changes are occurring in the measurement error. With the inspection process, you specify your sampling strategy, (i.e., position and orientation of probed points on the part). The inspection machine, you specify performance specifications, which are sensitive to all the geometrical errors. When you run the simulation for a best-fit circle, you end up with a standard deviation, σ, of the measured radius. The uncertainty, U, is 2σ. The interface is still under development, in particular, we are still developing the inspection plan. The process of inputting points is very difficult, where you have to specify the points (parameter space) by the percentage of your feature of interest. For example, if you want to measure 180° of an arc, and then specify the measurement of one line at 0 to 50%. These are the types of issues we are working on with the interface to the model.

After the model simulation was running, we decided to test the robustness of the model with a simple measurement. [Slide 8-13]. We decided to investigate point to point measurements of a step gauge in the work volume. We measured a step gauge at several different positions in the work volume (i.e., horizontal, high horizontal, low horizontal, face diagonals, etc.) and looked at the CMM measurement error and made an uncertainty prediction based on the numbers that I showed earlier. This is the result of that test, which is a little complicated. [Slide 8-14]. This is the result of one measured length of 1000 mm. I believe we measured five total. Plotted on the vertical axis is the measurement uncertainty. The calibrated gauge is actually the measurement error, where we know the true value. The black line represents three measurements of the step gauge in several different positions, I believe we measured a total of 43 positions. What is shown is vertical offset probe, *u* and *i* position as specified by the standard. What is important is the red line, which is our uncertainty prediction. Our uncertainty prediction was arrived at by simply looking at the manufacturer specification, six numbers (i.e., linear displacement errors in X, Y, and Z and other metric performance) which gives you a simplified measure of geometric errors of the machine. This comes from the range of measured deviations from ballbar measurements, 21 positions in the CMM work zone. We also include the offset probe, which needs to be included since the form of the parametric errors is being estimated. This approach gives you a minimal effort uncertainty measure. You can represent the area that has small measured errors.

We also decided that most users aren't interested in point to point measurements but want feature measurements. We used an aluminum, diamond-turned plug gauge, which was made by Chris Evans at NIST. [Slide 8-15]. It is ground to a few tenths of a micrometer, which is perfect for this experiment. We measured the plug gauge using 12 symmetrically spaced points and measured it 36 times. [Slide 8-16]. Then we changed the sampling strategy. We still used 12 symmetrically spaced points, but measured only ½ of the circle. [Slide 8-17]. Each time we measured the plug radius, we incremented the points 10°. After 36 measurements, we completed the entire circle. This is a graph of the plug radius. [Slide 8-18]. Plotted along the vertical axis is the measured radius. Where you see the 360, 180, and 90, that is the angular portion of the circle that was measured in that experiment. The first interval was 360 ° using 36 measurements. What is shown in this blue area in the measured data is a complex structure. It isn't obvious to expect this cyclical behavior, which has a lot to do with the asymmetry of the axis of the machine. The red line (plot envelope) represents uncertainty calculation. We are satisfied with this result.

We looked at the X and Y symmetries, this is the change in nominal position of the X-center as a function of the sampling strategy. Because the uncertainties were on the same order, we expected to see a symmetric behavior and to get the same behavior in the Y-center uncertainty that we saw in the X-center, but that wasn't the case. [Slide 8-19]. It had to do with the fact that in our machine, the X-axis stacked on top of the Y-axis, so there is an asymmetry in the kinematics chain. There is more variability in the X measurement.

Summarizing, we are happy with the results we obtained from the simulation by constraints. We believe that it is adaptable to many different applications. You have a set of performance data that is sensitive to all possible errors, not necessarily just geometrical errors and may not all be characterized. For a full parametric simulation, the PTB approach is the limiting case of simulation by constraints. The PTB approach is very time intensive and yields a very small uncertainty. Our method yields results very quickly and the uncertainty is larger, however simulation by constraints is better than a blind guess.

KRULEWICH: How many times do you simulate your error bounds? In the PTB simulation, what type of probability density function was assumed, normal, uniform?

SAWYER: Two hundred machine states are calculated per simulation. We have never gotten a definitive answer from PTB, so we don't know what method they use to perturb their functions. He also uses an algorithm that limits the number of simulations and still obtains a statistically significant result.

DONMEZ: How did you determine that you needed 200 machine states per simulation?

SAWYER: Dr. Phillips determined that he wasn't seeing significant changes after he reached a threshold of 200 machine states, given the order of magnitude of errors on our machine.

DONMEZ: Then from one machine to another it might take a different number of simulations.

SAWYER: Yes. It only takes a few minutes to run a simulation.

DONMEZ: As you can see, there are areas to think about for machine tool aspects. The principle itself sounds very interesting because you start with a very limited number of measurements and then calculate uncertainties. In our case, we can think about starting with small amounts of data and then determine what the Cpk numbers might be based upon using a similar type of analysis.

Machine Tool Classification

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We heard in Vivek Chandrasekharan's presentation that Caterpillar is using NIST's Machine Tool Classification for the description of machine nominal conditions. That work has been done in another division at NIST by Kevin Jurrens and Mary Beth Algeo. Unfortunately, Kevin could not be here to present their work, but he gave me his slides. In the short time frame that we have, I will very quickly show you the Machine Classification web site.

Kevin's project was called Rapid Response Manufacturing, which means that they generate information models of different aspects of manufacturing, some of which are listed in this slide. They have CAD data, process planning data, CAM data, and they list many types of resources such as machine tools, cutting tools, tool holders, collets, and assemblies. They have started to develop information models for all of these resources and ways to combine those resources in electronic formats to be able to make decisions (i.e., process planning, CAD/CAM operations, etc.). I'm really only interested in the machine tool portion.

The web page that describes this work is at address http://www.nist.gov/rrm. It describes the manufacturing resource data interface. If you have any of the resources, such as machine tool, tool assembly, cutting tool, etc., then you can develop this information by stepping through the standard definitions that they have created. When I choose machine tool, I am given some options. Kevin emphasized that this has not been reviewed by industry, so this is in raw form and there will be changes in these types of definitions. We are given alternatives such as milling machines, vertical-turning machine, and horizontal turning machine. If I pick milling machine, then it will ask specific questions about the product. It asks how many axes does the milling machine have, where the default value is three. It also asks how many parallel spindles does the machine have, how many separate worktables does it have, etc.. When you answer all of these questions, then you are basically defining your machine tool. You should be able to categorize the nominal functions of your machine and be able to electronically store this information. In the last meeting, we discussed how to describe the machine controller. There is a set of parameters about the machine controller. What we will do for the NAMT program is extract the relevant aspects of the Rapid Response Manufacturing project and incorporate them in the machine tool data repository, similar to what Vivek presented.

Data Dictionary
Hans Soons
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I would like to give an update on our work on an information model and data dictionary that defines information elements that can be used to communicate and store performance data of machine tools. First I will classify machine tool performance data, then discuss the data we are currently modeling. I will explain the chosen approach to information modeling and the structure and content of a prototype data dictionary. I will conclude this presentation with an example. There is still a lot of work to be done. However, I hope that this presentation will give you an impression of the goals, methods, and challenges. Obviously this cannot be an isolated effort and we would welcome a discussion as to whether this part of the project addresses your needs, if the chosen approach is right, and how we can increase your participation.

The goal of this NAMT project are (1) information models to represent, communicate, and store machine tool performance data, and (2) tools to improve the use of that data. One such tools is a virtual machine, i.e., an algorithm that predicts the output of a machining process by simulating the actions of the machine tool in response to a part program and the machining environment. [Slide 9-2]. Virtual machining promises to significantly reduce the time and effort spent on prototyping and debugging the manufacturing process. It will lead to more optimized part designs, process plans, and resource allocation. The outputs of a virtual machine in which we are particularly interested are the tolerances within which the actual geometry of the part will be.

A critical enabler for virtual machining is an efficient access to relevant data on: the design of the part to be machined, the process plan, the machine tools that will be used, tools and fixturing, and the machine tool environment. [Slide 9-3]. Machine tool data can be divided into two categories. First, data that applies to all machines of a series. Usually this is design data published by the machine tool builder, for example, maximum spindle speed, spindle power, number of axes, travels, minimum programming increment, available canned cycles, etc. The second category of data applies to a specific machine tool. An important part of that data is the result of machine tool performance tests. I will focus on that part.

We envision a layered approach in the representation and storage of machine tool performance data. [Slide 9-4]. At the bottom level, which is in red, there is detailed information about the performance tests and the equipment that was used. At the top level, there is summarized data such as B5 performance parameters or the estimated coefficients of error models.

As an example consider the shown performance test taken from the draft B5.57 standard. This test addresses the straightness of the Z-axis motion of a vertical lathe as well as the parallelism of the spindle axis with the Z-axis. A straight edge, colored purple, is mounted on the spindle. First the probe is mounted on the left side of the spindle and the straightness of the Z-motion is measured. Next the spindle is rotated 180 degrees. The measurement surface of the straight edge is now on the right hand side. The probe is re-clamped across the center and the same straightness measurement is performed. There are now two sets of straightness measurements. Because of the straight edge reversal, the straightness of the Z-axis motion can be accurately measured even if the straight edge is not straight. The difference between the slope of the two measurements can be used to calculate the parallelism error between the Z-axis motion and the spindle axis.

The lowest layer contains detailed data about the experiment such as: the two measured signals (or more if temperature and other factors are recorded), information about the measurement equipment that was used, including serial numbers and settings, the measurement setup, the effective tool length, information about the machine status such as the warm-up and exercise procedures, and finally data about the environment. At a higher layer there is data that is extracted from this detailed data. In this example, that would be the parallelism error, and straightness error data organized into a column with Z-axis positions and a column with straightness errors. The relevant machine status would be, for example, the length of the tool and the position of the machine axes at the first point of measurement. At higher levels, you might find the parameters of a piecewise polynomial fit through the data, or B5 performance numbers, such as one number for straightness accuracy and one number for straightness repeatability. At higher levels you will also find data extracted from a combination of tests, such as the coefficients of the full error model of a machine. During this presentation, I would like to address the most challenging data: those in the lowest layer.

During the first step of the information modeling process we use a tool called a data dictionary [Slide 9-5]. The purpose of this tool is to provide the names, definitions, and relations of the data elements that can be retrieved from a database of machine tool performance data. It does not have the formalism of an EXPRESS model but we think it can be translated into one. The focus of the data dictionary differs from the classical data dictionary, which addresses the structure of a database. The dictionary discussed here tries to define the information that can be retrieved from and stored into a database, not how this information is stored internally. On the right hand side of the slide you see an illustration of this concept, which will be actually demonstrated during the next presentation. A user asks a question about a machine. Analysis software, before, after, or on both sides of the Internet, processes the question and may decide that machine tool data is needed to generate an answer. The software formulates a query to the database, the data is retrieved, processed by the analysis software, and an answer is returned. What we would like to address is the interface between the analysis software and the database.

There are two different approaches to data modeling. The first is a top down approach. It tries to anticipate the queries that will be made of the database. The second is bottom up. It tries to assess which information elements fully describe a particular performance evaluation test, without trying to predict the possible use of that data. Our focus is on the latter approach. Analysis of performance evaluation data is an evolving field. Applications for machine tool performance data are being developed that were not anticipated five years ago. Therefore we try to develop the data dictionary in such a way that captures the intrinsic information of a test without linking it to the possible use of the test results.

There exists a variety of software packages for the performance evaluation of machine tools. [Slide 9-6]. Many of these are made by the manufacturer of a measurement device, such as a ball bar, and tailored to that particular instrument. Why can't we store and communicate performance data using the file formats employed by these packages? First, different data models and formats are used even for similar measurement instruments and tests. Second, sometimes the formats are proprietary and the data may be hidden in a binary file whose content can only be retrieved by the software in a form dictated by the software. Third, most formats are tailored towards a specific type of performance test and may not be adequate for tests not found in the standards, or recently standardized tests. Finally, and most important, not all the data relevant to a particular test is stored. Usually the stored data is limited to the information required to produce the graphs and performance parameters specified in current machine tool standards. For example, the effective tool offset or location of the test in the machine workspace is rarely stored. Such information is essential for error modeling purposes and to combine or compare the results of different tests. In practice this information is often lost or entered in notebooks with a life different from the data files.

Our goals are a unified information model and associated data format that will allow a straightforward interchange and storage of all relevant information about a test. It should allow for the reconstruction of the nature of the test, who did it, when it was done, and why. [Slide 9-7]. The used equipment and respective settings should be identified. We hope to be able to reconstruct essential information about the setup, measurement procedure, machine status, machine motion, and environmental conditions.

We will focus on standardized tests, but we hope that the developed data dictionary and associated information models can also be used for special tests. The models should not enforce the storage of all information, but provide standardized possibilities to do so. The modeled information has to encompass the information currently stored by the major data acquisition packages (e.g., Renishaw, API, HP, Heidenhain, etc.). It should allow for an efficient handling of queries and will be translated into an EXPRESS model.

This slide gives an indication of the information elements that can be used to describe test equipment. [Slide 9-8]. Examples are the manufacturer of the equipment, the model number, the ID number, the settings of the equipment during the test, the type of compensations that were applied, how many samples were averaged, the applied filters etc. The software that was used with the equipment should be known including its version number. If artifacts are used, their important properties, such as the effective coefficient of expansion, have to be stored.

I would like to stress that the data dictionary is still being developed and that your participation in this process is crucial. The dictionary consists of two parts [Slide 9-11]. The first part is a master list of entities that you can use to describe the performance test. The second part is essentially a user guide. Given the nature of the test, e.g., a circular contouring tests involving two machine axes and using a ballbar whose length is unknown, it provides a list with the entities that can be used to describe that test.

There are currently two Web pages at the NIST site: one pertaining to workshops and associated documents and another to the experimental data repository that Larry will talk about next. On the first web page you see a link to the data dictionary. If you click on this, a database with the current master list of attributes will be downloaded to your computer. You can only read the file if you have MS Access 97. We will be working on a web page that does not depend on Access.

On this slide you see the most important form of this database. You can interpret it as an index card with the definition and possible specifications of an entity. In this particular example you see the entity approach_direction. It can be specified in two ways. The first specification, indicated by the identification number 1, is an enumeration. This specification is used when the test involves an ordered succession of target points, e.g., the positioning accuracy test of an axis. The first enumeration item describes the case where all target points are approached from a negative direction. The second enumeration item describes the case where each target point is approached in two directions, first negative and then positive, before proceeding to the next target point. Each enumeration item has its own form with the appropriate definition. The second specification specifies the approach direction as a vector in the machine axis space. As stated, this list of entities is under development and changing. For easy interpretation you need the graphical schemas that are being developed in the second part of the data dictionary.

For the second part of the data dictionary we are developing a tree structure. It will provide a list of the relevant entities given the properties of the test and the used equipment. The challenge that we are encountering is a large variety of tests for machine tools as well as measurement equipment used for those tests. I have tried to give an impression of this variety for the case of a circular contouring test. In this diagram a vertical line connects the properties that apply [Slide 9-11]. Diagonal lines are branches and are used to indicate the different instances for a particular property.

A circular contouring test can be performed using a ball bar, a circular disk, or a grid-plate. A circular disk is a circular reference artifact. A 2-D probe is used to measure errors in the circular path of the tool holder relative to the disk. The grid-plate was introduced a few years ago. It is a 2D scale that is used to measure the position of the tool holder in two dimensions. The nature of the measurement data obtained during the test depends on the type of measurement device. The ball bar measures changes in the radius of the circular path. It is implied that the contouring speed is constant. Thus one can deduce the angular position of the ball bar from the sequence number of a measured value. A grid plate measures the X and Y coordinates of the tool holder. These can be translated into an angle and a radius.

A circular test can be performed either statically or dynamically. During the static test the machine is moved to a target point, the machine motion is halted, a measurement is taken, and the machine is moved to the next target point. During the dynamic test measurements are taken when the machine is moving. This mode is used most often. Different properties are applicable to static and dynamic tests. For example, during a static test a reported measurement value may be the average of a certain number of samples. Also the properties of the used trigger to initiate sampling differ and may be important.

The machine motion for the dynamic test can be programmed in two different ways. When G02 or G03 codes are applied the circular interpolation capability of the machine is used to generate circular motion. As suggested in e.g. the recent ASME B5.57 standard for lathes, you can also perform the dynamic test using a large number of small linear movements, i.e. a part program with G01 codes. This can provide insight into the controller's capability to handle high data densities (e.g., to see whether data starvation occurs and its effect). A different set of parameters applies to describe a test with G01 or G02/G03 codes.

If we limit our further discussion to ball bar measurements there are several options to consider. First, the ball bar can have an uncalibrated length (you don't know what its true length is), a calibrated length (you know the absolute length), or its length can be determined using a so-called calibrator. A calibrator is a reference artifact that incorporates one or more known lengths. Placing the ball bar into this reference allows the software to compute its true length. Again the applicable entities differ. For example, in the case of a calibrator, the ID number of the reference artifact might be important.

A second option to consider is the method used to align the center of the ball bar. Often a kinematic alignment is used. Here the tool is moved to the center of the circular path. The position of the center sphere is then adjusted such that it contacts the tool socket in a kinematically well-defined way. Other alignment techniques are available. The B5.54 standard describes the quadrant method. Here the ball bar is successively placed along the coordinate directions. The center of the circular path is adjusted such that the average of the ball bar readings equals zero. Another alternative is to use the machine probe to assess the coordinates of the center sphere.

Third, the ballbar can be in the plane of the circular path or it can be inclined relative to this plane. Finally, if the machine has one or more rotary axes, a variety of tests are possible that involves movement of these axes. Examples of such tests can be found in the Appendix of the B5.54 standard. If the machine has a rotary table, the table can rotate during the test such that the table socket chases the tool socket. The entities that describe this test are obviously different from the classical circular contouring test that involves movement of only two linear machine axes.

I hope that this diagram gives you an impression of the challenge that we are facing in trying to define information models for the large variety of performance evaluation tests and measurement equipment, even if we limit ourselves to those that are described in the standards.

I would like to conclude this presentation with an example: the measurement of the positioning accuracy of a linear axis using a laser interferometer. [Slide 9-13]. In the next slides I will show the relevant entities and their relations. Note that the various groups do not necessarily correspond to tables in a database. Our focus is on what information can be extracted from a database, not how it is organized internally.

The first entity contains general information about the test. It helps you to quickly identify what the test was about. In this case the test addresses a single axis, the Z-axis. The test was performed as part of a machine acceptance procedure. The default unit system is metric. In the data dictionary you can see that this implies that, for example, temperatures are always in degrees C unless otherwise specified. Units are challenging, and their use in the data dictionary still needs refinement.

The next entity contains information about the standard that describes the test. Like many entities it has a unique identification number which can be used to refer to it. The standards entity contains information about the standards organization, the number and name of the standard, the name of the test in the standard, the respective section number, as well as the date when the standard was published. In a database an entity like this would probably be organized into two or more tables, e.g., one table with standards and another table with various sections of standards with pointers to the previous table.

The next entities contain information about the machine, the operator, and the machine status during the test. [Slide 9-14]. For example, the C-axis, which is the spindle axis, was clamped during the test, the software compensation of the machine was active, and the coolant was off. The machine was warmed-up by turning on the servos for two hours prior to measurement. Of course here we have to compromise between ease-of-use and level of detail. Coolant, for example, can be applied in many different ways. Currently we have only implemented an on/off state.

Next you see information about the data acquisition software. [Slide 9-15]. The manufacturer_ID entry is a unique identification number that points to more extensive information about the manufacturer, such as address and contacts. The trigger entity contains information about the mechanism used to trigger a measurement. In this case the software looks at the laser reading. When the reading is close to the target value it waits for a specified amount of time and takes a measurement. This mode is indicated by the trigger_target value for the trigger_mode entity. The target_window entity is the width of the zone centered on the target within which the signal has to be for a specified time before measurement is triggered. The respective delay is specified by the trigger_dwell entity. The identification number of the sensor that is being used as a trigger is denoted as SE_1. Later we will see that this sensor is a laser interferometer in distance mode.

On this slide you see some sensor definitions. [Slide 9-16]. The first sensor measures air pressure. We will see that this sensor is used to compensate the laser interferometer reading. The next sensor is used to measure the temperature of the machine scale. This sensor will also be used to adjust the reading of the laser interferometer to compensate for the thermal expansion of the scale. The sensor is indeed a temperature sensor, it measures temperature by sensing changes in resistance, its resolution is 0.01 degrees C, and it is located near the Z-scale of the machine. There is still some work to be done on how to specify the location of sensors. Note that the sensor entity contains an entry for the identification number of the readout, which points to more information about that readout.

This main sensor is of course the laser interferometer itself. [Slide 9-17]. The measurand is displacement. The sample average entry is 20, which means that each recorded measurement value equals the average of 20 samples. These samples are measured with a frequency of 10 Hz. The sensor is connected to the same readout as the previous sensors. The sensor uses a trigger that we have already defined. The sensor_direction entry indicates that a positive measurement value equals the displacement of the target when the machine moves in positive Z-direction. The target, the retro-reflector, is connected to the second turret of the machine. The reference, the interferometer, is connected to the spindle axis. The sensor_datum_when entry indicates when the sensor datumed. In this case the sensor is datumed at the beginning of the first run as opposed to at the beginning of each run. An important entry is the effective tool vector that describes the position of the retro reflector. The effective tool vector, together with the position of the machine axes, defines the position of the measurement line, as discussed this morning in the LLNL presentation. A laser interferometer usually does not record the raw measurement values. The measurements have been compensated in some way. In this case they have been compensated for the velocity of light in air and the thermal expansion of the machine scale. The used sensors for air pressure, air humidity, air temperature, and material temperature are indicated, as is the used coefficient of thermal expansion. The compensation did not address the dead path length of the setup.

The next entry defines how the machine moved during the measurements. [Slide 9-17]. The measurements are performed in a static mode, i.e., the machine motion stops before a measurement value is taken. In between target points the machine has a programmed feed rate of 2000 mm/min. The targets are on a line parallel to the Z-axis of the machine. When the machine axes are at the coordinates indicated by the target_line_start entry the target is at the start point of the measurement line. The individual target points are specified as a table of target numbers and distances relative to the start point. In order to avoid the aliasing effect that we saw this morning, the targets are located at random positions along the Z-axis.

Now that we have defined the purpose of the test, the used machine tool standard, the machine, the status of the machine, the various sensors, readouts and triggers, we can finally specify the measurement data. [Slide 9-19]. The data is organized into runs. The approach direction for the first run is indicated as pilgrim_positive. As discussed this implies that each target point is approached in two directions, first positive and then negative, before proceeding to the next target point. Next, we see a table with measurement data as well as entries that define how this table is organized. Finally there are entries that summarize sensor data taken during the run, in this case the maximum, minimum, and average temperatures measured by three sensors.

This concludes the example. You can find the terms that I used in this example in the data dictionary. I hope that this example and the rest of the presentation gave you an impression of complexity of the information that we are trying to model as well as the chosen approach. I'd like to open up for discussion. [Slide 9-23].

KATTER: Why did you use the key word approach_pilgrim_positive instead of just "positive" for your approach direction?

SOONS: This is an enumeration item that we defined to have a certain meaning. It is one of the four options of the approach direction entity. It implies that each target point is approached in two directions, first positive and then negative, before proceeding to the next target point. Use of this entry avoids the indication of the approach direction for each individual target point. However, the data dictionary does provide means to specify the approach direction for each target point by placing in the data table a "+" for positive approach direction and "–" for negative approach direction.

WELSCH: What tends to happen in systems discussions, is that terms get longer as you add more adjectives and definitions get longer as you add more specifics. The adjectives allow for concise definitions of key words. In a regular dictionary you may have several definitions for one word, we want one definition for each key word.

SOONS: At this stage we have not yet spend much time on a systematic and more optimized naming scheme for items in the dictionary.

CHANDRASEKHARAN: Is this schema what the EXPRESS language outputs?

DONMEZ: The EXPRESS models are being worked on, but aren't presented today.

SOONS: This slide shows other topics about which we would like some feedback. [Slide 9-23]. One item is the focus of our effort, especially if the presented level of detail is desired. As I said before, we are making our life difficult in trying to model the lowest tier of data. It requires a lot of detail when trying to capture everything that occurred during a performance evaluation test. Perhaps we should concentrate on higher levels. For example, in case of a circular contouring measurement, the main data is a table with angle versus error. Another area of discussion is whether to tie the data dictionary closer to the design of a database. It probably would ease the information modeling and make the dictionary easier to apply. On the other hand, we may also want to link the definitions more closely to existing file formats. Another item is whether we should restrict ourselves to the performance tests and measurement equipment described in existing standards or if we should also try to capture more exotic tests and instruments. We would also like some feedback on the approach that you are taking to information modeling of performance data. We would appreciate comments about the organization of the items in the data dictionary. Finally we would like to discuss how to increase participation and when.

COVINGTON: I think that we should stick to standardized tests. I think that we need to draw a line somewhere, because there are too many tests out there to try and capture all of them.

SOONS: To follow up on that, in the current B5.54 standard for machining centers there are some unusual tests in the appendix. Would you say leave out the tests in the appendix as well?

COVINGTON: I would say incorporate the standard tests first, then the tests in the appendix.

SOONS: I did get the opportunity to visit a Boeing plant where I saw that they were using one of the ball bar tests, outlined in the appendix, which involves a rotary table. Are you currently including that test in your database?

COVINGTON: Yes.

KRULEWICH: Are you defining a database, or just a standard language that someone else can use to develop the database.

SOONS: I believe there is more than one application. What I showed you here, basically at the interface between database and application, can be interpreted as a language or data format. On the other hand, we are also trying to use the definitions to develop a database by translating the dictionary into an EXPRESS schema. We are experimenting with a prototype repository, which Larry will show you. However, the first step is to catalog the information involved. That is the main goal.

KRULEWICH: I don't have much experience with databases, so if Boeing performed some specialized tests, how difficult would it be to add one more test to the repository?

WELSCH: It would be nice if the repository were extensible.

KRULEWICH: So the user can add one more tests to the repository.

COVINGTON: I think we should start small and get a functional repository and then expand to other tests in the future.

SOONS: One of the reasons that this data dictionary has more complex definitions is because of the extensibility. We want to use a few words to describe a large variety of tests and equipment.

COVINGTON: Could you explain EXPRESS in more detail?

SOONS: I am not an expert in this area. Has anyone successfully used data modeling tools in this area? One of the challenges that we have encountered is the large variety of properties that are not mutually exclusive, which makes the tree very wide.

CHANDRASEKHARAN: We downloaded the database and found that it works O.K. The second thing is that the road map should define the level of detail that you want to get to. One thing that we would like is the capability to download data from the repository for our specific applications. Right now we only have the capability to upload data. Until we have application tools that will enable us to manipulate data, we need to stay closer to existing file formats so that we can continue to use the existing software packages (i.e., Renishaw, API, etc.) for data analysis.

DONMEZ: Do you think people on the shop floor can provide data in the level of detail that we've talked about here?

COVINGTON: I looked at the list and saw that it was very comprehensive and well done. But no, the shop floor can't provide that level of detail. What we try to do is to keep a log file where all the parameters are provided for tests that have been pre-defined. The user can change certain parameters for a specific test, but doesn't have to enter redundant information every time.

CHANDRASEKHARAN: Same with our shop tests. All data gets loaded in automatically, but the user will change certain fields such as when the last calibration was performed, etc.. The problem is that this procedure may vary from shop to shop.

DONMEZ: Could we collect from Boeing and Caterpillar the log files that you keep for your internal use to give us a better idea of what information you are looking to store in the repository?

CHANDRASEKHARAN: We can help you develop the templates, but we'll have to work towards sharing the templates at least within the CRADA.

DONMEZ: It seems like most of the information is generic and there shouldn't be too much proprietary information.

DAHILIG: Back to the question on whether or not we should be linked closer to the database design. It seems the attributes of the tests and the machine data are specific data. Each company will have different uses for the data and have their own tests with their own set of attributes. I think that we should concentrate on creating a database that is generic/standard (i.e., for the ball bar), but where each company will have their own unique fields to add.

HEMMERLE: In your data, when you for example perform Z-axis laser measurements, is that as you find the machine, compensations not active, or after you compensate the data?

SOONS: Under the entities for machine status, you will find an entity that states whether the compensation was ON or OFF. It doesn't say what types of compensations were active, though. It is your choice.

HEMMERLE: On our machines, we keep track of the raw data and the compensated data.

SOONS: Some people may want to keep track of which compensations were active, and the details of the compensation. Do we want to go into more detail than ON or OFF?

DONMEZ: With ON or OFF representation, could we capture, say, 90% of the data? When the machine starts with some exotic type of compensation, then maybe we want to note that. We have to keep our scope somewhat limited so that we can produce a repository in a reasonable time frame.

COVINGTON: We need to get something useful in a short time frame, say 1-2 year time frame. We are running into funding issues and have to show some progress to our management.

DAHILIG: As part of the project plan, while we are sharing information with this group, we would like to see a standard repository with analysis tools. Our management is looking for a return on their investment.

COVINGTON: We could put more people on this project and have greater visibility. We could try and have a link to the MCDRS site.

KRULEWICH: Is your database functioning on the web?

WELSCH: Not at this time. We are still in the experimental stage. The repository is not fully implemented at this time.

Data Repository
Larry Welsch
National Institute of Standards & Technology

This presentation is made from more of a programming perspective than from a machine tool perspective. I'm doing this presentation, but Hans has probably done more work on this repository than I have. Neil Wilkin from NIST is key to the pages incorporated in the repository.

I want to present a framework for talking about issues. [Slide 10-2]. I will present where we were at the last workshop, where we are today, and where I want to be tomorrow (Jan.-Feb. where we will achieve more stability where data will be more maintained than it is now). I will also talk about where I want to be the day after tomorrow, I'm not sure of the time frame here. There are certain things that we are encountering, i.e., firewalls, that tend to blur the vision.

When I speak about platform, I'm speaking about the operating environment: hardware, software, and the things that I expect to have on the machine. [Slide 10-3]. CGI scripting tools: CGI is the common gateway interface, which is mostly performed at the back end of the Web server. CGI is the way you get to the back end of the Web server, and there is a set of scripting tools for doing that. Analysis tools give us the graphs, and Hans mentioned this in his presentation, where he was saying that the query goes into the database through analysis tools, but we also will go through analysis tools coming back the other way.

When I started with the repository, I was running on a fairly small system with small disks and was running on Netscape fastback server under Windows NT, Pentium 200, with slow disk access. [Slide 10-4]. Everything was fairly portable to/from NT to UNIX and we could use a common set of tools. The exception there in terms of portability, is related in the file name extensions. This is a UNIX shell or user interface dating back to the days when terminals were ASCII and we didn't have graphics, called the Korn shell (Kshell). We are also using, fairly extensively, the Perl language, which is the new language for managing text, where text is both coming into and flowing out of the repository. This is the language of choice for the back end. Analysis is being done with MATLAB. We were doing stream search linearly through all the files in the repository, which was very slow. The design was what I would call a classic web methodology with one exception of the MATLAB performing analysis. The big change in the platform is that we went to high-speed disks that have a tremendous impact on performance. [Slide 10-5]. We also moved to a dual processor system, and are not running NT server. We have also moved from the Netscape FastTrack server, to the Enterprise server. That is the environment in which the database is incorporated.

Portability Today. We are now limited to the NT platform because of DDE, dynamic data exchange, which we are using very heavily. This is a Microsoft method of exchanging data, which we are using to communicate from the web to MATLAB. MATLAB is used in the analysis, but also is currently used as the database. Basically, the database is just a bunch of vectors that get loaded into MATLAB, messaged, and then displayed on the Web in the form of a graph. This is faster than the method we were using, but will not be used in the next stage. The user interface will talk to Perl, Kshell, CGI, MATLAB, and then the data comes back through MATLAB for calculation. MATLAB is the central engine.

We will go through the demo at this time at the NIST Machine Tool Data Repository site. We will go to the machining centers page, go to vertical machining, machine A, then submit data. We have a table of possible tests for machine tool performance, but there are only two operations that are functional. When we submit data, we are submitting a call to MATLAB, which is generating a page dynamically. This is a form that is generated each time by MATLAB. When you submit data, no matter what name you input for the machine, the software will encode this name. For example, if there are currently Machine 1, Machine 2, ..., Machine 8, then the next machine you input, if not matching the current machines will be encoded as Machine 9. If you resubmit data for that machine, you have to use the name Machine 9. After the data is submitted, the data first encounters a Kshell script (Perl couldn't handle all of the data in the initial design), messaged by Kshell, then messaged by Perl, then encounters MATLAB which incorporates the new file into the database and generates the form stating that it the file has been incorporated into the database. Now we will return to the machining centers page go to vertical machining, machine A and go to the analysis side. The analysis graph is generated dynamically.

SOONS: We have one sample database in MATLAB format, which contains the Renishaw header information: operator, machine, etc., the data is stored in ASCII files.

Tomorrow: I don't expect the platform to undergo any changes. [Slide 10-6]. I expect to be adding Microsoft ODBC, which is an open standard, but isn't called ODBC in the standard. I expect the analysis package to remain as MATLAB. I expect to merge the database to Microsoft SQL server, which is the first software that passed all of the SQL certification tests that NIST formulated for passing SQL servers. I'm told that from the people in the SQL group at NIST who perform the testing. Perl is free and available off the Web, yet available commercially. I downloaded the ODBC interface for Perl from the Web as well. The database that I intend to initially build in the February timeframe will capture the lowest level that is captured with the ballbar data.

The Day after Tomorrow. [Slide 10-7]. I believe that we are going to move to a design that is database centric. For example, if we wanted to add another machine type, then we would just add another row in the database. We want to capture all the information from top to bottom as relations with the use of templates, so that if we make changes, then we just have to change the templates. I anticipate that we are eventually going to have a table of functions, analysis functions, so that we can add to those functions. Another aspect to this is that we want the repository to be distributed, which means that we might have a pointer to say the Boeing database and may have a password. The analysis would then have the capability of querying the Boeing databases (at least those in which we have been granted permissions) where the linkage is performed with ODBC. We need to talk about the management and security issues of this type of database. This might point to a data dictionary at another site. This would mean that NIST doesn't have to be the central location for the repository. Other companies may use all or part of this design for their systems. Another thing that is very important is extensibility. I want to push the relational model to see how much extensibility we can practically obtain. I heard somebody say that there might be performance issues with ODBC. Remote Database Access (RDA) might be a faster method of accessing databases, but I haven't tested this method.

Functionality and Design. [Slide 10-8]. The critical issue is to design the database for extensibility. We need to work on management of the distribution. One of the problems with a distributed system is the firewall. Vivek talked about cooperation and demonstrations. The firewall technology blocked us from setting up communication (audio and video) from NIST to a Caterpillar shop floor.

KATTER: In terms of functionality, are you going to link to the machine tool classification work?

WELSCH: We probably should.

COVINGTON: I was thinking about the functionality and priorities of your layout. We need to get visibility on these before they happen.

WELSCH: Right now, achieving the distributed aspect of the repository is important to me.

COVINGTON: I am concerned about the functionality and what the repository is going to do.

DONMEZ: Those are essential questions for the road map. We don't have too much time to discuss today. However, we can discuss the road map the first thing tomorrow morning. I would like everybody to think about what type of functionality, how to fill in the gaps, and what priorities are needed for the repository.

Integrated Design and Build Processes at Raytheon/Texas Instruments
Richard Johnson
Raytheon/Texas Instruments

We have been doing work for the last 9-10 years on our design process. We've undertaken a 6σ initiative where we've tried to implement the concepts of 6σ into our design process instead of only the manufacturing arena and use those techniques to predict what defects we will have and then design the defects out before we get into the production domain. That has required us to bring a lot more information that normally resides downstream upstream. Some of that information is the data that we have been talking about in these workshops. One of the problems that we had when we started doing this, is that the data, which was in the format used in manufacturing to control the shop, really didn't do the design engineers any good until it was translated into what should be specified in a drawing (i.e., dimensions, tolerances, materials, features, etc.).

When we looked at the design process, looked at the product lifecycle (probably at the highest level), you design something, you build it and you can see. [Slide 11-1]. You break that design and build down. When we go through a conceptual design or we're handed a set of system level specifications and have to back translate that to a set of requirements and specifications that flow down into lower levels of product structure. Then we go into detailed design. Then we usually prototype. Then we go into build. This prototyping phase is what we are talking about at this consortium and what we're trying to do in a virtual manner instead of actually building hardware, which would be a big improvement over what we're doing now. If you look down here at the bottom end of the process, where you have the build process, we use machines to build. [Slide 11-2]. We collect data from the machines, get the trends and other types of information on what's happening with those machines, and we use that information to control the machines. That's, at a very high level, of what we've been doing with the data in the past.

What we're trying to do in this consortium, is take that same data and probably some other information that we don't currently use, build models for these tools and try to simulate what is going on in the process. [Slide 11-3]. Input our feature geometry for virtual prototyping and output what our capability is of those production processes. Actually verify that we can produce this part. I should have included a feedback loop to the design in case the design doesn't work, and build several prototypes.

What we've been doing in the last 4 years is that we've skipped the virtual prototyping step and haven't been building any models for our tools. [Slide 11-4]. We have been building process models where we've taken information that we normally use in the shop and have translated that into models that will give us the predicted output of the process in terms of the cost cycle, given the part geometry, that is a set of features, not just one individual feature. That will, basically, give us information about our yields. We're trying to move upstream and improve the designers' capability to design the something right the first time so when we go into the prototype phase, we don't go through several iterations back into the design and then prototyping.

Ultimately, we are doing some work here too, we have what we call process technology levels and modeling different process technologies of metal fabrication, which could be casting, sheet metal, composites, hog outs, which do you use and we make those kinds of decisions up in the conceptual phase of design before we move to the detailed design. [Slide 11-5]. We need models up there to help us decide what are the right technologies to use in our detailed design to help point us in the right direction. Instead of getting all the way down here in prototyping and find out that we should have made this in casting instead of a hog out or vice versa. Up there we have system level specifications that we feed into the models, which gives us back which technology is the best fit for your requirements for this system.

One thing that we have found out now that we're starting to develop those models, is that expert knowledge plays a large role in this, because all of the data that we can collect doesn't tell us everything. [Slide 11-6]. There is a lot of information that's impossible or very difficult to put into numbers. We have expert knowledge that we have to add to the modeling process. This is our vision where we would like to see the modeling go, and bringing production data into the design process.

I think there are probably four levels of modeling that need to be done, one was added due to what we're doing in this consortium. [Slide 11-7]. What we're trying to do with the technology models is really to vector the design team in the right direction. Build those models at a level of abstraction that will allow you to understand which technologies you should use given your system level requirements. For the process models, we're using those to try and optimize, once we determine which direction we're going to go, what kind of technologies we're going to use, then we use the process models to optimize what we've made a decision to do. Then, as we start implementing virtual prototyping capability, then the prototyping will initially be a part of the design process, that is, we will go to virtual prototyping to help us make design decisions as we improve our process and technology level model. Eventually, we see that is ideally just a verification, and that we can confidently state that "this design is ready to go into production". Then, of course, you go into the build cycle, and this is what has been out there for years: the capability to collect data and use that to control your production cycle.

HEMMERLE: In your stage 1, where you show build in machine and data, is that product data or machine data that you are looking at?

JOHNSON: Machine data in the context of controlling at the shop level.

HEMMERLE: By machine data, the geometry of the machine and the squarenesses of the machine or the resulting? 6σ to me goes pretty strong on product, as opposed to the machine level. Were you looking at the hardware produced from the machine or were you actually looking at the machine for that data?

JOHNSON: In the past, it has primarily been looking at what has happened to the product and what are the trends in generating these types of features. We're talking about building prototypes now, which will probably bring into that database additional information like what you're talking about for the machine itself, trying to model the machine. The database is somewhat notional and all-inclusive and as you move up the stream, the database gets larger with the types of information included. Some of that information for tool models will probably be used eventually for us to improve our process models. Then our process models will be used to give us the ability to build good process technology level models. We have some activity going on in the top levels of the diagram. The last up in level IV. This is our vision of where to go with the modeling and what role the data plays in the lower levels. It is somewhat undefined at this point specifically what information is needed to do the entire diagram, but for the prototype models, that is what we're talking about in this consortium; what information do we need, what format would we put it in, how would we use it, how do we actually go do virtual prototyping? That is going to help us, once we start getting information, from that level, to improve our ability to model those higher levels. I want to get some feedback to see if this seems reasonable to you. I know that the objectives of this consortium are limited to primarily level II.

DONMEZ: We are concentrating on Levels I and II at this time, which is my impression based on all of the discussions that we are having. Don't you need machine tool models in process models in the prototyping stage?

JOHNSON: I look at the model as part of the data, as a type of data. I look at these different levels of modeling using different levels of abstraction of data. We have to use data at more abstract levels to model those technologies at the higher levels.

DONMEZ: So when you talk about process models, you are not talking about modeling the cutting process?

JOHNSON: I'm talking about modeling the turning process that we use (OD, ID, roundness, lengths, diameters, etc.). If I have a part that is a turned part, instead of just saying that I have a diameter here, have a roundness at the nominal at this feature, etc.. I have a part that I have described every dimension, put all of that together and use your data and process model and tell me what is the expected defect rate for this process. It doesn't look at each one of the surfaces we have available, but it looks at the feed, speed, and what is going to show up when I inspect this part, the type of information we are looking at is at a lower level of detail. We're are looking at a lower level of abstraction.

DONMEZ: Are you talking about Cpk type of information for your process models?

JOHNSON: Yes. We're looking at Cpk, 6σ.

WELSCH: When you bring in the expert knowledge, what are your thoughts on representing how that information will be used from a software/systems standpoint?

JOHNSON: I'm not sure since I'm not a software person, so I'm not sure I understand the question. There are different levels of abstraction that we have to look at to determine the overall system. When we put our process models together, we found out that roughly half of the information we needed to model processes was not available. So we had to go to the process experts, ask questions, and have them reach a consensus to what the most acceptable answer to a particular question, then put the result into the database. The reason we allow that, as opposed to purely numerical data, since there is no existing data for those questions, we would have to go through that process anyway. However, since you don't get the same answer from all of the experts, the answers may be within some range of the spectrum, you need to come up with a consistent/acceptable answer to the question as part of the model. We have software guys that are working and integrating that information into our models. I'm not sure how it is included in the database. We do have information that is non-numerical. We have restrictions and interrelationships that we get from our process engineer. We have rules where we know if we do "x" and "y" then you better not do "z". Alternatively, if you if you do "w" then the result is "3v".

WELSCH: How that expert knowledge is integrated into the database would be a significant contribution to this consortium.

JOHNSON: I can check with our software development people. Maybe we can work something out.

COVINGTON: We're dealing with some of the same issues and trying to get data from process experts from the shop floor.

MCCLURE: Alkan Donmez, Dave Hemmerle, and I are involved with writing a book, and this fits in perfectly and it's something I'd like to talk to you and maybe the four of us could get together later. At the very least, I would like copies of the viewgraphs.

JOHNSON: I'd like some feedback on this. I had left that level out before.

DONMEZ: We're concentrating on Levels I and II in your diagram, but we can't ignore the higher levels. That's why in my agenda I wanted to capture the role of this repository in the big picture of virtual manufacturing information systems.

JOHNSON: These aspects of Levels I and II are the foundation for being able to do any of these Levels on the diagram. My interest is when the standard is set for machine tool capabilities. Keeping in mind that the same database and architecture may be used for modeling upstream.

COVINGTON: The things you're talking about are my key objectives and that's what I want to produce. We're doing these things in a machine measurement arena in order to satisfy some of the requirements.

JOHNSON: I think this fits into the concept of the layered database, that is, different levels of abstraction.

COVINGTON: Do you have anything that you could give us which is more detailed?

JOHNSON: We're running into legal problems, being an engineer that's the part I hate, but I can talk to you later.

MCCLURE: I'll just call your attention to something else that just came out of your shop a couple of years ago. John Schaeffer at one of the American Society for Precision Engineering (ASPE) Spring meetings presented a case study that came out of Texas Instruments (TI), which was the most concrete examples of concurrent engineering that I've ever seen. He did a beautiful job, it's in parallel to this. He did an actual optical system, and his case study took it from the conceptual design to the manufacturing and how all of the interconnecting loops (people connections instead in data connections) but it's analogous to what you presented.

JOHNSON: These are tools that those people use.

MCCLURE: Right. Nevertheless, it was a beautiful description of concurrent. It was the first time that I understood that concurrent meant concurrence between people, not simultaneous. Is that the way TI sees that?

JOHNSON: That's the way everybody interprets concurrence the other way. Nevertheless, I agree with what you're saying.

DONMEZ: I received a short white paper from Richard Jennings of MIMITEK, who was in the first workshop. You saw some of the software pieces that they developed in Dan Sawyer's presentation yesterday. They are looking at uncertainties in CMMs but are also interested in applications to machine tools as well. The white paper is included in Appendix III.

I had another discussion with Don Esterling this morning. About the simulation tools and how useful they are, what are the potential uses in your operations. Don has some ideas that he would like to share with us to make some points more clear.

ESTERLING: Alkan Donmez asked us to think last night, which could be dangerous. I had some conversations with Jim Covington (Boeing) and Chris DeForge (Deneb), who brought up the issue of "how are you going to use these simulation packages". As I understand it, you have a significant amount of data that is being developed and then filtered down to some point where you're generating some kind of part. The point that I made yesterday was that men are not angels. The metrology engineers may understand the data that characterizes the machine tool and may know what to do with the data in terms of predicting the part on the machine tool. However, you have a guy on the shop floor who may not be having a good day, chooses to ignore the data, or just doesn't understand the data. You need to develop some kind of tool where the guy on the shop floor can easily make sense of the data and gives a simple answer to whether or not the system will work. We need a system that's easy to use, convenient, automated, and reliable. That's the point that we're trying to make with the error modeling system. With an error modeling simulation system, whether it is API, Deneb, or N-See, you have a possibility of experimenting. I'm not sure Dave Hemmerle wants his guys experimenting on the shop floor with production parts. If they have a system inside their computer, they can experiment and try putting the part at different places of the workspace. Given the part characteristics and the part program, I can "machine" the part at different places and get a sense of where best to machine. The shop floor guys will learn from the simulations and get a better gut feeling about how to use the raw data that is coming from machine characterization tests. The second point that I wanted to make is that men are not perfect. Mistakes may be made from the part program, another may come from the CAM system itself, where modeling at the tool tip you have an insert where the back edge of the insert may brush against a curved surface and the poor part programmer doesn't have any way to model that. Even on perfect machine systems, you need a simulation tool that will check the part tolerances given the part program. However, maybe a perfect system doesn't gouge the part, but the part program coupled with the error model predicts that the tolerances will not be met. In theory, rough-cuts never invade the tolerance level. In practice, there are all kinds of war stories that prove otherwise where gouges take place where you don't even expect tolerances to be violated.

DONMEZ: The other point is, that we are talking about a significant amount of data, in order to make some sense of the data we need some visualization tools.

MCCLURE: There are many things in error modeling that can be added for simulation procedures. I will agree with you that there is more than the finish. Results of all of this, is a better understanding of processes, how to control them, and how to predict what the final part will be. The result of controlling and managing this whole process is that there will be new generations of machines. Continuing the evolution that has started with N-See Software, will yield multifunctional machines which will bore, drill, turn, etc.. Particularly if the results of a group such as this bear fruit. The things that are not going to be covered, such as the subtleties of: fixturing problems, the effect of one operation on a part where the material is, or how the part will spring back when fixturing is removed. Those issues are several layers down. I agree that we can't afford to oversimplify.

HEMMERLE: By the time you get all of the error modeling done at the great manipulator in the sky, do you not think I will have volumetric compensations at the control level?

ESTERLING: Controls will get smarter. There will be some compensation that comes out of this effort.

DONMEZ: You are right. If you have models, and those models are correct for your machine, then you can compensate for the errors. However, how stable the models are, is critical. You may introduce apparent nonsystematic errors into the system with your model. For example, if I have a model that gives me purely geometric compensation of the machine, what will happen towards the end of the day? But with modeling, we can put bounds into the characteristics of the machine, as we saw in Dan Sawyer's presentation of apparent uncertainties in models, and you can then predict changes that are occurring in your machine and how that effects the part. That doesn't mean that your prediction will exactly match your part, but you will have range of dimensions/errors of your part that you can estimate for a given time and condition of the machine. Since you are not tracking every detail of the machine that effects accuracy of the part, then you will not be able to make all of the corrections on the machine. You can make some baseline corrections, such as lead screw (which everybody already does). In the next few years, most of the new machines will probably have basic geometrical correction capability. However, you still end up with errors on the machine, which will be changing slowly.

HEMMERLE: Just before I produce high accuracy into the workpiece, I check certain characteristics. Immediately upon finishing those characteristics, I check it again. In addition, I see that the self-induced and process-induced thermal (I'm calling it thermal) distortions that occur. Now, when that becomes fairly consistent, I statistically infer the compensation needed. If I know that I'll tend to always grow slightly left, and by how much and I have a good correlation/control on that. When I go through and pick up my initial offsets, I will throw it a little to the right so it will grow in before it grows out. Therefore, I do some live-time adjustment for the reality, not real-time.

DONMEZ: In order for you to do that, you have collected a significant amount of data, and this is probably for one machine. The amount of data builds up significantly.

HEMMERLE: There is a significant amount of data and it is very machine sensitive.

DONMEZ: You are going to have to make sense out of that data, and that's where the visualization/simulation tools appear. It makes the analysis easier when you can visualize what effect the current environmental conditions and behaviors of the machine will have on the resulting part. If I can look at the (virtual) part as a function of time, instead of making parts, and shrinking all of the knowledge of the process into the computer domain, then I can see the trends and I can convert those trends into actions. It is very useful to see these things happening on the computer screen first rather than on the shop floor.

ESTERLING: I think you're right Dave, but again the issue of how much do you compensate. Wouldn't it be nice to have a tool where you can try out different compensation strategies.

DEFORGE: I keep coming back to the question of what are my customers going to be using these simulations for? How does our company fit? Right now, our customers are saying "we have problems with capacity, and the only way to increase the capacity quickly is to take the production process offline and move into the virtual environment and keep our machines running". That's one area where our customers have asked us for help. Another area in which they have requested assistance is understanding more about the overall process (part or tooling) early on in the design phase of that process and our customers need the tools to help in these areas. Those are essential areas. There are so many subtle pieces of information that varies from machine to machine. I look at all of this data and can't see an interface that would be clean and easy to use. I have to focus on areas that, I think, the customers are asking for now. For instance, if I were able to take an entire work envelope, and say, make a cloud pixels or color shade, that would give me a 3-D perspective of where the inaccuracies of a particular machine are. I think the design phase would include fixtures and processes that we develop, since I would have to "fit" my part into the most accurate zones of this particular machine. What kind of data do I need to do that? I need you all to help me understand that. As opposed to just grabbing all of the information and making sense out of it, I think we need to focus on, from the simulation side of this project, who the customers are and what they are going to be asking simulations to do, and what is going to remain part of the company's knowledge base or experts, such as you, who know the machine tool very well and have to make human judgments of how the machine can perform instead of using the software making decisions.

HEMMERLE: Also, we are rapidly going away from process centers to product centers. Part ABC is only going to be ran on this machine, that style, that style, that style. We will no longer have a bank of machine tools and the part may go to any one of them. They are all being split up into product cells. That's going to cause real difficulties.

ESTERLING: I think that is what Caterpillar is doing. They are compiling errors, say for straightness, and only worrying about what you're doing with the part to see which errors are most crucial for what features.

COVINGTON: I do things a little bit differently than they do. We still have many different types of parts associated with each machine. We have many parts, close to 20000 parts. I don't have time to force all of these parts into a particular area of the machine. I want to know, by pressing a button, if this part is going to be machined within tolerance or not. I don't have time to go looking at the pixel information of a simulation system. I want to know if my machine can handle the job. I want a yes/no type of framework. I'm looking for more than a smarter system that tells me whether or not I can make the part on existing machines or if I have to outsource. I need a quick answer to the problem; not on a part by part basis. I need analysis on a part family basis based on tolerances of the part and geometry. Capacity is a big issue. I can't have my NC program center looking at pixels trying to figure out how to fix the machine or where on the machine to put that part. While they're doing that, the schedule is slipping.

DONMEZ: Maybe the maintenance people on the shop floor would be looking at the problem from a different angle.

COVINGTON: They're not looking at it from a part specific angle.

DONMEZ: However, they still need to look at the data to gain some understanding of the process.

SOONS: On the compensation issue, it makes a difference whether you are making different types of parts with the same machine, or using one machine to make only one type of part. If you use the same machine to make the same part over and over, then there are more effective alternatives than what we are discussing here for compensation.

DONMEZ: I think the general trend is that you are changing product lines more quickly, so you don't have the situation where you are making only one part on one machine repeatedly.

KATTER: I think many times, to answer the yes/no questions, you have more issues than just the machine tool errors. You have fixturing problems, environmental issues, etc.. It's not as simple as a yes or no question.

KRULEWICH: I was wondering how much of this is machine specific and how much is machine family specific? It seems like if you're designing a part and if you want to know if you can make that part on a specific machine, then you probably want to know more generally on a particular type of machine for the lifetime of the machine; not looking at the machine for this one particular instance in time when the errors are acting a certain way. I can't imagine in a high volume production that you would have a machinist optimizing a part for the way the machine is acting today. The question is, are you looking for a family of machines that can be classified to having certain types of errors? We don't have high volume production, but I can't imagine our machinist trying to optimize the part placement on a particular machine. In high volume production, I can see where it would be prohibitive. Then we were talking about errors that you can compensate for machines.

DEFORGE: That's what I was asking you yesterday. Can you characterize some of these errors that can be associated with a particular model of machine tool?

KRULEWICH: I think it would have to be more in a statistical sense, such as a Monte Carlo simulation looking at parts with certain features, looking at errors with some tolerance range.

COVINGTON: You have a lot of variation in health quality of machines of the same model as they age.

KRULEWICH: Given that you have two machines of the same model, you might have a certain part that you could make on one but not the other. It's on a custom basis.

COVINGTON: In the best of all worlds, all machines of the same model should perform the same. In our maintenance capability, we have to look at each machine individually. Each machine has its own specific problems.

HEMMERLE: Debbie, when I get 48 pallets from four load stations from 16 machines. You tell me any operation and I can tell you the best, second, third, fourth. That's going to be response time. So it is automatically calculated.

DEFORGE: I have a pretty fundamental question from some of the data that we saw yesterday. We were talking about data along the XY plane. Can that data be extrapolated out into the 3-dimensional sense or do you have to go in and identify its own characteristics? How do we go from 2-dimensional to
3-dimensional?

HEMMERLE: Yes. We have a plot of where all of the high accuracies are produced. Low accuracy is like runway behind you and altitude above you, it doesn't count. Where high accuracy is produced, that is your mean tool point intersections. That is where I want my compensations to be effective. Now, can I take them lower and project them there? Yes. I have my pitch, rolls and yaws and I believe that I can mathematically project.

DEFORGE: Are we clever enough to do the projections?

HEMMERLE: From Hans Soons' presentation of the data dictionary, the placement of the metrology sensors is critical to the projection calculations. From Hans' data format, I can project the accuracies to any lines I want.

SOONS: Your question is very valid. There are certain theories about what kind of errors you need in order to project. One of those theories that is most often used is that each axis has 6 errors associated with it, 3 displacements and 3 rotations, and you use simple mathematics to translate the errors into the machine workspace for every machine axis. So if you have a 3-axis machine you end up with 18 errors plus 3 errors added for squareness. By that limited set of errors, it is hoped that you will be able to predict every error in the workspace.

DEFORGE: The various tests that you were describing in your presentation yesterday. Does each one of those tests provide the same information ultimately and just different methods for gathering them?

SOONS: They were different methods of gathering various classes of errors. In addition, when you use this type of error model you have to be very careful. For example, the error that you measured depends very much on where in the workspace the measuring took place. Basically, the position of your machine axes. The projections that we are specifying here, you definitely need to know where you are measuring that error. That is one of the reasons we are so insistent of having the level of detail of how the data was taken integrated into the database. Back to your original question, the message is that there is a limited number of errors. You can do a 3-dimensional prediction of your errors.

DONMEZ: I think what we should keep in mind, is that some visualization/simulation capabilities would be beneficial. How much and in what circumstances still need to be determined and we shouldn't place any boundaries at this time. What we should keep in mind, if we need such visualization/simulation tools, what do we have to provide to those tools as information/data and how can we standardize that such that N-See, Deneb, and other companies can develop tools based on users' requirements/needs. That's where I think our focus should be, not on the specific application of the simulation, but what kinds of things that we need in the future and how to provide standardized interfaces for the tools. Eventually different types of tools will emerge.

DEFORGE: Would it make sense, for the quick decisions that Boeing is asking for, that if you just have a 3-D error map for machine tools based on data collected for a specific machine. Just take a finished part, manipulated through that 3-D map, to see if this machine would produce the part within tolerances. If not, then go to the next machine and perform the same evaluation based on the last set of data for that particular machine. Would that be a comfortable evaluation? That would be a fundamental check, does the machine have the capability to produce the part within tolerances or not. Once that decision is made, then you can include more information into a model and address more of the process evaluation issues, such as fixturing, optimization of placement of part, etc.. Just take the data and evaluate it visually. Do you think that is valuable? If I can get a consensus, then I can start moving in that direction.

COVINGTON: I don't think the visualization is necessary, just a yes or no on whether or not the tolerances have been violated within a certain workspace. I don't want to make any decisions, just a yes or no.

HEMMERLE: If it doesn't pass on one machine, you have to go to another machine.

COVINGTON: You may want to do that, and have that capability.

DEFORGE: I take it the next step is then, that there are going to have to be other decisions about fixture design, etc..

COVINGTON: I don't want to go in and change the NC program.

WELSCH: You are saying that you don't need the visualization. You have to analyze the data along the function points. What are the heuristics, how do you do that? There is something about the visualization, about the human eye making a snap decision, that a program is going to find very difficult. I agree with you, but I don't know how to do it, as a software engineer.

ESTERLING: I think that you need to model the entire process. Data at a single point, a yes or no there, depends on what process you used to machine that part at that spot, what errors or combination of errors come into play. At any time you look at a plot of 3-D points, not 2-D points to make a decision, it's much better to include the part program. I showed some plots yesterday, where basically you feed in your as designed data, in your part program, you feed in your error model, and come back with the estimate of your part.

WELSCH: You're doing it through a visualization program.

ESTERLING: No, the pretty pictures just help you get funded. The software can tell you where the worst point is, or the depth of the gauge and its (x,y,z) location. It doesn't have to be pretty pictures, the pretty pictures are what sells.

PATTERSON: I think we have a good example of the value of why we, at least started out, are here. There are differences in how we use the data and what the applications are, and what we think our controllers are going to do. However, the fact is, that we aren't going to be able to do any of that, unless we can move the data between pieces. What we end up doing with the data will differ. The applications are different, operations are different, and some will make fortunes. No one will be able to do it unless we can move the data around. I'm really interested in seeing how Alkan Donmez is going to get us there to actually be able to move the data around.

DONMEZ: That's a very good point. We should not be looking into the details how we will use the visualization tools, at this stage. What we should be concentrating on is what type of data should we be feeding to systems like visualization. Let's move on to the road map and then we can come back to related discussions later.

Discussions on the Road Map

Data Repository

DONMEZ: We need to fill in the blanks of our draft flow chart. The first slide comes from Ray McClure's summary of the last workshop. [Slide 12-2]. He asked some key questions. We are building this program to try to address these issues. If you look at the questions, the core of the answer is in the data and information. We are trying to standardize data/information so that we can share it from system to system, tool to tool, or company to company. We have to have tools to help us with tolerance budgeting, machine simulation, process simulation, inspection planning and simulation, performance tracking of the machine to aid in maintenance activities [Slide 12-3]. We have talked about these tools in past meetings. If we need all of these tools, how do we get them? We already identified that we need a data dictionary, standard file formats, information models, and we need a repository for all of this. In my rough plan, we have to get there this year. We can't delay any longer. We have been talking about these ideas for about a year and a half now. By the way, our fiscal year is from October to September, so we are already into fiscal year '98 (FY98). By the end of September, I would like to see that we have formats and information models for specific sets of experiments, and we should bound that for 3 axis machines. In order to get there, I need participation from all of you. We have a rough draft of the data dictionary that Hans Soons presented yesterday. What we need is for the consortium members to start looking at the dictionary. I'd like to get the comments and inputs back as soon as possible.

WELSCH: Currently we have examples of the Renishaw ballbar data in the repository. We could list all of the different formats that we would like to see. Then ask the question of, where do we measure these? Does the data dictionary cover that format? That might be one way of proceeding.

SOONS: I was thinking that we could use a Web page, similar to the example that we showed yesterday of the machine tool data format, and put up a sample set of questions. For example, you would answer questions like, (1) I'm going to do a ballbar test, (2) I do have a calibrator, (3) I'm going to measure along one incline, and (4) I'm going to use 3 axes. After a certain set of questions is answered, the web page could then extract the attributes that were relevant in that test. This will give those of you that are already using ballbar tests and have already started using the database a quick opportunity to compare the attributes that are currently in the data dictionary to which attributes that you are currently using in a specific test. Similarly, we are definitely going to compare those attributes with the data format. That is one of the things that I mentioned yesterday, that we want to capture all of the attributes and don't want to lose any information in the current data formats, for example, Renishaw. I will be interested if anyone uses any other software like API, Heidenhain, and Renishaw. If you can send us information on those data formats, it would be very helpful. I think that once that part of the web page is up, then we can start getting meaningful discussion on the attributes in the data dictionary. So my proposal is to put up another web page, perhaps concentrate on circular tests, and try out that method of feedback. I was getting the impression that the alphabetical list of terms in the data dictionary wasn't the best way for the consortium to assess the current attributes in the dictionary. I think we have to develop the structure of the dictionary in a meaningful way.

DONMEZ: This is an important point, because it is very difficult to look at and analyze the list of things in the dictionary in alphabetical order. You have to make logical connections between all of the terms. This will help us get the structure of the dictionary. You can see which terms are relevant, missing, etc..

HEMMERLE: Hans, isn't that further clarified then, because what you're saying not what's in the Appendices, but what is in the ASME B5, or just the ballbar by January.

SOONS: I am talking about solidifying the attributes only for circular tests, as a starting point. Parallel to that, I think that we have to work on putting a more visual structure to the data dictionary, so that we know which groups of attributes apply to which tests. The reason why I want to go into specifics, is that we have to gain experience by getting into the details to test out the process of formalizing the data formats.

HEMMERLE: So you want some of the Appendix for the details?

SOONS: No, just the front section.

DONMEZ: Three axis machines are covered in just the front section. Keep the bounds on three axes and learn as much about the process as we can before we go any further.

SOONS: Circular tests, B5.57 standard for the lathe, already give you the opportunity to use gridplate, disks, and the ballbar. It gives you a lot of variation.

HEMMERLE: The only plate I know of that's on the market is Heidenhain. So we can just go directly to Heidenhain and do that one. With the ballbar, there are several vendors.

SOONS: The problem with taking just the data format from the manufacturers, is that you don't get all of the information you need, in general. For example, if you look at software that has mostly been discussed here, it doesn't ask you where in the machine workspace you took your test, it doesn't ask you your tool vector, it doesn't ask you a host of questions that you need to store other than just getting plots or the B5 numbers.

KRULEWICH: How far along is the data dictionary for other tests? I'm asking because I'm about to perform a number of tests on our machine. If I had the requirements, I could incorporate those in our software.

SOONS: For the basic setup, everything is there. However, there are some specific terms for spindle error motions that aren't included. That is one example, there are specialized measurements that aren't covered.

DONMEZ: I think everybody here probably uses standard measurements on their machines, for example, linear displacement accuracy, straightness, angular errors, ballbar test, etc.. They are all pretty much covered in the data dictionary. Therefore, you should be able to start implementing the dictionary into your measurements, see what the deficiencies are, and then give us some feedback.

WELSCH: My biggest concern, is that we get the feedback that we need and maybe we should have another meeting soon.

DONMEZ: Logistically and financially meetings are hard to attend. I would like to get most of the feedback electronically (i.e., through the Internet or email).

KITNA: I can't say that I've seen the NIST/NAMT site. I know Jim Covington has access. Do you have anything that tells you what new features have been added to the site, maybe a date associated, and an index of the site?

DONMEZ: That's a good point and that should be added.

COVINGTON: I'm not going to be casually logging on to see what new has been added onto the site. I think all of the consortium members should be notified (by email) when any changes are made to the site.

KATTER: Do we all have access to the page?

WELSCH: Almost everybody in here has been added to the list. If you're not, come see me.

DAHILIG: On the data dictionary, I keep hearing what you want us to provide (files, how we use data, file formats). We have identified some standard tests and software associated with those tests (API, Renishaw, etc.) but don't you think that it makes sense to just talk to Renishaw; maybe they have test procedures and methods of manipulating their data that you could acquire and add to the data dictionary. They are the experts on their systems and should be able to provide us with some information.

DONMEZ: Renishaw indicated that they are interested in participating. They couldn't make this meeting, however. In the last meeting, API promised to give us information, but we haven't gotten that yet. Let's get back to the schedule. We said that the data dictionary has the terminology for all of the standard tests and it will be growing. However, we need feedback and formats, from all of the participants, starting with the circular tests. We would also like to put on the schedule to acquire other types of formats, such as linear displacement errors, laser interferometers, and other types of instrumentation. I heard the January timeframe for commenting on the data dictionary and then a final data dictionary.

WELSCH: We shouldn't use the word "final" since the data dictionary will be revised many times after May.

DONMEZ: It will be a living document as other types of tests are added. For circular tests, it should be in a final form. There is a point where changes to the dictionary will be minimal.

KATTER: How about the word usable data dictionary?

DEFORGE: Would any visualization tools be of value as part of that data dictionary? For setup and evaluation tests?

DONMEZ: As far as dictionary. I can't relate dictionary to visualization tools at this time. Can anyone help out?

WELSCH: When you're looking at the questions that we ask, we put up diagrams to help people know what is going on; images that show what is being defined in the dictionary.

DONMEZ: O.K. In other words, you're saying to include visualization in the dictionary, not to include terms to aid visualization. I will put on the schedule to have a usable data dictionary by the April/May timeframe. Between now and then, you will get a "structure" from us and then we will see your comments and iterate back and forth until the April/May timeframe.

COVINGTON: Do we see everyone else's comments?

DONMEZ: In our website, everyone sees everyone else's comments.

SOONS: Like I said yesterday, the dictionary will not be in an alphabetical list, but will have more of a tree-like structure to make the terms relate to each other in a more meaningful manner.

DONMEZ: If we're shooting for a usable dictionary by April, then the dictionary should be restructured by January. We are currently working on a limited set of information models. We have experts in information models who are working with Hans to use this dictionary and try and develop the activity and information models. I hope that by the time we get to this point we will have some useful information models to proceed towards the structure of the repository.

WELSCH: So far, I see in April that we will have a fairly rigorous set of attributes for circular tests by April.

DONMEZ: By April, we should have all of the standard tests for 3-axis machines in the dictionary. Hans already has, I believe, about 80% of the required terminology (except for spindles) associated with all standard tests, linear displacement, straightness, etc..

SOONS: I have to put a caveat on that. There are procedures, especially in the latest standards, such as reversal procedures and such that will not be included by April. Also not all cutting tests will be included. The main tests we are talking about are Environmental Temperature Variation Error (ETVE), spindle, laser, ballbar, circular, squareness by April.

WELSCH: What formats besides circular tests are we going to include by April?

DONMEZ: Laser interferometer.

KATTER: What is the timeframe for the laser tests? Because the data that comes in from the laser tests has several files associated with them. The repository now, for the ballbar tests, we are only uploading one file. Do you want to develop a format where we can upload several files at once?

WELSCH: It is hard to say what level of effort that is going to be required for the forms for the other types of file formats. If we are developing two more like the Renishaw formats, then the March timeframe is achievable. If you are talking about 50 more, no way.

COVINGTON: We should be looking at who the primary users are and which ones we use the most. Maybe we should do a survey to see what types of formats are most popular among the consortium members.

DAHILIG: Now as far as the Renishaw tests that Larry Welsch was talking about developing the parsers for, that's fine for now. Nevertheless, eventually we want Renishaw and the other vendors to standardize their files because as a software engineer, we want the data to be generic enough that we don't have to use a translator.

WELSCH: Do we at NIST need to hold a workshop on that topic?

DONMEZ: Larry Welsch's suggestion of the focused topics might be more helpful.

WELSCH: We need to prioritize which formats to finish by the April timeframe. By January it would be reasonable to pick, I'll say arbitrarily, five other formats to start working on and finalize by April.

KATTER: I haven't gotten to use the repository too much. I know that we can currently upload data. Can we download data?

DONMEZ: Currently, we don't have that option, but it should be included soon.

KATTER: Can we get the data back in the same format in which it was uploaded?

COVINGTON: What types of data are you interested in downloading?

KATTER: I guess a typical application that might be possible is if we were considering using the same type of machines available to the database. If we could get that information and use it in our virtual manufacturing and simulation.

WELSCH: One of the most straightforward ways, if you download the data using ODBC you can get the data back in a standard format that you could use in Excel or a database such as Access. You pose the query on the Web and then get the data back in either of those formats. I expect by the April timeframe that will be the most straightforward way of downloading the data.

KATTER: Now it is easier to get the data back in the format in which it was sent so that we can use the available software to plot the data.

DONMEZ: I think the data should be stored in the central repository in a standard formats not company specific formats.

SOONS: I think you should have the option that allows for downloading in the original format because it will take some time to develop applications where you can use the data in standard formats. So initially, we should include the option of getting the data back in its original format.

WELSCH: My feeling is that it will be much easier to download the data in tables since you are going to be using queries. Nevertheless, we can store the data in the database in both standard and original formats.

KATTER: Right now, we don't have a standard format, and the standard format is not usable because we don't have the analysis tools to extract the errors.

COVINGTON: Right now Renishaw is a black box so I can feed data back in the package to get a plot.

SOONS: Right now when files are uploaded, the filename and machine names are encoded. Do you want operator's names encoded as well?

COVINGTON: That was a question I was going to ask. Is it our responsibility extract that information?

SOONS: I thought that if you are going to be sending us an enormous amount of data, perhaps it should be our responsibility to encode.

DONMEZ: If we change the machine name, and then they want the data back, they wouldn't know which machine the data represented.

COVINGTON: Could you all build a table of which parties submitted what data?

WELSCH: The short answer is yes. We can use some straightforward checks. We need to implement some management and security tools on the server.

KATTER: Are we going to have the link to the machine classification site? Will it be our responsibility to take out the machine names and operators?

DONMEZ: We are talking about two different types of linkages. First, we will have a linkage to the page for machine classification so that people can get an idea of what types of information classify machine tools. Second, and more importantly, we have machine identification which links the particular data file you are uploading to an encoded name.

DAHILIG: I don't want to have to keep track of the encoded filenames. The solution should be giving the data back in an uncoded form only if the party which uploaded the data is requesting the download.

DONMEZ: It seems more complicated from our end.

WELSCH: I think you can do that with some generic capabilities.

DONMEZ: We will give our recommendations on the management and security issues of the repository and then have to get feedback.

WELSCH: I anticipate having a white paper on the management and security issues.

DONMEZ: What other functionalities do we want to see in the repository? For example, we have uploading and analysis, but we don't have a simple straightforward presentation of data.

COVINGTON: We need that because if we want to detect any spikes as opposed to the trend in the ballbar data, for diagnostic purposes.

WELSCH: It would be extremely straightforward to ship you the either the raw files or view that your query has produced, either numbers or graphs (whichever is appropriate) for the data.

COVINGTON: Is there an Access 97 viewer? Does it require that everyone have Access 97 on their machine?

WELSCH: I'm not sure of the answer to your question. It requires that they have a program capable of acting as a client of ODBC. Windows 3.1 version will not work.

DONMEZ: We have one hour left and haven't gotten very far. So let's not talk about details at this point and cover all of the items and timeframes on the agenda. By the end of FY98, I would like to see us upload/download any type of information. Incorporation of data analysis tools started this year and will go on for some time. I don't think we can incorporate all of the analysis tools that are needed by the end of FY98. We haven't really dealt very strongly about what type of environmental information will be associated with the data that we're incorporation into the repository. I noted the physical description of the machine, we have covered that. I also noted uncertainties, we need some information about the uncertainties of the data (measurement results) that we're incorporating so that eventually we can use tools (as stated in my previous slide) to estimate the machine capability in a statistical sense. I don't have a clear picture how we can get there by the end of FY98. We have some ideas that we can incorporate, but I'm not sure if the uncertainty tools will be finalized by the end of FY98. Let's move on to data analysis tools.

Data Analysis

DONMEZ: Currently we have some basic ballbar data analysis capability, as you have probably already seen. Now we're looking at, probably at least a two-year effort.

WELSCH: Sometime in the future, I would like to see us being able to upload data for tools like N-See and Deneb. I'm not sure how to capture that at this point.

SOONS: What I've heard at this workshop is that people want to do some timeline comparisons. As far as diagnostics go, somebody mentioned earlier, Renishaw has some kind of diagnostics. We have some diagnostics. In terms of timeline analysis capability, we currently don't have any capability.

WELSCH: Related to that, Deneb needs some form of numbers to implement in their software.

DEFORGE: That's why I was asking yesterday, about visualizing data from simulation. We may plot some points, that would be one thing. But if we're going to actually change the kinematics of the machine, that would be another. That's why I was trying to find out how people were planning to use the tool, how do you want to visualize these databases? I don't think anybody knows the answer to this question.

DONMEZ: How about if I say modeling? Modeling can be very simple, you can take just one axis and just fit a polynomial around the data to represent the errors. Or combine several errors into one volumetric performance type of model. Or we can be very extensive and incorporate kinematics.

DEFORGE: These are all interesting ideas, and they're all conceptual at this point. We need to determine what is realistic for computation and speed.

DONMEZ: There are many efforts going on at Caterpillar and Boeing, of comparing machines and comparing machines over time. Do you think these tools will be available in the repository eventually? What is the company policy around that? If NIST is supposed to do all of this development, that is a lot of work. What we would like to see is that the generic models developed in these companies incorporated into the repository.

DEFORGE: Some of the activities that we have going on right now is we don't always get access to their algorithms, we just supply information to their algorithms. It's not necessary for me to have their algorithms, just a standardization of the data format. Then again, they can supply me with their data from the simulation model. I don't think we need to know how to manipulate the data.

DONMEZ: In his presentation yesterday, Vivek was making some charts about the time dependency of the machine's error behavior and he also showed the comparison between machines A, B, C, and D for a given time frame. Those types of tools, obviously, exist right now at Caterpillar. I'd like to investigate how proprietary those things are and the possibilities of sharing them in this consortium.

KATTER: These issues I have to consult with my management. I have to find out what you can access to and who gets access.

ESTERLING: To answer you question earlier about simulation tools. The current formulas that you provided us to model the turning operation. You have error in X as a function in Z for 2-D systems it is in parametric format. If the data is not available in parametric functions and a generalization into 3-dimensions, then as a function of (x,y,z) and (i,j,k) as a function of all of your parameters. That would be the most convenient for me, the one easiest for me to implement. If the data were presented in some numerical formula, errors that you expect for a given type of tool mode at different locations and it's O.K. to interpolate between the two, then that's a smart program, and not a barrier. We can take both numerical and parametric data.

KRULEWICH: You are not prepared to take straightness, position, and other types of data like that?

ESTERLING: No. I don't want to take raw data.

WELSCH: How would you like to see the parametric equations represented?

ESTERLING: I don't care, just write the code.

SOONS: Somebody has to build the kinematics model into the error parameters taken for that specific machine. Different people model the machines in different ways. So it is the responsibility of the person who took the error data provide information for the kinematics model of their choice. We have to have the locations of the coordinate frames, the signs.

DONMEZ: We're going back to the sign conventions, which we haven't covered yet.

WELSCH: My question is to you Hans, why don't we have the person taking the data translate their parametrics using their kinematics equations? That's basically what I heard Don say, that is, give me the translated data in a form that I need.

DONMEZ: I want to make a simple proposal for the sign conventions, since we need to address that. Why don't we just use the standard EIA267?

SOONS: In the data dictionary, I basically wrote it so it doesn't force you to take any sign convention. The sign convention will be treatable from the data. The reason that it is written that way is because there is a lot of old data out there that wasn't performed via a standard and there is still is a lot of discussion going on about sign conventions. I don't think this is the proper forum to discuss sign conventions. There is currently some work in the B5 standard.

HEMMERLE: I think we should address the sign issue.

DONMEZ: The sign issue certainly effects our repository. However, I think the solution that Hans came up with is that if you have a sign convention, then put it in. I think we should have a default sign convention eventually. My position is that there is a standard that people already use for axis nomenclature. It is recognized nationally and internationally.

HEMMERLE: The EIA-RS267A standard did not address rise and fall, side to side. Rise and fall was in and out of a way plane; not an axis direction. We can go that way but when I say positive it should be rise.

DONMEZ: When you say rise and fall, you are talking about straightness in horizontal and vertical directions?

HEMMERLE: Yes. Rise and fall: positive was away from the way plane, negative was into the way plane. Put a way system like that on a horizontal milling machine, positive away from the way plane is negative in the z direction. Those were never described in the standard.

DONMEZ: Let's talk about 3 axis machines which are very well defined, whether the part is moving or whether the tool is moving. The basic coordinate frames are well defined. If I'm looking at one axis motion and if I'm looking at the straightness of that motion, and certainly I'm looking at straightness in one plane which has the other axis already defined and straightness in the horizontal of the other axis which was also defined. So if I can define my straightness along with the main sign of the axis direction, then what am I doing wrong?

HEMMERLE: If your dictionary has that, then I would certainly buy it.

DONMEZ: Let's put the B5 standards aside for now. If we just stick with the nomenclature standards, then it is unambiguous in my view. Except if you have a rotary head, then you have to think about it a little bit more. But first, let's address the straightforward 3-axis machines, which is unambiguous.

HEMMERLE: From the mathematical world.

DONMEZ: If you are trying to have an intuitive interpretation, then you have to think a little bit more.

KRULEWICH: I think where it is still ambiguous, yes we always know what is positive (x,y,z) but not when your part is moving. If you're trying to figure out if the part is moving in the positive x or y and you are looking at the part from a stationary point, you get one answer. But if you are sitting on the part, you get a different answer.

DONMEZ: You're trying to have an intuitive, on-the-spot evaluation. The only reason for these complications, and the same argument goes for the B5 committee, is that we want to generalize some intuitive interpretation for a variety of different configurations. I don't think that is easy, that's why we are having so many problems.

KRULEWICH: I guess the part has a prime axis.

DONMEZ: If the part is moving then use the prime axis, but your positive x is still positive. It makes the standardization simplified, but it makes intuitive interpretation a little harder. We have to make sacrifices somewhere. I think, going back to the NIST approach, I think that the sign convention is incorporated into the dictionary. But for the future, we should think about a default case, which is in the existing standards EIA-RS267A or ISO 841, which are both the same.

KRULEWICH: So as it is now in the dictionary, the user has to specify the sign convention? If we were going to interface with the model, the user would have to process the data accordingly?

SOONS: I still have to work on some aspects of the dictionary with respect to sign convention. For example, if you were doing a laser measurement, and the error was in the, say, positive z, it depends on which direction your measurement was taken. So basically, no matter how you choose your sign convention, you have to incorporate it so you can retrieve the data correctly. I don't think it is a good idea to force definitions.

DONMEZ: Some of these analyses will depend on others. For example, how are you going to perform time dependent analysis without some parameters extracted from the data? You're not going to just overlay plots to do time dependent analysis.

SOONS: You may just want to compare the current performance with previous performance by overlaying the plots.

COVINGTON: All we are interested in is seeing changes in the system over time, so we will want to just overlay the ballbar plots.

DONMEZ: It is a good way to look at the plots, but you may also want to look at the numbers. For example, straightness number of ABC over time, you plot that and see what the trend is. In order to get those numbers you have to rely on this type of analysis: take the data and fit it, come up with the single number or equation and so forth.

COVINGTON: I am not a metrologist, so I don't really understand the example.

DONMEZ: For example, if my straightness is changing, something like that, I can fit the data to polynomial equation, and track the maximum number over time; a very rough idea.

COVINGTON: I was hoping we could talk about some data analysis i.e., extracting points from a graph. What about dynamic graphics on the web?

LING: I believe Excel will allow you to extract points from graphs. I think with graphics, it might be better to download the data to your machine and use your own graphical analysis package.

KRULEWICH: I was hoping we would be able to, at least, select columns of data and then plot it just out of the repository.

DONMEZ: Instead of just analysis, I'd like to see viewing of data and that's just to plot it to see what it looks like.

WELSCH: I think it would be a good idea to just get the most common plots that everyone likes to see and have the code available for viewing on the web. We have a dynamic plot already on the web with the ballbar data.

DONMEZ: We should be able to do that with MATLAB or a similar package.
COVINGTON: I'd like to talk about comparisons of machines over time as well as machine to machine comparisons. I don't know if that's a subset of the modeling?

DONMEZ: Yes. When you do comparative analysis, you can do it along a time frame or along machines.

COVINGTON: What would a simple tool for that be? Some simple way to compare your machines.

KRULEWICH: You could do some time dependent analysis without the modeling, like what you just drew. Rather than curve fitting, just record the maximum value of your data.

DONMEZ: That's true, but then you're sensitive to noise and especially for the straightness, you need some pre-analysis, fitting or smoothing. Any other basic analysis tools that we need to get us there in about a two-year time frame?

KRULEWICH: If you just did the modeling, that would be an amazing tool.

DONMEZ: We didn't really specify what modeling we were going to do, but we can cover a lot of ground. I don't think we can cover everything in modeling in a two-year time frame.

KRULEWICH: I guess, two years down the line, if the controllers are ready to truly compensate a machine, then they can use that package. Then you'll need the controller people involved with the repository.

DONMEZ: For now, I'm not considering the kinematics modeling as a part of this. I'll leave the kinematics modeling for software developers, simulation tools and such. What I need here is to be able to understand what the raw data means; that type of model. Next is simulation tools, Don has already given us a demonstration of one package. What I mean, is the integration of simulation tools in the repository? Don should be able to access the repository, get the information that he needs and begin to use his simulation tools. That smooth transition, I'd like to see happen by FY99.

ESTERLING: If the simulation tools exist today, then what is there to transition to? The tools that you need don't exist today.

DONMEZ: In the time frame that I am talking about, the tools should be in existence at that time. Based on all of these discussions, you simulation tool developers will go back home and develop tools that are more extensive. I'm saying at that point (two years), we should have a seamless interface between the repository (all the information that we are collecting and generating) and simulation tools. That is my target.

DEFORGE: What we have to look at during that development is that we need a business case to start doing that development. We need a justification that people will buy the product. I certainly can't get the product developed if people aren't going to buy the product. In terms of the two-year time line to develop, we also need to spend some of that time making sure the business base will be there.

DONMEZ: You are at least getting some feel for what these people are wanting for their applications? You have a good grasp of what your capabilities are. I'm talking about the near future, where you know the market situation, you know the technology potentials, and now you're learning what these customers (at least) need. Therefore, by that time you should be able to have some, at least, prototype tools that we can start checking to see if we can have seamless interaction with the repository. But as far as NIST effort is concerned, are there any areas where you would like to see us concentrating? So basically, it's an assignment for you software developers to be there by the end of 1999.

Performance Tracking Tools

Performance tracking tools are somewhat an extension of time dependent analysis. [Slide 12-5]. I wasn't quite sure how extensive we wanted to be in that analysis. Starting in FY98, this year, it could go a couple of years effort, depending on the type of things we want to do there. I think it is an important tool that people need. The second item there, capability evaluation tools; from a statistical point of view. I keep bringing this up, but I don't see much reaction to this topic. I don't know if it is not important at all to you. Everybody talks about wanting to be a 6σ company, what do you mean a 6σ company? If you don't know the capability of your machine, how can you tell?

COVINGTON: I'll give you a quick answer to your question of why I haven't responded. We have so many parts Cpk is unrealistic unless you have some way of tracking those numbers.

DONMEZ: I use the term Cpk for a lack of a better term. Somehow, if you have a machine, how can you put some statistical bounds around what you can estimate the capability of the machine is? The machine is certainly deterministic, but there are apparent nonsystematic problems associated with things that you don't characterize and you don't measure. That puts some uncertainty in the evaluation of your machine's actual behavior. If you spent a whole year on that machine, you would find out many cause and effect relationships and could characterize that. That's what everybody means by deterministic machines. If you only have one day to find out how your machine behaves, there is some uncertainty in the understanding of that behavior. The machine, over time, will change as a response to environmental characteristics, and you are capturing some of those characteristics by going through the standard measurements. What is the implication of the standard measurements as opposed to the actual capability? And what are the uncertainties that you're introducing or overlooking when you evaluate that machine's capability. That's what I'd like to capture.

COVINGTON: I think that's a capability that we'll eventually need, but it's pretty far down the line.

DONMEZ: You all have been asking for a 5-10 year road map, so I'm trying to look ahead.

SOONS: Perhaps you are already working with some of the issues related to Cpk. We are trying to translate part inaccuracies to the machine performance by collecting data over time and getting the statistical information.

DONMEZ: With the kind of data that we are and will be collecting, you should be able to deduce some information about your machine's capability. We don't know how to do that yet.

COVINGTON: If it is a goal, we will definitely support that goal.

DONMEZ: So maybe it is too optimistic to expect something by the year 2000.

COVINGTON: Maybe not, if we can make things happen.

DONMEZ: If everybody starts thinking in that direction, maybe we can come up with some nifty solutions.

Inspection Analysis Tools

DONMEZ: You have already seen ICAMP's work. There are already some work going on in inspection analysis. What I'm hoping is that we can integrate inspection analysis systems into the repository, so we can get closer to the overall virtual machining and virtual inspection systems. I have set a time of FY01.

COVINGTON: Did you have anything about new test methods and the analysis of three axes machines?

DONMEZ: We need to look at new test methods and the data associated with those methods. I think there are many ongoing efforts at various institutions and we should certainly try to get that information to see how it fits into our model of things.

Dynamic Models

DONMEZ: Of course, a few years down the line we need to look at the dynamics (FY02). We've been looking at the quasi-static errors, machines and how they relate to the parts, things like that. But we never have addressed the issue of how we can integrate dynamics into the repository. What do we store? Do you store the (impact) hammer test results for a baseline machine? If so, how do you do that, the frequency domain or other domain?

SOONS: What about the loaded tests?

DONMEZ: I had that in mind, but didn't put it down. It should be accomplished in the nearer term than FY02. Of course, when we talk about modal machine tests, there are no standards in existence. It is going to be hard to define a standard data format in the dictionary if you don't have a standard test. So, it is something we have to keep in mind and hopefully drive the B5 committee to come up with some standard tests. But we have some standards in place to look at machine dynamics, to eventually integrate some machine formats into the repository.

Machine Process Models Integration

DONMEZ: Of course the ultimate in virtual machining capability is to integrate the machine process models into the repository. I think it is very optimistic to put a six-year time frame on this goal (FY03). But at least we should keep these ideas and targets in mind and have some hope of getting there someday.

KITNA: What is the prioritization, what is the visibility for progress? Could you have a Gantt chart and some means of telling us about updates with who has signed CRADAs, etc.? It would help us a great deal, if there were prioritization of essential elements as we move forward. What are the essential milestones?

DONMEZ: I think we've pretty much covered the first year. We can go back to that again. Some of the essential milestones: 1. April '98 have useable data dictionary for all basic tests, 2. December '97 Security and Management Issues of web.

KITNA: You had analysis tools listed and a time line of when the goal of having a usable set of tools. It would be beneficial to have an incremental delivery of tools, maybe if there are 3 or 5 that come up, but don't wait for the delivery date to deliver those tools, so alert us of any progress and status of NIST site.

HEMMERLE: In your road map, you need to focus on getting more people involved.

COVINGTON: By more people, do you mean more people out of the same organizations or different companies?

HEMMERLE: Different companies, or more potential users to get involved.

KRULEWICH: What about machine tool companies?

DONMEZ: Machine tool companies are very reluctant to participate in these types of efforts. The only hope is maybe the big users, if there is a push for them to collaborate. If we get too big then we have to compartmentalize the discussions. We could certainly use the automotive perspective. We don't currently have any participants from that industry.

SOONS: Unfortunately, we had a scheduling conflict with the ASME conference for this workshop. It would be nice to get Renishaw involved as well.

This concludes the third workshop.

Editor's Note: The time line resulted from the discussions are presented in Appendix II.

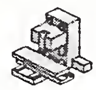
Appendix I – Presentation Slides

1. Alkan Donmez

Slide 1-1

Machine Tool Performance Models
and
Machine Data Repository

Third Workshop
November 20-21, 1997
Pleasanton, CA



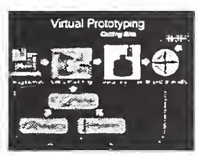
Alkan Donmez
Project Technical Leader

Slide 1-2

Project Summary

Goal: To develop tools necessary to enable virtual manufacturing

- Data Dictionary and Information models for machine tool performance data
- Distributed repository of data and analysis capability
- Low order generic machine performance models



Slide 1-3

Needs

- Machine capability evaluation
- Process variability evaluation
- Make/buy decision tools
- Machine performance tracking
- Capacity planning
- Maintenance planning
- Inspection planning and algorithm evaluation

Slide 1-4

Challenges

Generic virtual machining and inspection modules

Information models for representing, comparing, and communicating:

Distributed repository

Slide 1-5

Summary of Last Workshop

- Machine tool metrology information modeling
- Data requirements and formats
- Web-based experimental Repository
- Interim machine tests
- Simulation tools
- Representation of machined part

Slide 1-6

Critical Issues Raised

- Need for capturing complete measurement information
- Sign conventions
- Frequency content of performance data
- Machine/process interaction
  - Fixturing, material properties, dynamics
- Machine/environment interaction

Slide 1-7

Critical Issues Raised

- Physical description of machine
- Economic performance info (scrap rate)
- Ability to store model coefficients
- Visualization for maintenance
- Translation of info into simple, concise results to present to decision makers
- Performance tracking by part probing

Slide 1-8

Critical Issues Raised

- Graphical representation of machined part
- Need for high level info for simulation
- Three approaches to simulation
  - part, machine and part, machine only
- Extent/accuracy/speed compromise
- Information in three categories
  - machine, instrument, measurement related

Slide 1-9

Consensus

Virtual Mfg is end goal, but

- Keep the scope restricted to machine tool errors and translation of these errors to part errors
- Concentrate on information models, database design and file formats

Slide 1-10

Action Items

- Create Data Dictionary
- Start moving data into Repository
- Establish a Consortium
- Establish electronic communication
- Develop a road map

Slide 1-11

Objectives of This Meeting

- Review progress of participants
- Review Data Dictionary
- Review status of Repository and analysis tools
- Review simulation tools
- Review road map and future work

2. Martin Kitna

Slide 2-1

BOEING

NIST Workshop — November 20, 1997

Factory Computing Architecture -
A Key Component of Boeing's 2016 Vision

NIST Workshop — November 20, 1997

Prepared by:
Factory Computing Architecture Core Team
Presented by:
Martin R. Kitna, FCA Measurement Domain Architect

1

Slide 2-2

BOEING — Factory Computing Architecture Users Conference

Factory Computing Architecture Is Strategic

✓A set of computing-based strategies :
- Enabling Factories Implement BCAG Initiatives
- Assure factory equipment investments have flexibility to change
- Assure connectivity to upstream and downstream data and functionality for future integration

✓These strategies are captured in:
- To-Be Architecture Framework
- Technical standards
- Transition plans -Business & Tech Forecasts
- Models capturing integration points allowing reuse

✓This architecture is deployed thru a common "Factory Upgrade Process"

Slide 2-3

Challenge to User and Supplier Community

Automation Strategies Forum — June 24 1997

- The Boeing Company is developing an integrated factory computing architecture
  - It will change the way we do business with our supplier community
- User Community - Team to define approach to evolve to common, open systems
- Supplier Community - Incorporate products into your business strategies supporting our transition to common, open systems

Challenge — 2

Slide 2-4

Boeing Corporation 2016 Vision

Automation Strategies Forum — June 24 1997

Customer focus Integrity Shareholder Value People Working Together

Business
- Integrated Aerospace Company
- ★ Global (International) Enterprise
- Competencies
- Large scale complex systems integration
- ★ Lean, efficient design and production systems
- Detailed customer knowledge & focus

People
- Select people carefully
- Retrain people extensively
- Expect involvement and accountability
- Work cooperatively with Unions
- Compensate at market rates with opportunity to earn more based on company success
- Strive to balance people's needs with those of the company
- Our people will reflect our geographic diversity
- Promote people fairly
- Provide opportunity for life-long learning
- Wellness both within and outside the company
- ★ Management's role is to support, remove roadblocks, and facilitate inter-team communication

Organization
- Small operating groups
- ★ Small business units
- ★ Small central organization providing critical integration
- Shared Resources organization
- Design & production 24 hrs./day - 7 days/week

Situation and Vision — 6

Slide 2-5

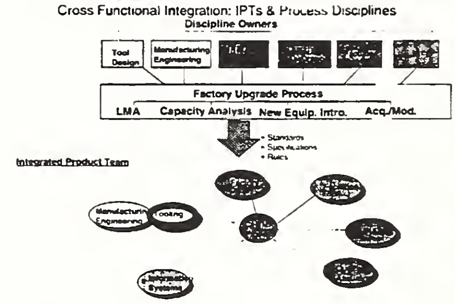
2016 Vision - Manufacturing Strategy

- Global enterprise
- Lean, efficient design & production
- Small business units
- Small central organization providing critical integration
- People and cultural change: Inter-team communication

Slide 2-6

BOEING — Factory Computing Architecture Users Conference

Cross Functional Integration: IPTs & Process Disciplines



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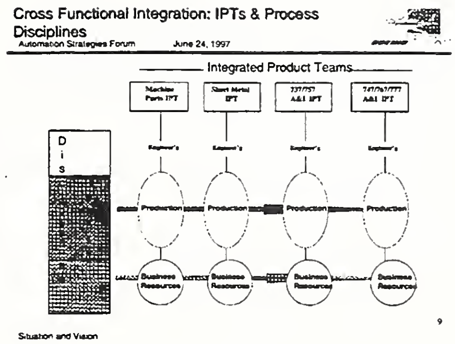

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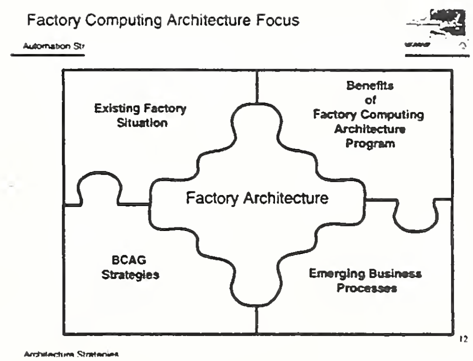

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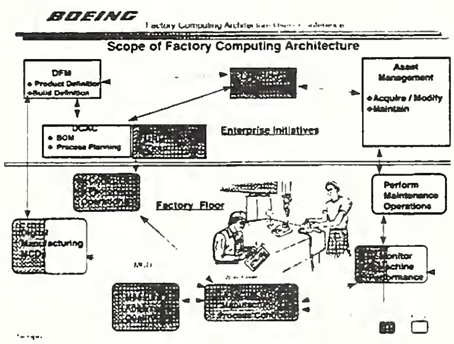
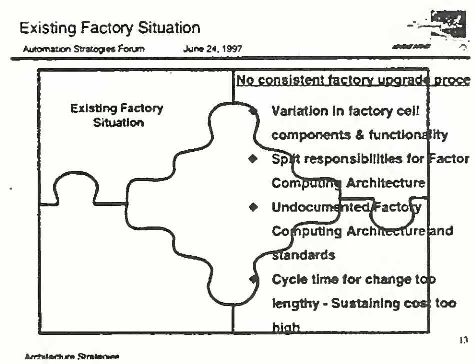


Slide 2-11



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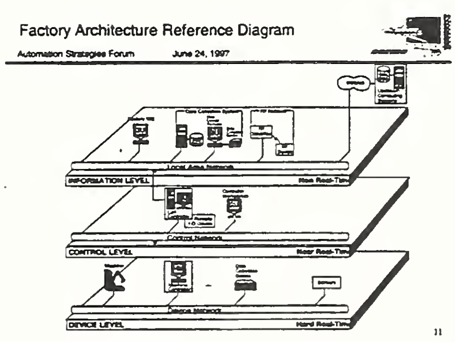

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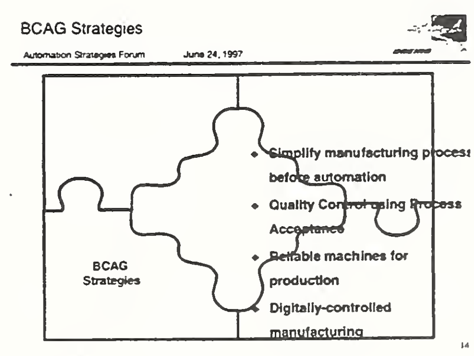
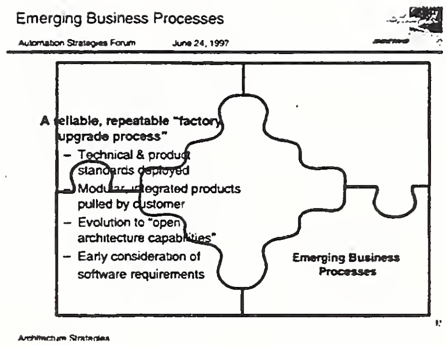
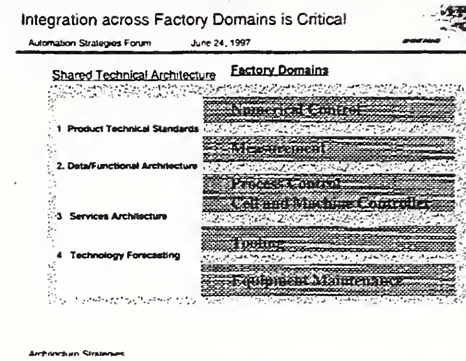


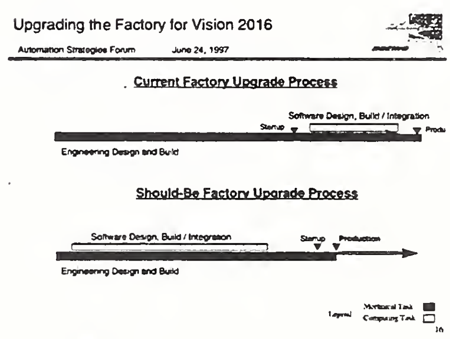
Slide 2-13



Slide 2-16



Slide 2-14



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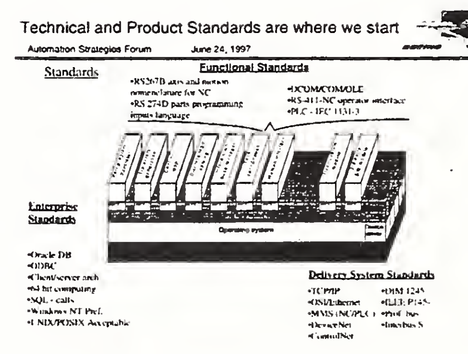

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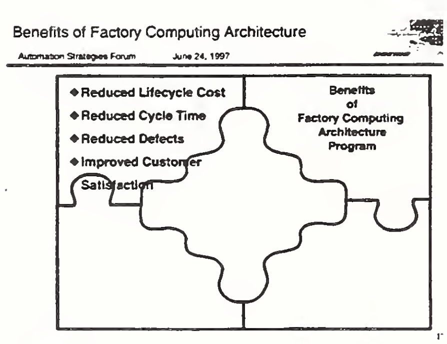

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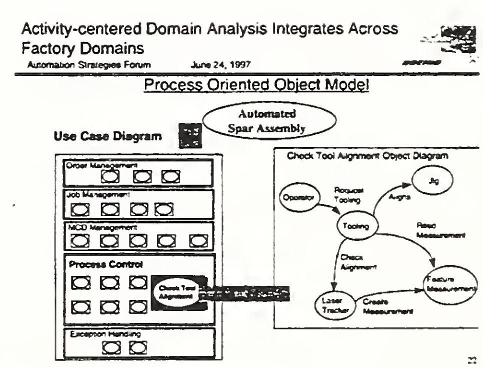

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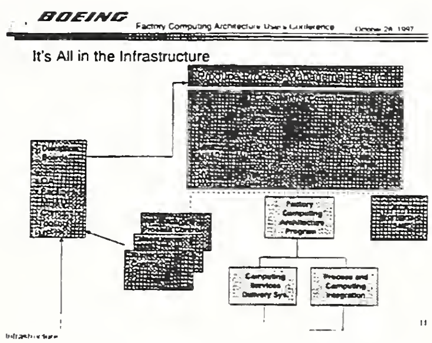

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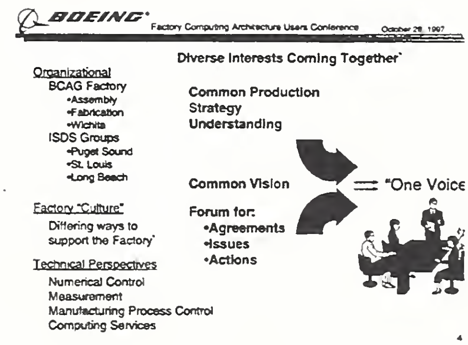

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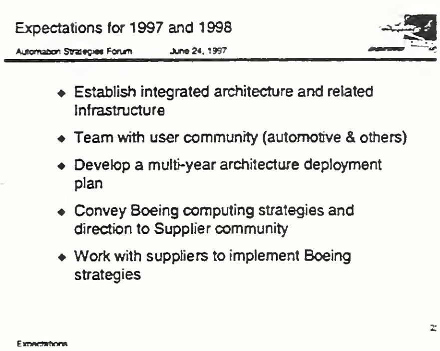

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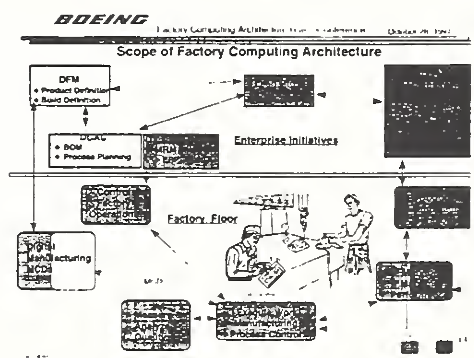

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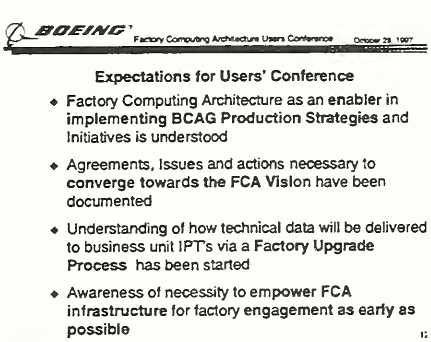

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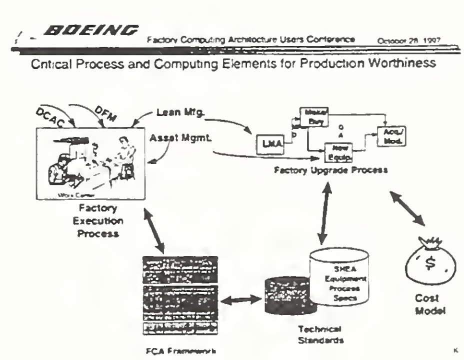

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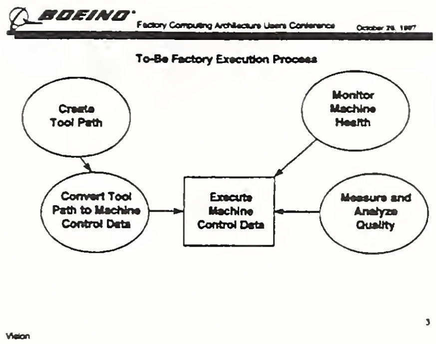

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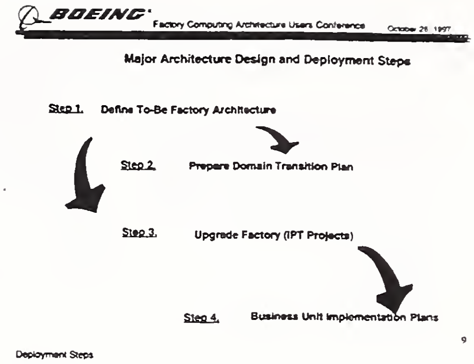

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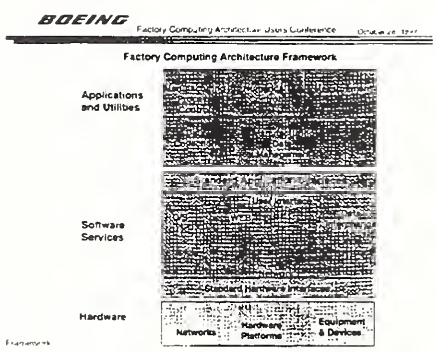

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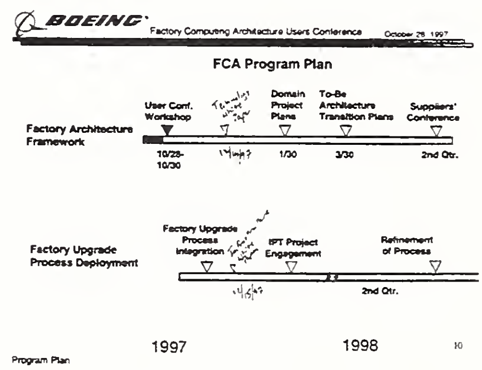


3. Vivek Chandrasekharan

Slide 3-1

CATERPILLAR®

Machine Tool Management &
Machining Simulation

Vivek Chandrasekharan &
James G. Katter
Sr. Mfg. & Systems Engineer
Mfg. & Logistics Technology Div.
Technical Center, Caterpillar Inc.

Slide 3-2

CATERPILLAR® Mfg. & Logistics Technology
Technical Services Division

Cat's View of the Machine Data Repository

- Our focus continues to be on three areas
  - Process Planning
  - Machine performance data and asset management
  - Simulation
- Our progress since last meeting
  - Increased pressure from plants to implement
  - Research partnership with Universities continues
  - Internal research, validation and implementation
  - Joined NIST-CRADA and collaborative work

Slide 3-3

CATERPILLAR®

- NISTIR 5707 - Modeling of Mfg. Resources
- Internal "machine folders"
- Validation of data models
- Identifying users and feedback
- Important characteristics to trend
- Platform / Implementation issues (layering)
- Link to commercial software databases for new machine tools
- Feasibility of Implementation

Slide 3-4

CATERPILLAR®

Research with Universities

- Understanding machine errors
  - thermal errors
  - ambient effects
  - repeatability
  - spindle analyzer
  - tool change repeatability
  - combining all errors
  - loaded conditions
  - correlation to part errors

Slide 3-5

CATERPILLAR®

Internal Work

- Validating data models, production machines
- Machine characterization
- Quasi static error integration
  - machine metrology to std. format
  - simulation and validation
- Correlation to part features
  - rough operations
  - finish operations

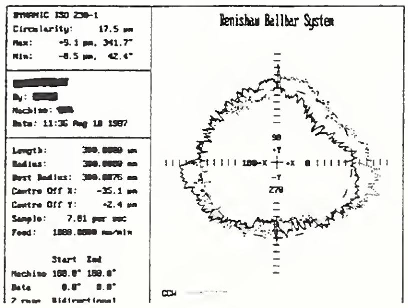
Slide 3-6

CATERPILLAR®

Work with NIST

- Testing the repository
  - successfully submitted ball bar data
  - comparative analysis (ISO 230-1, ISO 230-4)
- Data definitions referenced from documents provided at previous meeting (Hans Soons)
- Simulation methods
- Communications and demonstration

Slide 3-7



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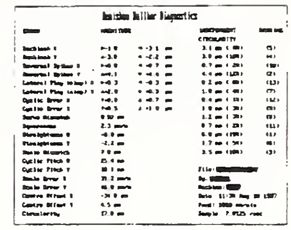

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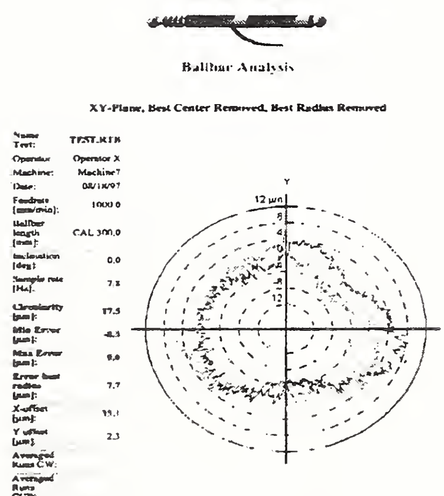

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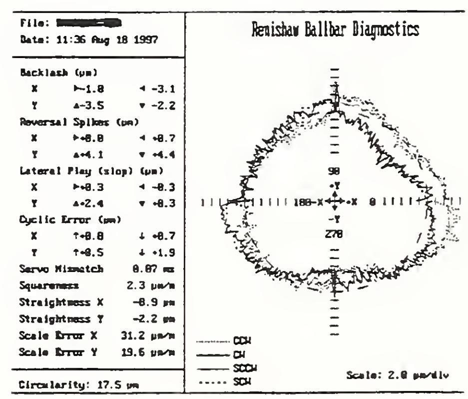

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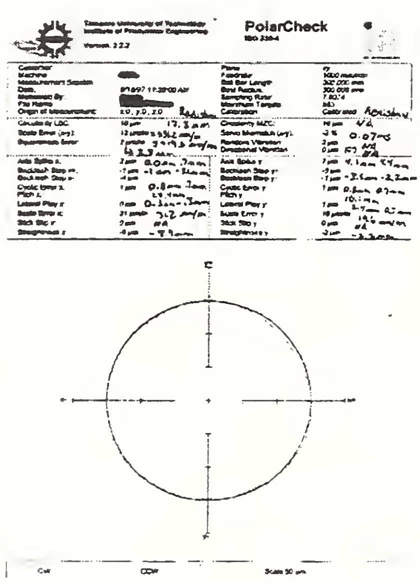


Slide 3-12

CATERPILLAR

Recommendations for Future Work

- Ball bar analysis from repository
  - Standardization of computing errors
  - Comparative analysis
  - Trending of errors
  - Supplier formats
  - Transfer of technology and demonstration

Slide 3-13

CATERPILLAR

Recommendations for Future Work

- Simulation
  - Combining errors
  - Internal representation of errors on CAD file
  - Visualization
  - Sensitivity for machine correction

Slide 3-14

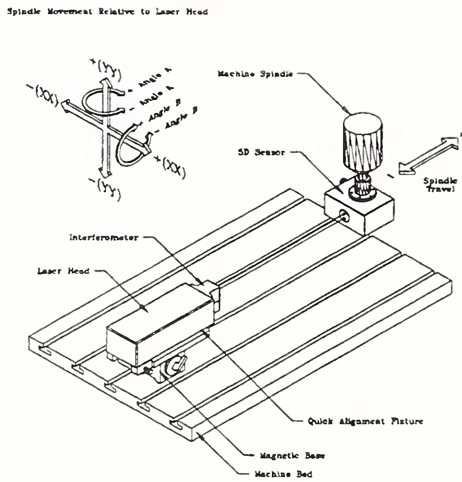
CATERPILLAR

Recommendations for Future Work

- Laser characterization of machines
  - Reporting file formats from different manufacturers
  - Standardize file format
  - Storing raw data?
  - Store data model coefficients
    - Standardize model
    - Residual error (goodness of fit)
    - File format / data structure
  - Repeatability (model, distribution)

4. Sean Olson

Slide 4-1



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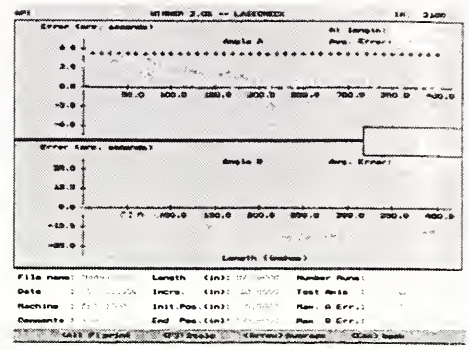

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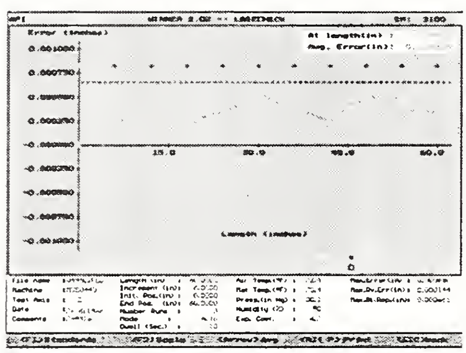


Slide 4-5

Error File Format

<u>Linear Measurement</u>
File: 1141a001.erl

Max. Error: 0.005925
Max. Rev. Err: 0.000468
Increment: 10.0000
Travel Length: 160.000
Unit of Length: inches
Air/Mat.Temp.(øF):78.0/77.0
Position: 462.763
Max.Bi.Rep.: 0.001247
Date : 8/26/1997

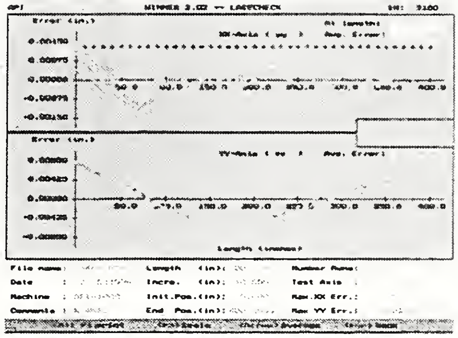
<u>Angular Measurement</u>
File 1141a001.era

Max. Err. -A-: 5.5
Max. Err. -B-: 7.1
Increment: 10.000000
Travel Length: 160.000000
Unit of Length: inches

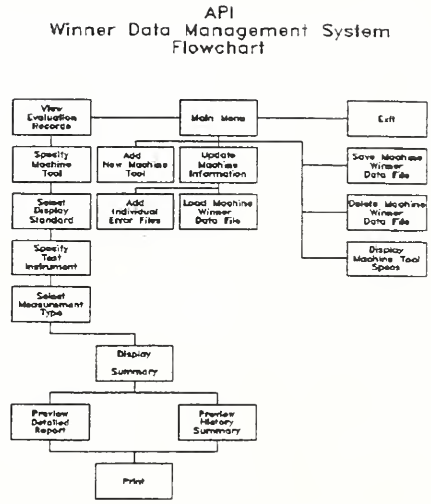
<u>Straightness Measurement</u>
File 1141a001.ers

Max. Err. -XX-: 0.001082
Max. Err. -YY-: 0.001197
Increment: 10.000000
Travel Length: 160.000000
Unit of Length: inches

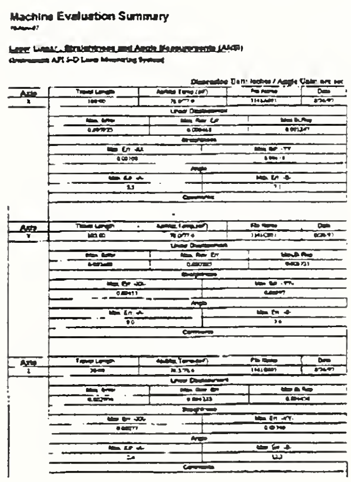
Slide 4-3



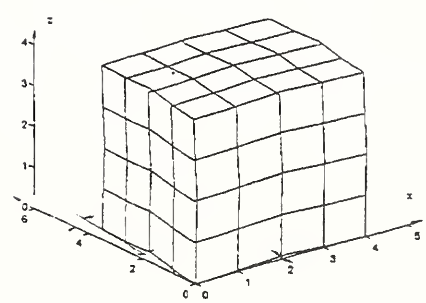
Slide 4-6



Slide 4-7



Slide 4-10



Slide 4-8

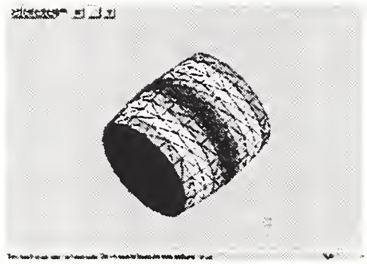


Figure 1 Radial Part Error

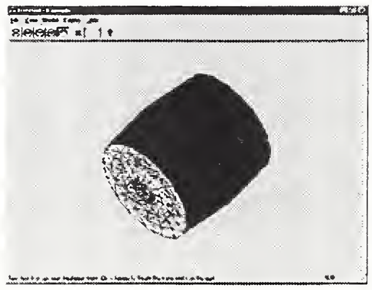
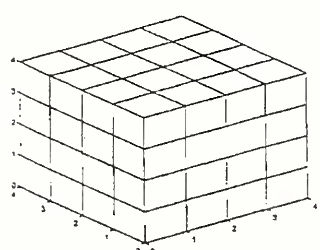
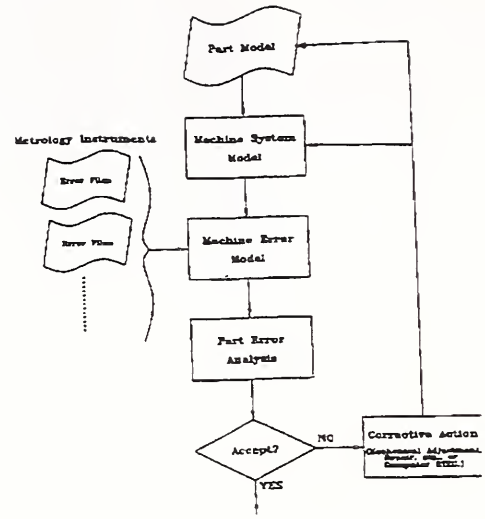


Figure 2 Axial Part Error

Slide 4-9



Slide 4-11



Interconnection between Part Model, Machine Model, Machine Error Model, and Possible Corrective Actions.

5. Don Esterling

Slide 5-1

Techniques for Modeling
CNC Machine Errors

Donald Esterling
N-See Software
Microcompatibles, Inc.

Slide 5-2

Objective

Starting from
- A collection of shop floor CNCs
- Error models for each CNC
- Particular CNC part program

Determine
- Which CNC(s) can deliver the part within tolerance

Slide 5-3

Pixel-Based Systems
(Animation)

- Accurate in view direction (1:32,000)
- Lacks accuracy in screen X-Y directions (1:500)
- Slow, Roughly the same speed as a physical CNC

Slide 5-4

Traditional (CAD-like)
Solid Models

- Useful for modeling work cells (large scales, complex scene)
- But for metal removal, must choose between
  - reasonable response time, fairly coarse accuracy
  - shop floor accuracy, hours or worse response time for complex part programs

Slide 5-5

CAM-Specific Solid Modeling

- Focus is on metal removal process
- Orders of magnitude faster than a CNC
- Retain shop floor accuracy

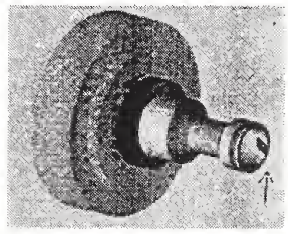
Slide 5-6

N-See Solid Model Verification

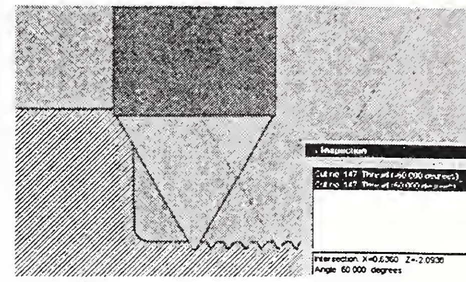
- Assumes a "perfect" machine tool
- Will demonstrate
  - 2 axis turning
  - 3 axis milling
  - 4 axis milling (indexing)
  - 5 axis milling (simultaneous)

Slide 5-7

N-See Lathe (Animation)

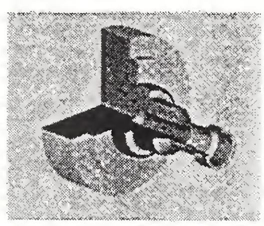


Slide 5-10



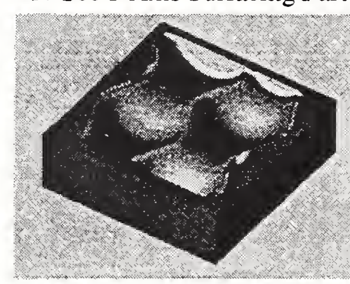
Slide 5-8

N-See Lathe (Solid Model)



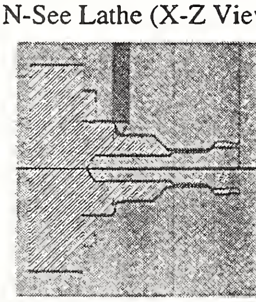
Slide 5-11

N-See 3 Axis Surfacing Part

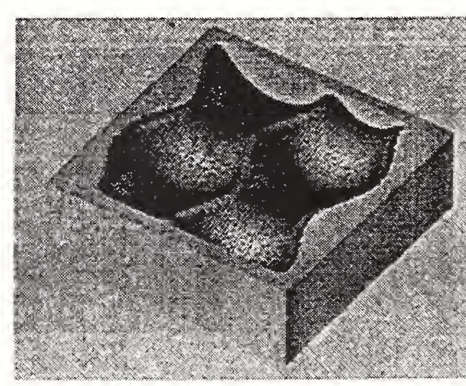


Slide 5-9

N-See Lathe (X-Z View)



Slide 5-12



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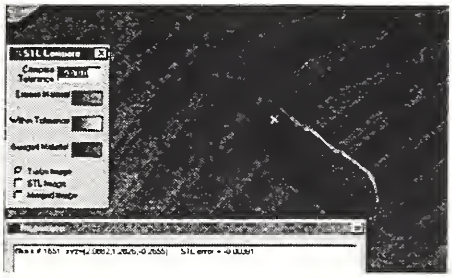
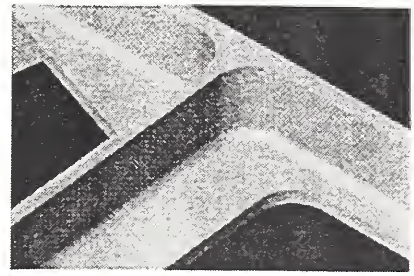


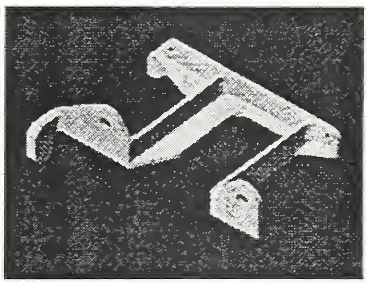
Slide 5-16

N-See 4 Axis (Zoom)



Slide 5-14

N-See 4 Axis Part



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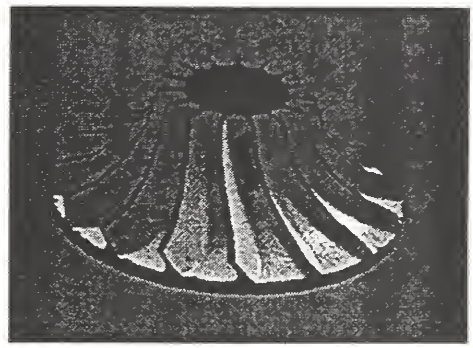
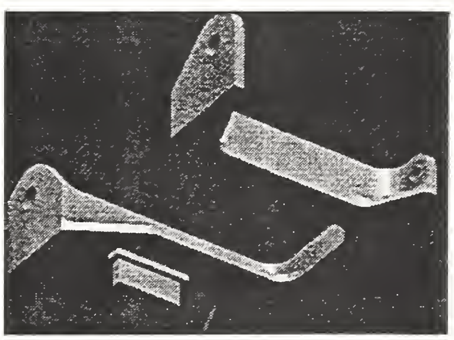


Slide 5-15



Slide 5-18

Error Modeling with N-See

- Done over a year ago, on experimental software
- Modeled CNC hardware errors with NIST error model
- Turning Only, NIST Demo Part Only
- Demonstrated feasibility

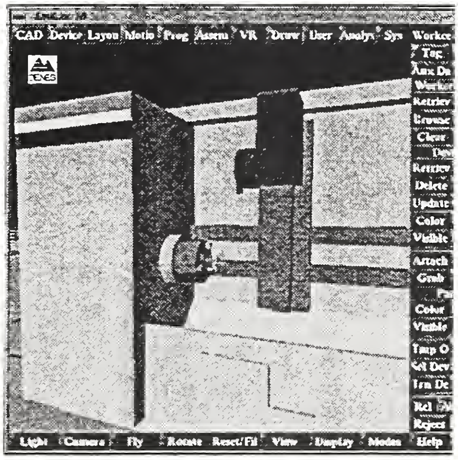
Slide 5-19

Next Steps

- Generalize to multiple turning centers, multiple parts
- Provide a convenient, automated comparison of different turning centers
- Milling Anyone ???

6. Joe Falco

Slide 6-1



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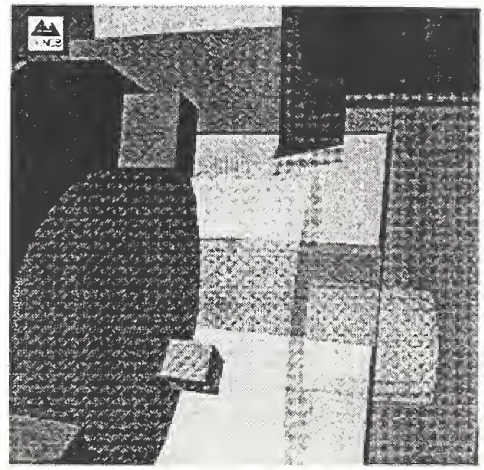

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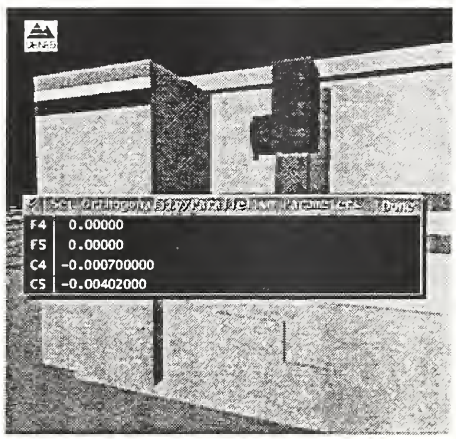
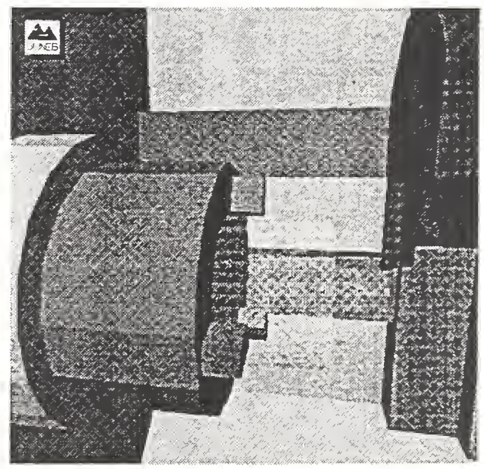


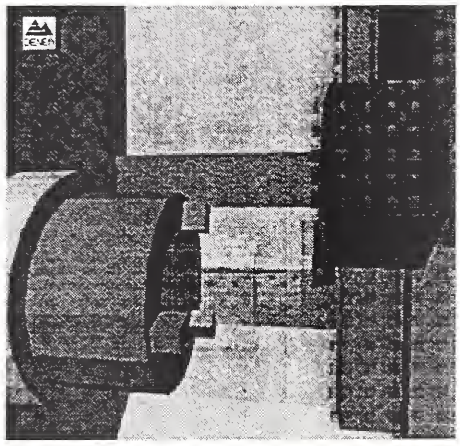
Slide 6-5



Slide 6-3

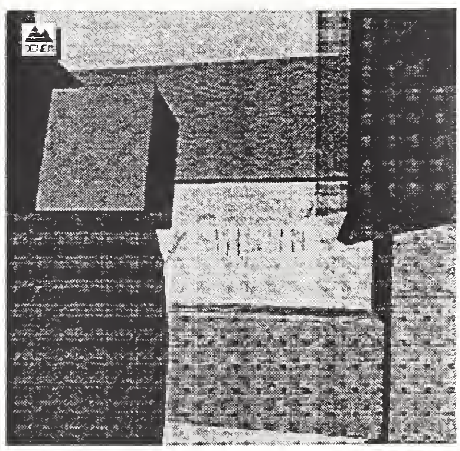
Slide 6-6

Slide 6-7



Slide 6-9

Slide 6-8



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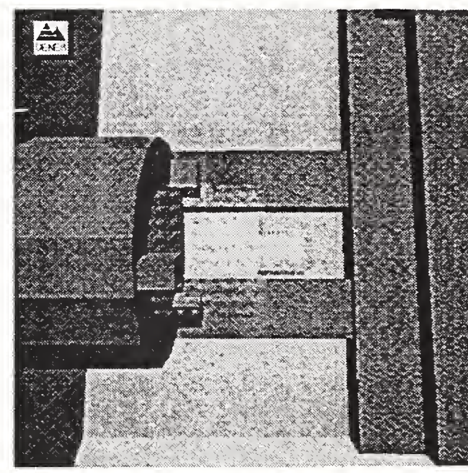


7. Debbie Krulewich

Slide 7-1

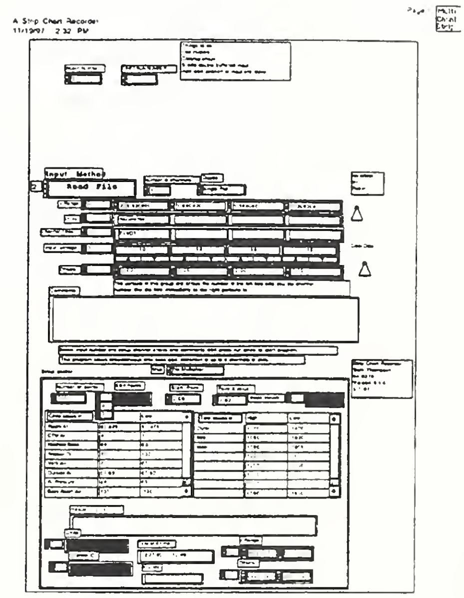
Debbie Krulewich

Lawrence Livermore National Laboratory

Workshop on Development of Machine Tool Performance Models and Data Repository

November 20-21, 1997

Slide 7-4



Slide 7-2

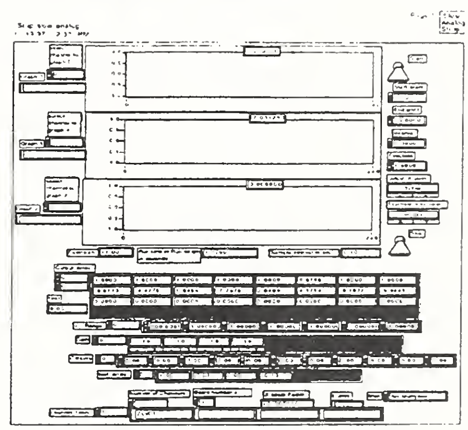
LLNL is interested in machine tool performance models and data repository

1. To archive and retrieve machine performance history
   - Currently, we use LabView data acquisition that records a header with user-specified information (sign convention, last type, etc.)
   - We have no historical record that keeps track of all the tests that have been performed.

2. To gather generalized information about machine tool errors
   - For error budgeting purposes, we would like to know typical errors for specific types of components.

3. For cutting force simulations
   - It would be useful to have access to cutting coefficients for different materials and tools.

Slide 7-5

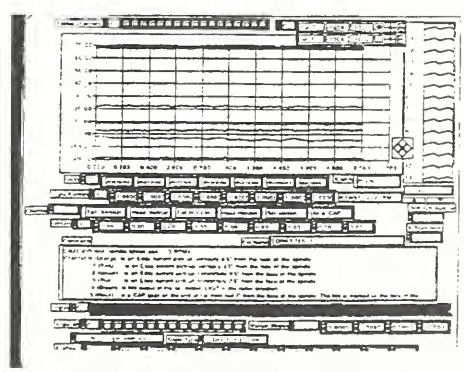


Slide 7-3

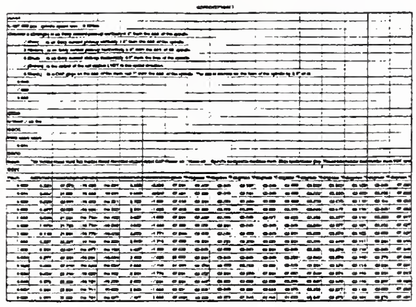
Important issues to resolve

- Data acquisition issues
  - sampling rate (spatial or temporal)
  - analog filtering
- Sign convention
- Non-repeatable error characterization

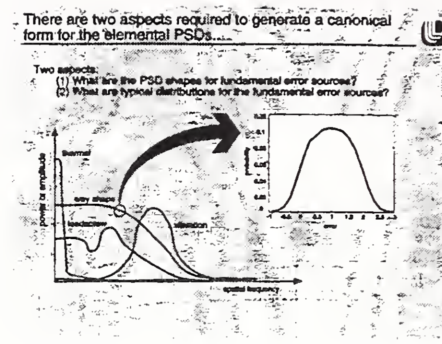
Slide 7-6



Slide 7-7



Slide 7-10



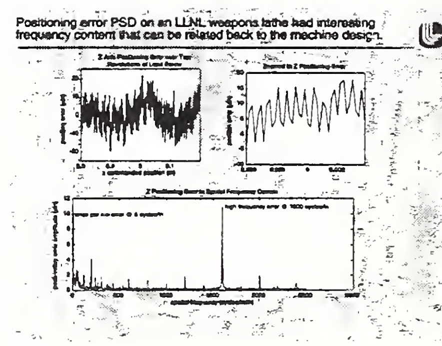
Slide 7-8

X HORIZ. STRAIGHTNESS.88

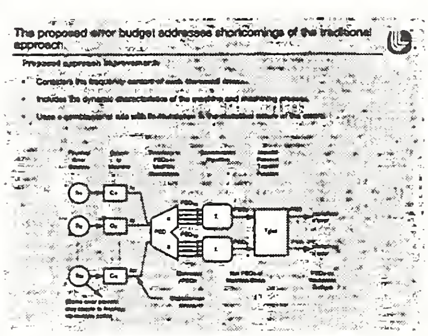
AAAA				
M 365				
BOSTOMATIC				
MILLING MACHINE Machine Positions at start				
X 1010.0 mm				
Y 200.0 mm				
Z 162.0 mm				
Location of measurement line				
X horizontal				
Y				
Z				
Axis X AXIS HORIZ STRAIGHT				
Plane X-Y				
Polarity -- MACH. PLUS				
Backlash REMOVED				
BBBB				
Straightness				
Bidirectional				
Fast Analog				
Number of runs 4				
Feedrate 470.000				
Start position 1010.0000				
End position 70.2000				
X increment -0.2540				
Data collection freq hz -30.839895				
CCCC				
Straightness tests using TOTO one meter straightedge.				
DDDD				
11/30/88 3:07 PM				
Test type				
3				
EEEE				
Chart X	force	displacement	weight	movement
FFFF				
mm	microns	microns	microns	microns
1010	2.4902344	2.2460938	2.7441406	2.4316406
1009.746	2.4804688	2.2363281	2.7441406	2.421875
1009.492	2.5195312	2.2363281	2.8853125	2.4121094
1009.238	2.4414062	2.2363281	2.8367188	2.4316406
1008.984	2.4804688	2.2460938	2.6660156	2.421875
1008.73	2.5488281	2.2558594	2.7050781	2.421875
1008.476	2.578125	2.2363281	2.7539062	2.4316406
1008.222	2.6074219	2.2363281	2.7734375	2.4316406
1007.968	2.5660156	2.2460938	2.8222656	2.4316406
1007.714	2.6171875	2.2363281	2.8027344	2.4316406

Page 1

Slide 7-11



Slide 7-9



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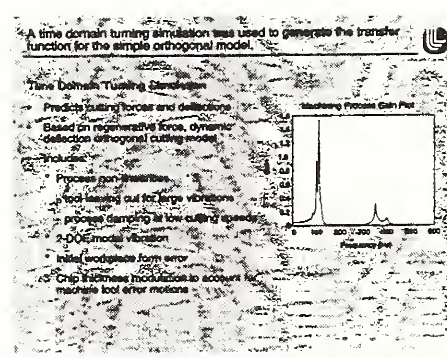


8. Dan Sawyer

Slide 8-1

THE CALCULATION OF CMM MEASUREMENT UNCERTAINTY VIA THE METHOD OF SIMULATION BY CONSTRAINTS

S.D. Phillips, B. Borchardt, D. Sawyer, W.T. Estler,
D. Ward, K. Eberhardt, M.S. Levenson, M. McClain,
National Institute of Standards and Technology

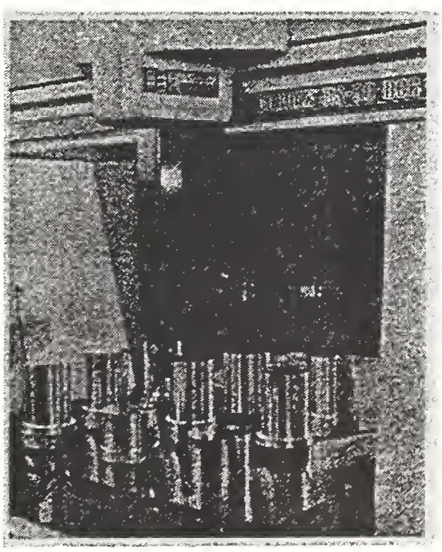
B. Melvin, ICAMP Inc.,
T. Hopp, ZigZag Inc.,
Y. Shen, G. W. University

Slide 8-2

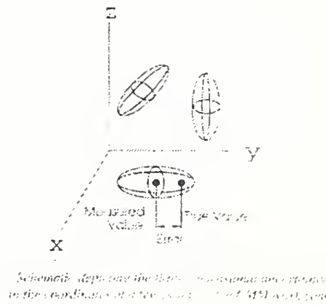
OVERVIEW

- Review CMM Uncertainty Concepts
- Current Computational Approaches
- Concept of Simulation by Constraint
- Results: Uncertainty vs. Actual Errors

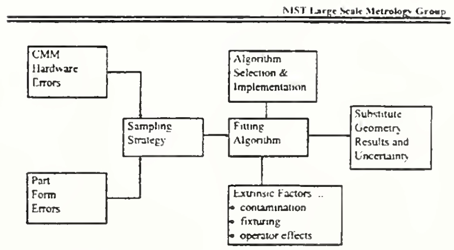
Slide 8-3



Slide 8-4

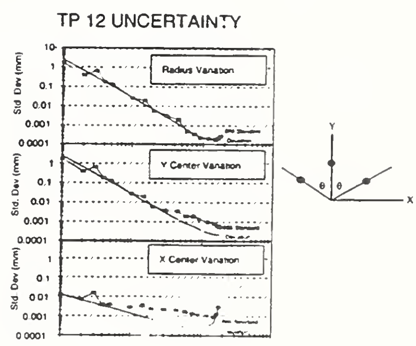


Slide 8-5

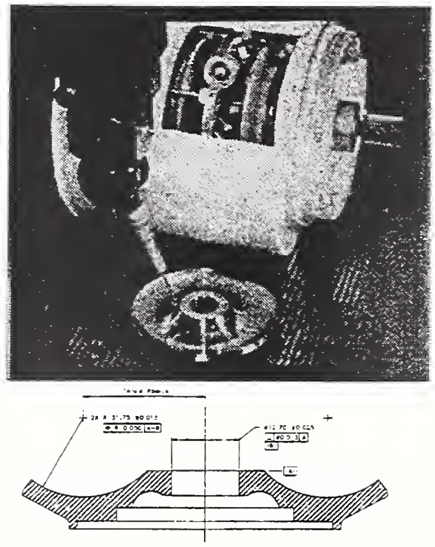


Schematic outlining the various factors affecting CMM measurements.

Slide 8-6



Slide 8-7



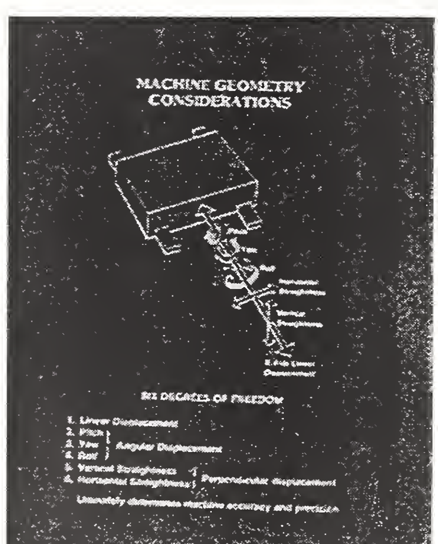
Slide 8-8

SIMULATION GOAL

Calculation of Task Specific Measurement Uncertainty from

NON-Task Specific CMM Test Data

Slide 8-9



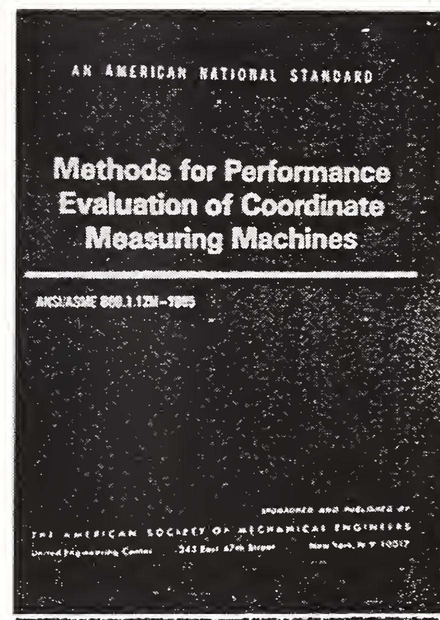
Slide 8-10

SIMULATION BY CONSTRAINT IDEA

Use Incomplete Performance Evaluation Data
to Determine a Population of Possible CMM States
that are Consistent with the Data

The Performance Evaluation Data Must Be Sensitive
To All the Kinematic Errors

Slide 8-11



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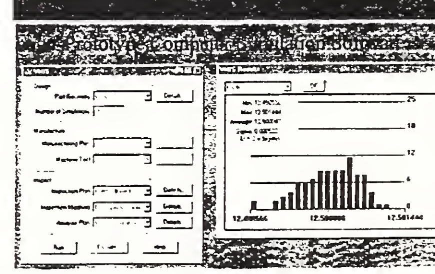

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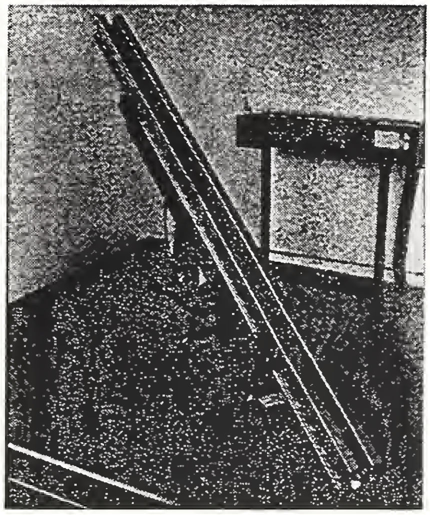

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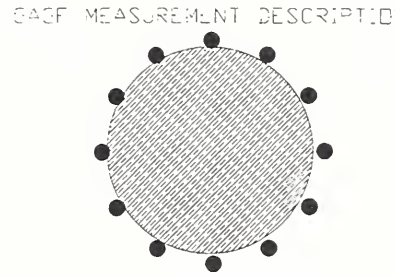

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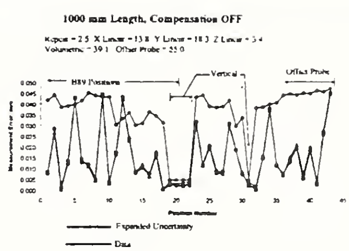

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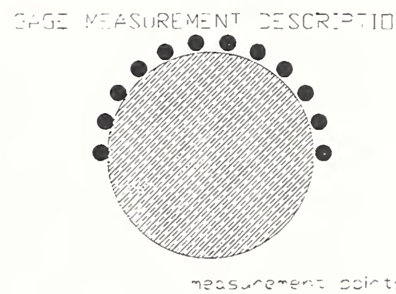

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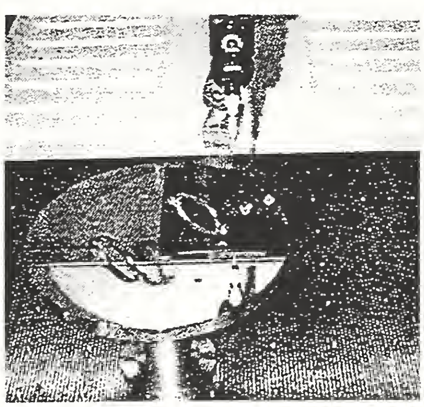

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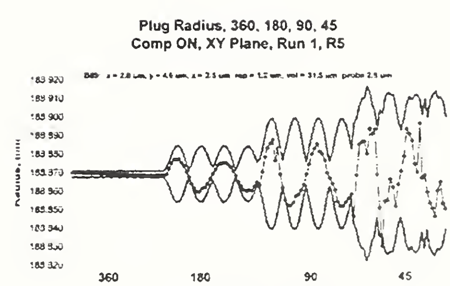

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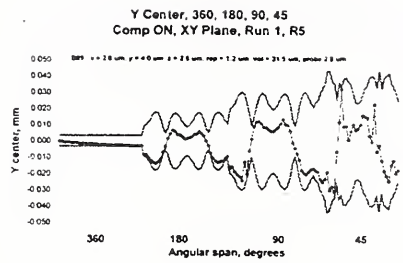

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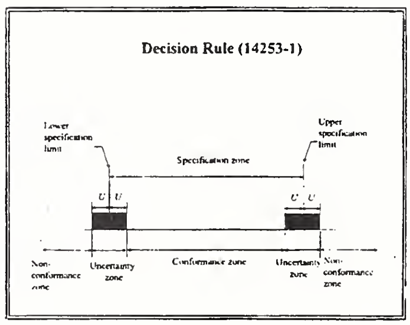


Slide 8-21

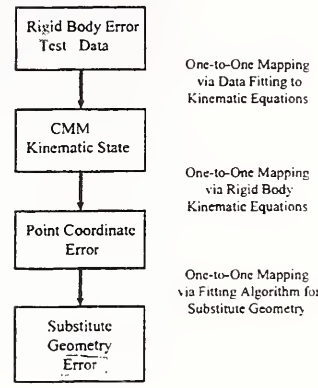
EXAMPLE OF PERFORMANCE EVALUATION DATA

ANSI/ASME B89.4.1 Values

Repeatability
X Linear Accuracy
Y Linear Accuracy
Z Linear Accuracy
Volumetric Performance
OffSet Probe Volumetric Performance
Point-to-Point Probe Performance

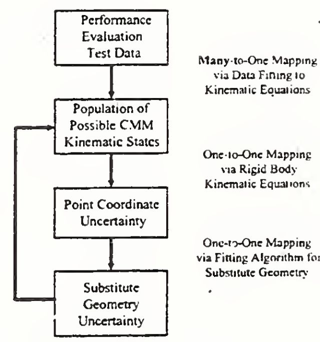
Slide 8-22

FULL PARAMETRIC SIMULATION FLOW CHART



Slide 8-23

SIMULATION BY CONSTRAINT FLOW CHART



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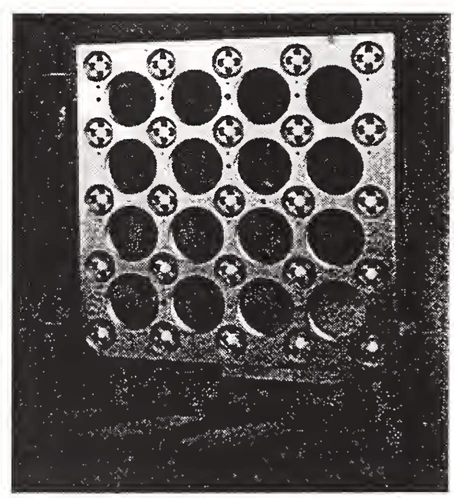
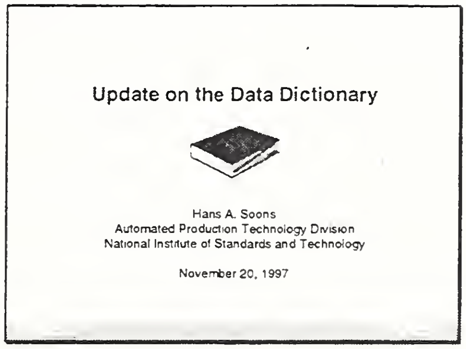


9. Hans Soons

Slide 9-1



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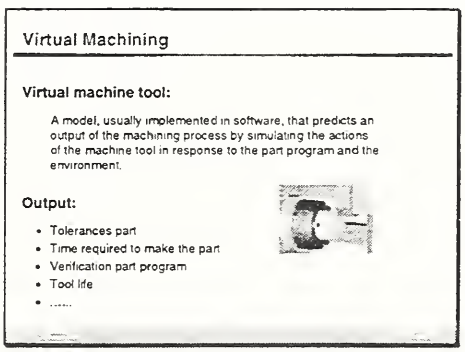

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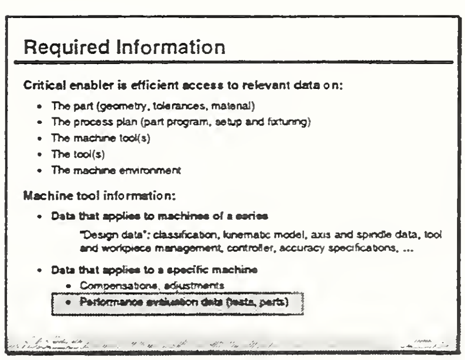

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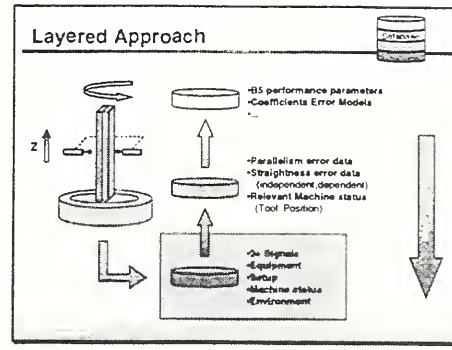

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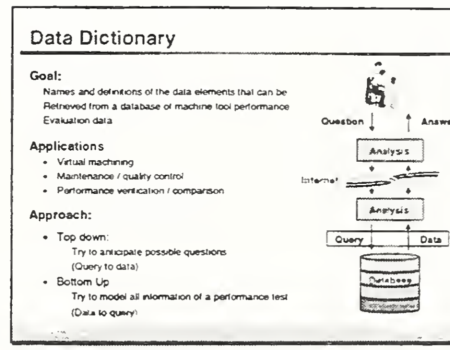

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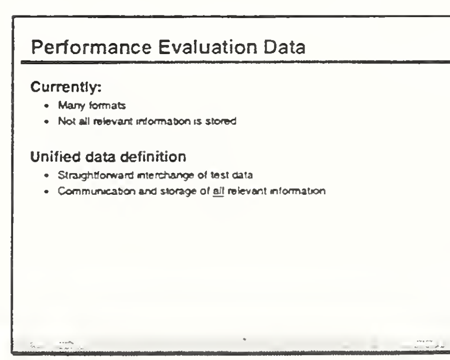


Slide 9-7

Criteria

- 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
- Efficient handling of queries
- Keep all information of original data files
- Express

Slide 9-8

Test Equipment (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

Slide 9-9

Machine and Environment

- Status of the machine
  - Applied compensations
  - Coolant
  - Clamped axes
  - Applied warm-up procedure
  - Temperatures
- Status of the machine environment

Slide 9-10

Setup and Machine Motion Pattern

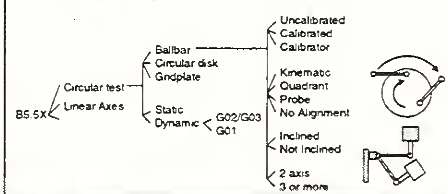
Classification according to setup and motion pattern:

- 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
- ....

Slide 9-11

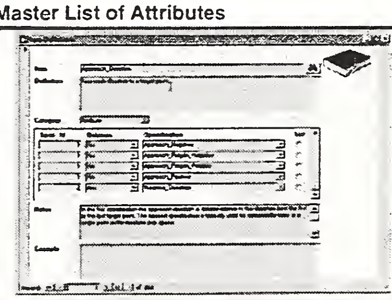
Development

- Master list of attributes
  - First prototype with over 250 definitions
  - Commercial database with added user-friendly interface
- Which attributes apply



Slide 9-12

Master List of Attributes



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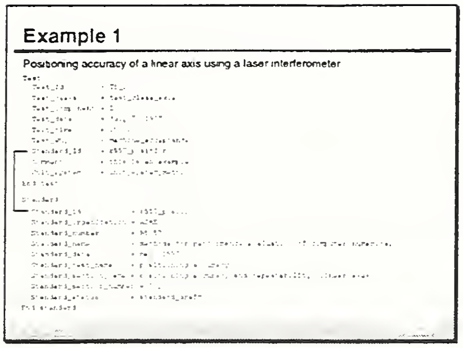

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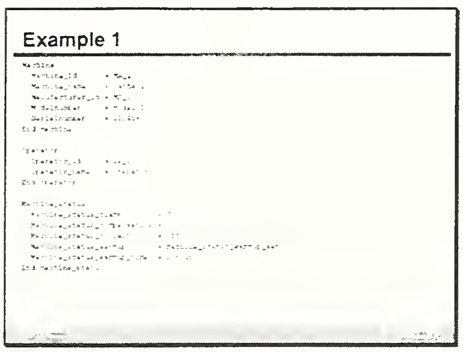

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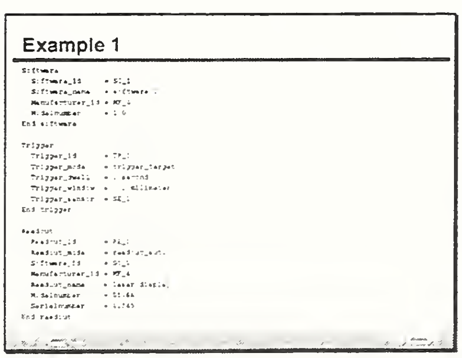

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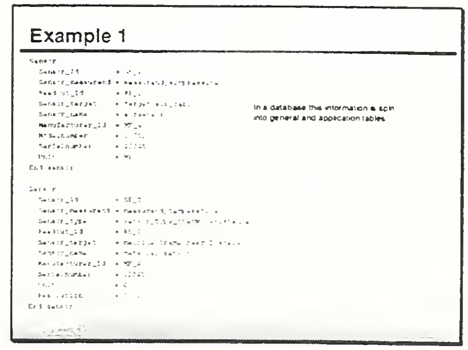

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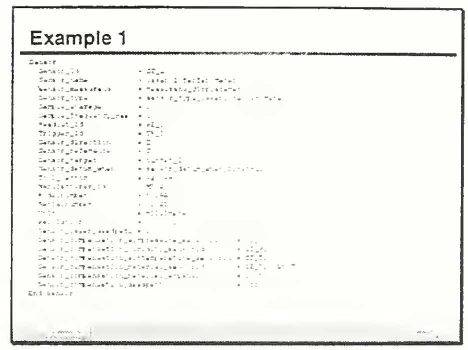

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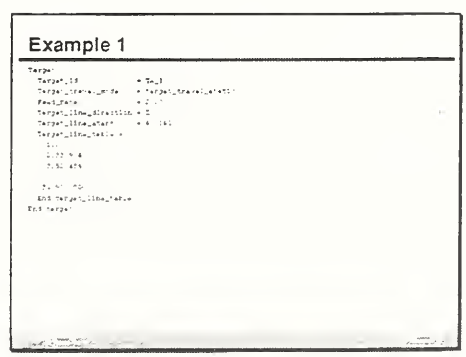

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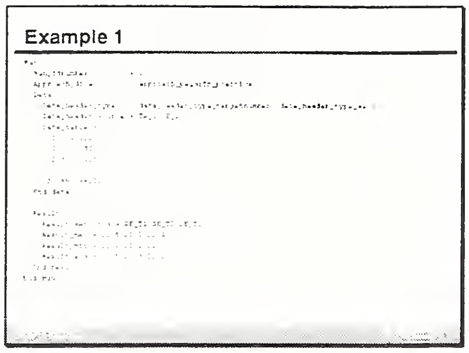

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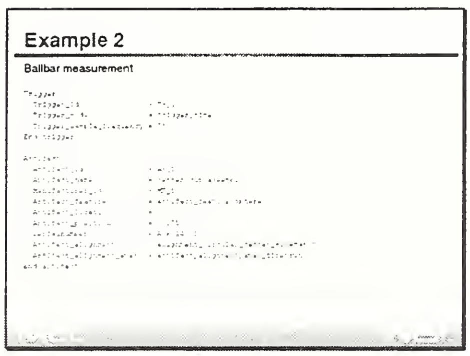

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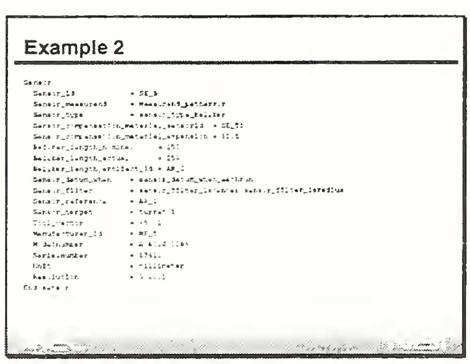

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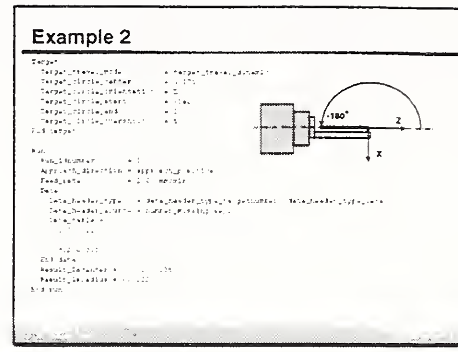

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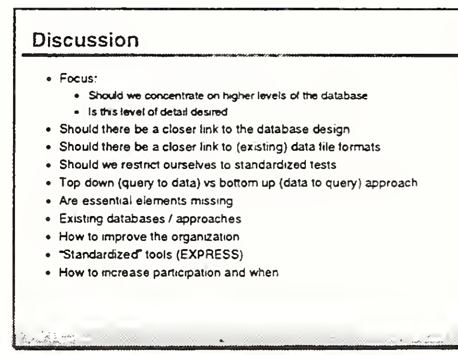


10. Larry Welsch

Slide 10-1

Update on the Repository

Lawrence A. Welsch, Ph.D.
Lawrence.Welsch@nist.gov

Slide 10-2

Status and Plans

- Software Framework
- Yesterday
- Today
- Tomorrow
- Day after tomorrow
- Issues

Slide 10-3

Software Framework

- Platform
- CGI Scripting Tools
- Analysis Tools
- Data Base Tools
- Design

Slide 10-4

Yesterday

- Platform
  - Hardware
  - Software
  - Portability
- CGI
  - PERL
  - KSH
- Analysis - MATLAB
- Data Base
  - Clear Text
  - Linear Search
- Design
  - Classic Web
  - Functionality (Barely)

Slide 10-5

Today

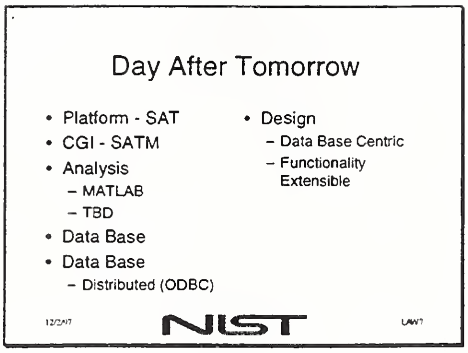
- Platform
  - Hardware
  - Software
  - Portability
- CGI
  - SAY
  - MATLAB
- Analysis - MATLAB
- Data Base - MATLAB
- Design
  - MATLAB centric
  - Functionality (limited)

Slide 10-6

Tomorrow

- Platform - SAT
- CGI
  - PERL + ODBC
  - KSH
- Analysis - MATLAB
- Data Base
  - MS SQL Server
  - ODBC
- Design
  - Classic Web
  - Classic Data Base
  - Functionality (limited)

Slide 10-7



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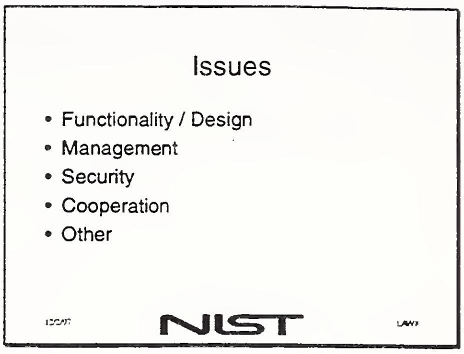
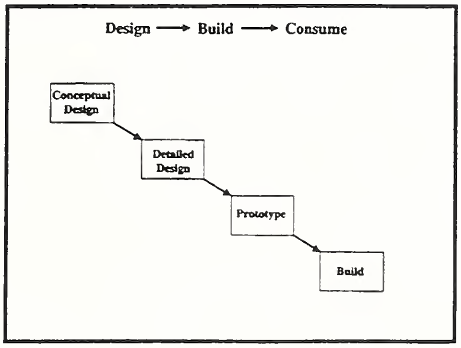
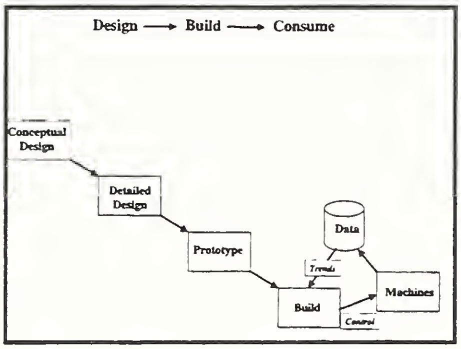


11. Richard Johnson

Slide 11-1



Slide 11-2



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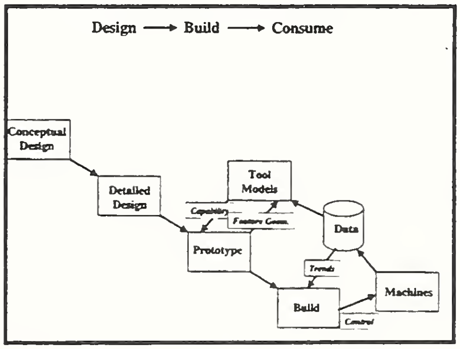

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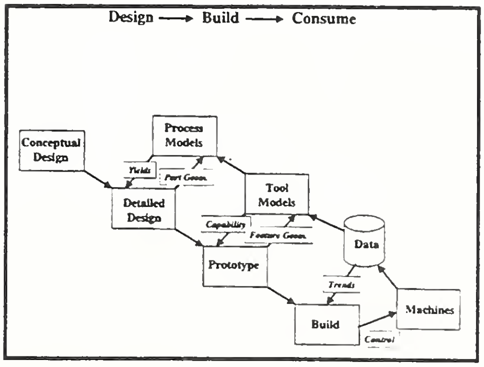

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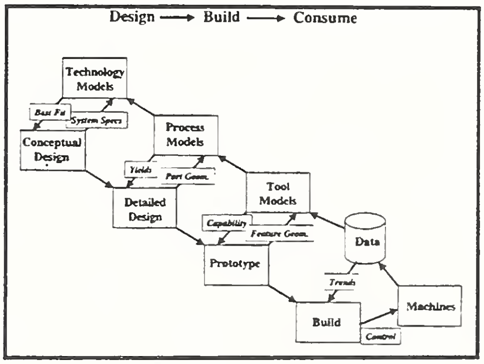

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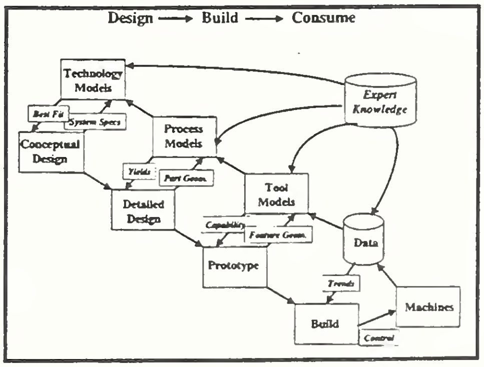

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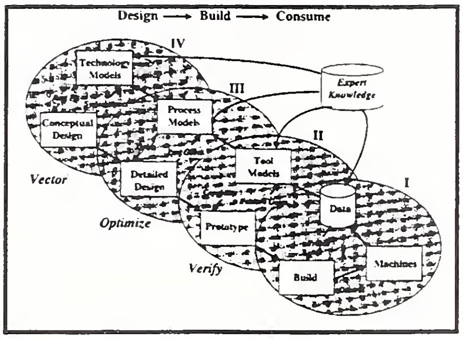
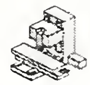

Design ⟶ Build ⟶ Consume
IV
Technology Models
III
Expert Knowledge
Process Models
Conceptual Design
II
Tool Models
Vector
Detailed Design
I
Data
Optimize
Prototype
Verify
Machines
Build

12. Road Map

Slide 12-1

Machine Tool Performance Models
and
Machine Data Repository

A Draft Road Map



Alkan Donmez
Project Technical Leader

Slide 12-2

Key Questions

- Can it be made?
- How can it be made?
- How can it be made competitively?
- How can it be kept that way?

Core of the answers: DATA and INFORMATION

Slide 12-3

Tools needed

- Tolerance budgeting
- Process/asset planning
- Capability analysis (Cpk)
- Machine simulation
- Process simulation
- Inspection planning and simulation
- Machine maintenance (performance tracking)

Slide 12-4

How do we get there?

- Data Dictionary, formats and info models for quasi-static machine tool performance and resulting Repository (including environmental info, physical machine description, and uncertainties) -- FY98
- Data analysis tools -- FY98 - 99
- Simulation tools -- FY99

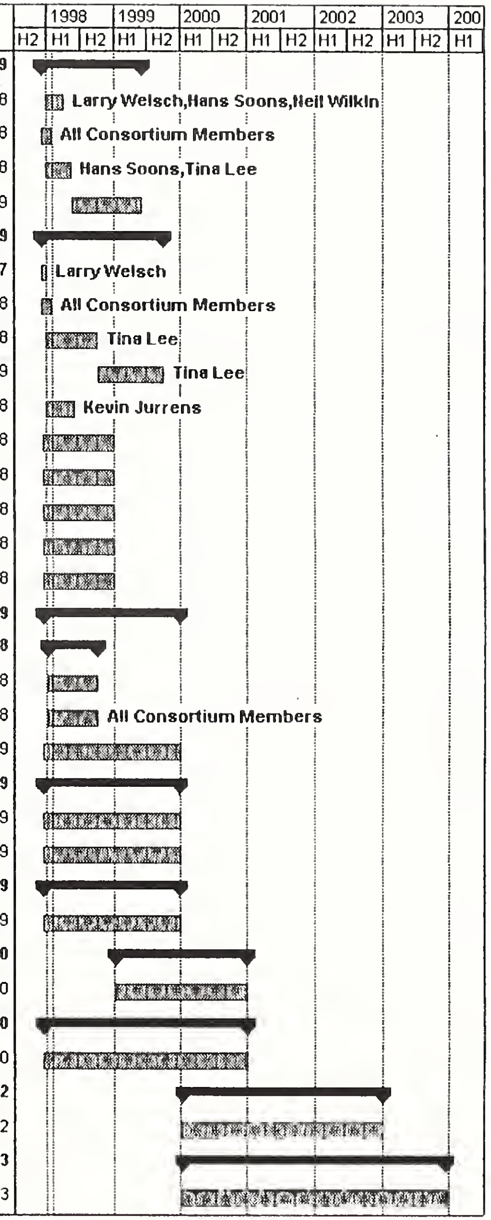
Slide 12-5

How do we get there?

- Performance tracking tools -- FY98 - 00
- Capability evaluation (Cpk) tools -- FY00
- Inspection analysis tools -- FY01
- Dynamic models integration -- FY02
- Machine/process model integration -- FY03

Appendix II – Time Line resulted from Discussions

ID	Task Name	Start	Finish
1	**Data Dictionary**	**Tue 12/2/97**	**Mon 5/31/99**
2	Web Page to Extract Attributes of Tests (circular)	Mon 12/22/97	Wed 4/1/98
3	Comments on Structure of Data Dictionary	Tue 12/2/97	Fri 1/30/98
4	Usable Data Dictionary for Standard Tests (tree structure)	Mon 12/22/97	Mon 5/18/98
5	Usable Data Dictionary Including Performace Parameters	Mon 5/18/98	Mon 5/31/99
6	**Repository**	**Tue 12/2/97**	**Fri 10/1/99**
7	Security and Management Issues of Repository	Tue 12/2/97	Mon 12/29/97
8	Send File/Formats for Circular Tests	Tue 12/2/97	Fri 1/30/98
9	Information Models for Standard Tests	Mon 12/22/97	Thu 10/1/98
10	Information Models Including Performace Parameters	Thu 10/1/98	Fri 10/1/99
11	Machine Classification Integrated into Repository	Mon 12/22/97	Fri 5/29/98
12	Optional Formats for Downloading Files	Fri 12/5/97	Thu 12/31/98
13	Multiple File Upload	Fri 12/5/97	Thu 12/31/98
14	Addition of Graphical Displays of Data/Performance Parameters	Fri 12/5/97	Thu 12/31/98
15	Stable Repository Information Exchange of Test Data	Fri 12/5/97	Thu 12/31/98
16	Involvement of More Potential Users and Vendors	Fri 12/5/97	Thu 12/31/98
17	**Data Analysis**	**Mon 12/8/97**	**Fri 12/31/99**
18	**Diagnostics**	**Fri 1/2/98**	**Thu 10/1/98**
19	Example of Ball Bar on Web Page	Fri 1/2/98	Thu 10/1/98
20	Submit Case Studies, Data, White Paper	Fri 1/2/98	Thu 10/1/98
21	Time Dependent Analysis	Mon 12/8/97	Fri 12/31/99
22	**Modeling**	**Mon 12/8/97**	**Fri 12/31/99**
23	Convert Data to a Set of Parametric Equations	Mon 12/8/97	Fri 12/31/99
24	Simulation Tools	Mon 12/8/97	Fri 12/31/99
25	**Performance Tracking Tools**	**Mon 12/8/97**	**Fri 12/31/99**
26	Cpk. Translate part errors to machine to get statistical info	Mon 12/8/97	Fri 12/31/99
27	**New Test Methods and Data Analysis**	**Mon 1/4/99**	**Fri 12/29/00**
28	Loaded Machine Tests	Mon 1/4/99	Fri 12/29/00
29	**Inspection Analysis Tools**	**Mon 12/8/97**	**Fri 12/29/00**
30	Inspection Analysis (ICAMP) Linked to Reposotory	Mon 12/8/97	Fri 12/29/00
31	**Dynamic Models**	**Mon 1/3/00**	**Tue 12/31/02**
32	Integration of Dynamic Models	Mon 1/3/00	Tue 12/31/02
33	**Machine Process Models**	**Mon 1/3/00**	**Mon 12/15/03**
34	Integration of Machining Process Models	Mon 1/3/00	Mon 12/15/03



Appendix III - MIMETEK PART AND PROCESS MONITORING AND ARCHIVING SYSTEM

Richard Jennings
ICAMP and MIMITEK

It is possible to use inspection data to characterize and monitor the dimensional "behavior" of machine tools and Coordinate Measuring Systems (CMS) and their associated software. NIST's ATEP-CMS is providing very interesting independent assessment of CMS data analysis software and ICAMP provides commercial, independent, and rapid data analysis software which can be used with CMS and machine tool sensors.

Think of a machine tool or CMS as having three major components and one very important option:
1) hardware platform,
2) motion controller,
3) cutting tool or sensor, and
4) *optional* data analysis software

The machines can be mapped and certified for point-to-point travel and point location measurement using B89 procedures and this "mapping" can become a reference.

With a known "good" machine, we can measure an artifact placed in the workspace and record all of the point readings from the artifact surface. Artifacts can range from reference spheres to the B5.54 "test part" to proprietary artifacts. The measurements on the artifact are archived as a reference "standard." At any time, the Reference artifact can be re-measured and the latest measurements compared to the reference. Renishaw adopted this procedure for on-machine tool inspection several years ago.

We want to compare measurements made on the artifact data at this time with measurements made at the time of establishing the reference. We want to determine:
A) Are there ***changes*** in computed GD&T measurements as well as location, size, and shape?
B) Which surfaces are exhibiting changes?
C) How much have the measurements changed?
D) Do the *changes* in the *new* measurements exceed acceptable limits (tolerance boundaries)?

MIMETEK will work with the customer to determine the acceptable "tolerance" boundaries for individual surfaces on the artifact. In fact, we can establish "interim" boundaries (before parts are lost, so that we can raise a "caution" flag to signal the eminent need for corrective action.

We have done a good deal of work with the B5.54 test plate for machine tool performance evaluation and we have established that more complex artifacts, such as the B5.54, can serve as a "viewing amplifier" to highlight problems.

In preliminary tests using commercial e-mail and Internet services during the 10:00 Am to 4:00 PM period, the elapsed time including sending probe data from a customer to MIMETEK and returning printed reports and picture diagnostics to the customer site has been less than one hour when we are working with inspection data on a known, commercially available artifact. This prototype process is not automated yet, but we would expect to be able to maintain the less-than-one-hour turnaround time for priority service.

This procedure can also be set up on-site for faster turn around and only the results need than be sent to MIMETEK for archiving and possible trend analysis. Data sets and results would be date and time stamped. For high throughput operations such as cylinder machining on automotive engine blocks, on-site processing is a necessity but even then it can be backed by remote "auditing" at MIMETEK's archival center.

Artifact measurement can be done on both CMMS (of any sensor type) and on machine tools. It is useful to note that CMMS are not viewed, as being production tools so "down time" is not perceived to be a problem. Machine tools that are sitting idle while inspection data is collected with the probing systems that now come standard with most machine tools cause great distress in management ranks. Better to be cutting scrap than to be idle.

At MIMETEK, we are satisfied that are probing sub-systems from Renishaw or Marposs on machine tools can do an acceptable job of data collection and that we can install robust data analysis software from ICAMP on new machine tool controllers or we can pass inspection data from the machine tool, over RS-232, RS-422, or fiber optic LAN to separate computers on the shop floor, or we can send the data over the Internet to MIMETEK for analysis.

The machine tools can continue to throw off chips, satisfying the psychological needs of management, but the date and time stamped inspection data collected on the machine tools can be analyzed off-line and when unacceptable deviations are found, the process can be stopped for corrective action on the machine tool.

At MIMETEK, we believe that the "10:1" rule on CMM vs. machine tool accuracy is a Trojan Horse and that the (usually audited) accuracy of Data Analysis software has a much greater impact on measurement accuracy and reconciliation.

We believe that by using independent Data Analysis software like ICAMP's, whose accuracy can be easily established, we can use both artifact inspection and "real" part inspection on-machine in the future. This will be especially attractive for expensive or thin walled parts which must now be cycled from machining center to inspection and back.

Parts processed during the interim can be shunted to the inspection (CMM) area for checking to see if these parts can be salvaged (if they are expensive) and to "audit" the results reported by MIMETEK.

Individual time and date stamped data sets for a common artifact collected on a particular machine can be archived at MIMETEK and trend analysis could be periodically performed to identify recommended maintenance frequency.

Much work remains to be done in system integration, but the basic technologies are available now and can be customized for each customer's needs.

If you have questions or comments, please contact Richard Jennings at MIMETEK and ICAMP at
(860) 643-1711 or e-mail us at mimetek@connix.com.

MIMETEK works with individual companies on a consulting basis to establish the best possible procedures for inspection, auditing, and archiving of machine and part characterization data.

National Institute of Standards & Technology
Workshop On
The Development of Machine Tool Performance Models and Data Repository

Thursday-Friday, November 20-21, 1997
Holiday Inn Select
Pleasanton, California

List of Attendees

Name	Company
Vivek Chandrasekharan	Caterpillar, Inc.
Jim Covington	Boeing, Wichita
Angel Dahilig	Boeing, Wichita
Chris Deforge	Deneb Robotics
Alkan Donmez	National Institute of Standards & Technology
Donald Esterling	N-See Software
Joseph Falco	National Institute of Standards & Technology
Dave Hemmerle	General Electric
Hooman Jajbakhsh	Lawrence Livermore National Laboratory
Richard Johnson	Raytheon/Texas Instruments
James Katter	Caterpillar, Inc.
Martin Kitna	Boeing, Seattle
Debbie Krulewich	Lawrence Livermore National Laboratory
Christophe Leoapitaine	National Institute of Standards & Technology
Alice Ling	National Institute of Standards & Technology
Ray McClure	Tumax
Sean Olson	Automated Precision, Inc.
Steve Patterson	University of North Carolina at Charlotte
Daniel Sawyer	National Institute of Standards & Technology
Hans Soons	National Institute of Standards & Technology
Irving Stowers	Lawrence Livermore National Laboratory
Sam Thompson	Lawrence Livermore National Laboratory
Larry Welsch	National Institute of Standards & Technology