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IMPLEMENTATION OF THE SURFACE ROUGHNESS INSTRUMENT (SRI) CONTROLLER

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TABLE OF CONTENTS

Page

LIST OF FIGURES

IMPLEMENTATION OF THE SRI CONTROLLER

I. INTRODUCTION

1. WHAT THIS DOCUMENT IS ABOUT

This document describes the implementation specifics of the surface roughness instrument (SRI) controller program. The SRI is part of the inspection workstation (IWS) in the Automated Manufacturing Research Facility (AMRF) in the Center for Manufacturing Engineering at the National Bureau of Standards. The AMRF and IWS are rapidly developing systems with continually evolving software. This report describes the SRI Controller program in place in March 1987. However, certain more recent features are highlighted where appropriate. This program runs under the control of the ECS program described in the document <u>Implementation of the Execution Control System of the Inspection Workstation</u> [A.2]. The SRI Controller program consists of state machine modules that "customize" the controller for its particular application--i.e. supervising the SRI.

2. AUDIENCE

Anyone who needs to understand the internals of the SRI software should read this document. This includes anyone who will continue the development of the SRI software or make modifications to it.

The document <u>Architecture and Principles of the Inspection Workstation</u> [A.1] describes the principles that the execution control system (ECS) and SRI Controller programs utilize. It is recommended that that document be read first.

3. OVERVIEW

Chapter II gives a top level description of the SRI Controller (SRIC). It describes the equipment, specifies the location of the SRIC in the control hierarchy of the IWS, and describes the main functions the controller performs.

Chapter III discusses the theory that the SRI uses to measure surface finish.

Chapters IV through X explain the implementation specifics of the SRIC program. Chapter IV describes the important data structures, both global to the AMRF as well as local to the IWS. The main functions that the SRIC performs are specified in Chapter V. These functions are decomposed hierarchically into separate task modules, and this decomposition is described in this chapter. Additionally, the task modules use functions and procedures that are specified in separate procedure modules. These modules are described in Chapter VI.

The actual interface to the SRI is specified in Chapter VII. Specific details used in the start up and shut down procedures are described in Chapter VIII. Errors that can occur during operation are listed and briefly explained in Chapter IX. Chapter X describes the user interface to the SRIC.

Finally, Chapter XI discusses future development plans for the SRIC.

The appendices include further information and implementation details. Appendix A lists the entire IWS documentation set. References specific to the SRI are listed in Appendix B. Appendix C contains a glossary of terms used in this document.

Appendix D specifies the internal file formats used to contain all the data used for a specific inspection.

Completing the document is a reader/comment form. You are encouraged to write down your comments and mail the attached form to the address specified.

II. TOP LEVEL DESCRIPTION OF THE SRI CONTROLLER

The SRI Controller (SRIC) supervises the surface roughness inspection of a part. It controls two pieces of equipment--the surface roughness instrument (SRI) and the automatic dial indicator (ADI).

The SRI monitors surface roughness by measuring the angular distribution of light scattered from the surface of a part. It does its job in coordination with the IWS robot. Using the SRI optical signals as sensory input, the robot properly aligns the part in front of the SRI so that a valid optical scattering reading is obtained. Figure 1 shows the robot positioning a part for an SRI reading.

1. DESCRIPTION OF THE EQUIPMENT (SRI AND ADI)

The SRI consists of two main components: a commercial Rodenstock RM 400 optical scattering sensor [B.1] and an electronic control box. The sensor contains an infrared light source and detectors mounted in a tube (see Figure 2). The light is shined in a focused beam on the surface of a part. The light scattered back is measured by a linear array of twenty detector elements. Based on empirical analysis, a value for rms roughness is estimated.

Additionally, an automatic dial indicator (ADI) is used along with the SRI to enable the robot to position a part at about 2 millimeters away from the sensor of the SRI. The dial indicator consists of a spring loaded plunger, that will record the distance it is depressed, and the electronics to control and monitor it (see Figure 3). When the robot presses a part against this indicator, a reading of how far the plunger has been depressed is recorded and later used for positioning the part in front of the SRI.

2. LOCATION IN THE WORKSTATION ARCHITECTURE

As shown in Figure 4, the SRI Controller is subordinate to the Inspection Robot Controller (IRC) and is the supervisor to the SRI and the ADI. In a future implementation, the SRI Controller will be able to access the IMDAS (Integrated Manufacturing Data Administration System), the distributed data system which provides common interfaces to the AMRF's user programs and underlying databases [B.17, B.18].

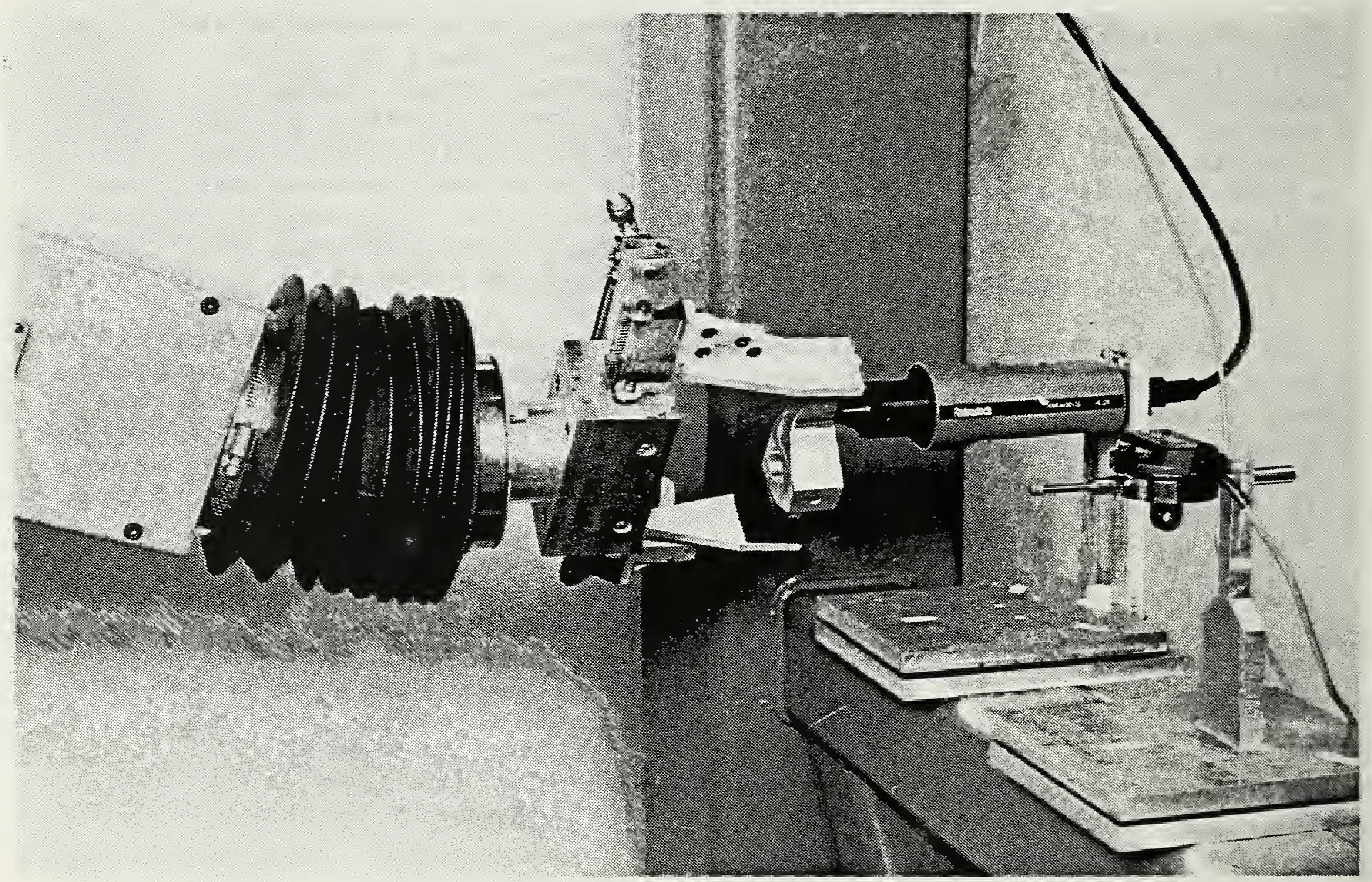

Figure 1. Photograph showing the IWS robot positioning a part in front of the SRI

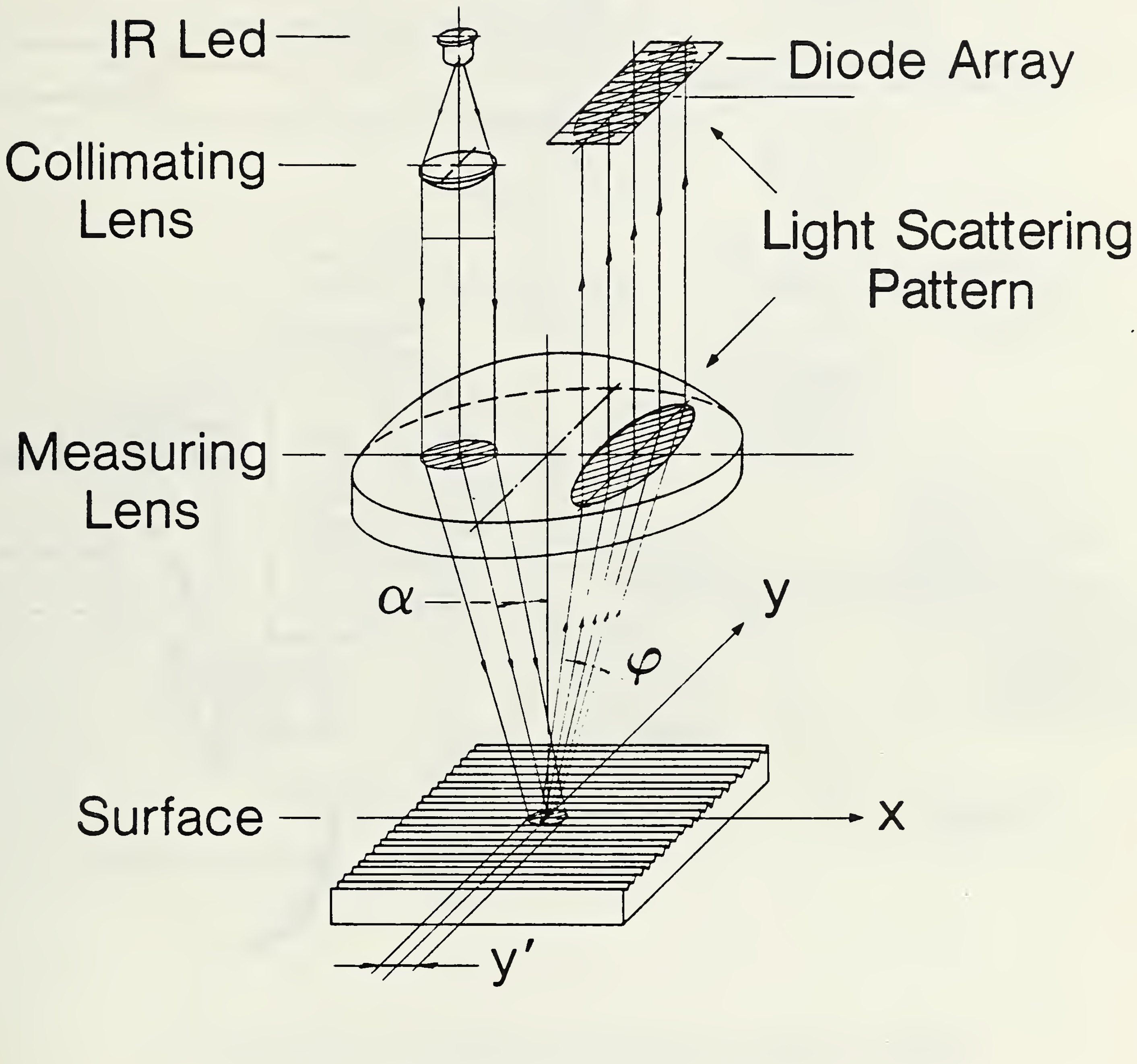

Figure 2. Schematic diagram of the optical system of the SRI

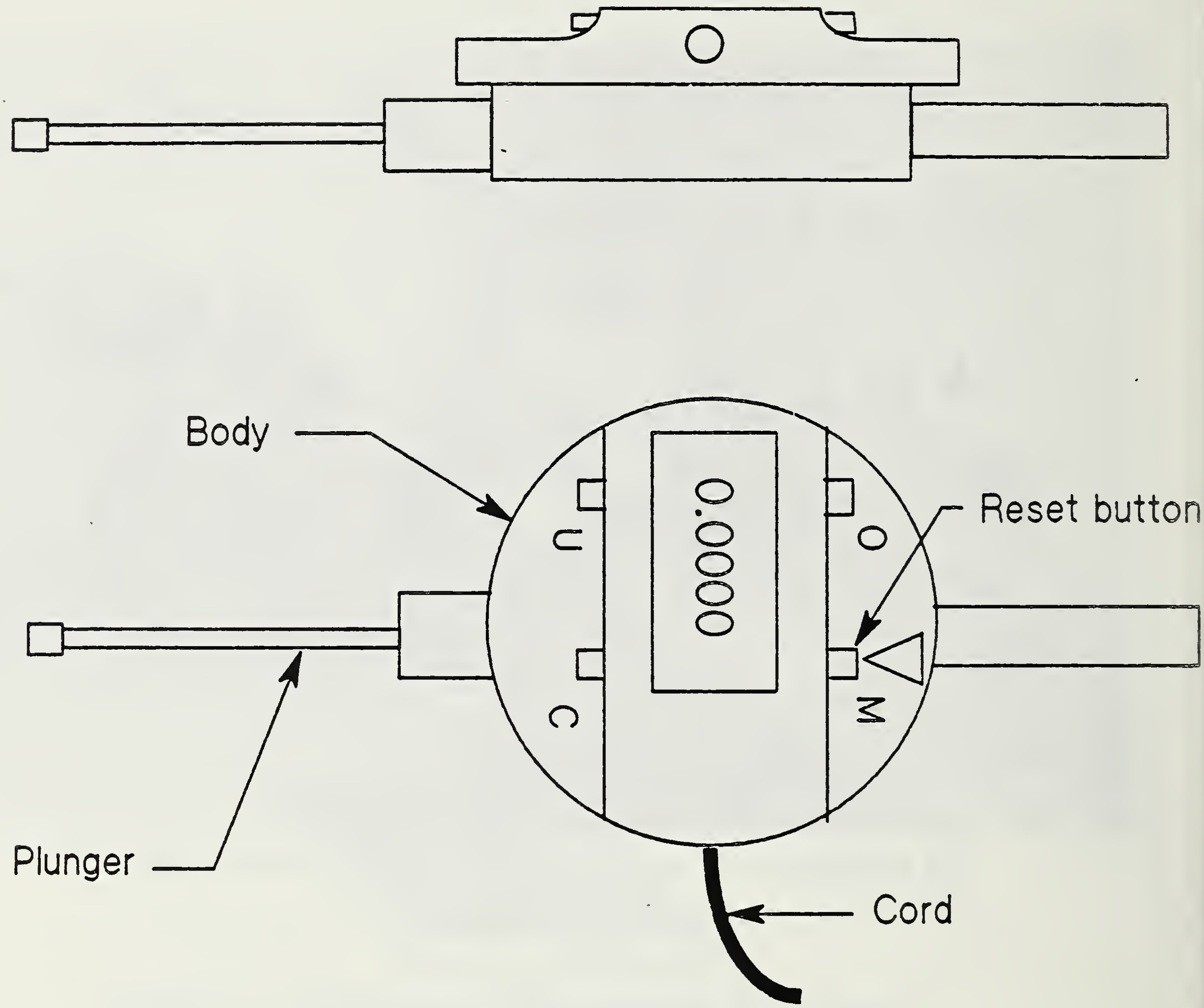

Figure 3. Automatic Dial Indicator

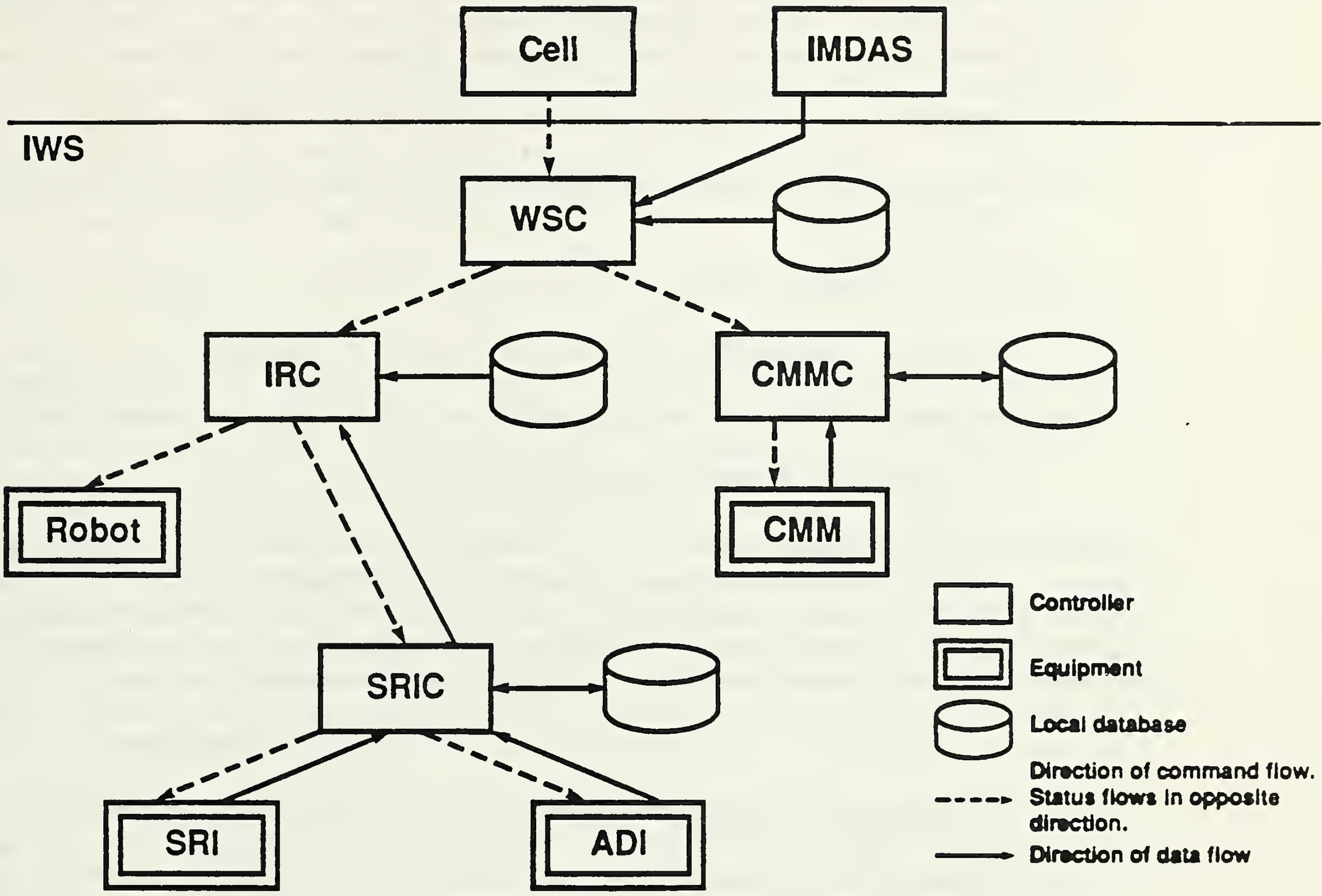

Figure 4. Logical architecture of the IWS.

3. MAIN CONTROLLER FUNCTIONS

The main functions of the SRI Controller are the following:

Respond to IRC commands and return status information.

Retrieve inspection programs from the IMDAS.

Control and monitor the SRI and the ADI.

Request the robot to reposition the surface in front of the SRI.

Analyze SRI data.

Report inspection results back to the IMDAS.

Display inspection results on the SRIC's monitor.

4. WORK ELEMENTS AND STATUSES

The SRI Controller receives commands from the Robot Controller. These commands are either transition commands (involved in the start up/shut down protocol), or work order commands (for operating in ready state), which contain the work elements that direct the main controller functions described above.

The work elements executed by the SRI Controller are:

LOAD_PART (loads the data for a part inspection),

READ_DIAL (read ADI and send that reading back to IRC),

INSPECT (directs the part inspection).

Statuses returned by the SRI Controller to the Robot Controller are:

WORKING,

DONE,

ERROR.

III. THEORY AND OPERATION OF THE SRI

1. THEORY

A schematic diagram of the SRI optical system is shown in Figure 2 [B.1]. The source consists of a light emitting diode (LED) that produces radiation at a near infrared wavelength of 800 nm. This radiation passes first through a collimating lens, then through one side of a special measuring lens that focuses and redirects the radiation, so that it illuminates the surface to be measured at a slight angle, but very close to the optical axis. The radiation scattered by the surface then passes through the other side of the measuring lens and is redirected to a linear photodiode array which measures a line sample of the scattered light beam to obtain an angular distribution of light intensity.

If the surface is smooth, the pattern of scattered light falling on the diode array is nearly the same as the circular pattern of the incident beam leaving the collimating lens. If the surface is rough, the scattered radiation pattern is broadened. When the pattern of marks (lay) left on the surface by the finishing process is unidirectional, the scattered radiation pattern is elongated along the roughness direction. Many kinds of finishing processes, including milling, grinding, and turning, leave unidirectional machining patterns on the surface and hence yield elongated scattering patterns. Figure 2 shows the SRI with the proper rotational alignment for sensing the unidirectional surface roughness, since the long axis of the array is parallel to the elongated scattering pattern.

Important parameters of the optical system are the angle of incidence of the light (α), the angular resolution and angular range (ϕ) of the detected scattering pattern, the illumination spot size y', and the axial distance of the surface from the measuring lens. The SRI gauge at the IWS has an angle of incidence of about 8.4° [B.1]. The angular range of the detector array is ±15° about the center detector. It is determined by the length of the diode array and the focal length of the measuring lens. Since there are 20 detectors in the array, the angular resolution is about 1.5°. The illumination spot size is ~1.8 mm in diameter. Since the SRI gauge was designed to be insensitive to misalignment in the axial direction [B.1], the axial distance of the surface from the measuring lens may vary by ±2 mm without inducing significant change in the readings obtained.

The sensor outputs a light scattering parameter called S_N that serves as a measure of surface roughness condition. The unitless parameter S_N is proportional to the variance of the light scattering distribution about the mean (M) of the data. Figure 5 shows a typical bell-shaped, light-scattering distribution as measured by the gauge. The distribution is composed of 20 diode readings indexed as $i = 1,2,\cdots,20$ with intensity values I_i.

The mean value M of the distribution with respect to the center of the array is then given by

$$M = (1/I) \sum_{i=1}^{20} I_i \cdot (i - 10.5), \qquad (1)$$

where I is the sum of the 20 intensity values of the array and the center of the 20-diode array is halfway between the tenth and eleventh diodes (i = 10.5). The light scatter parameter S_N is then given by

$$S_N = (\kappa/I) \sum_{i=1}^{20} I_i(i - 10.5 - M)^2, \qquad (2)$$

where κ is a normalizing factor that yields an S_N value of 100 if all of the intensity values I_i are equal.

In general, the value of S_N increases as the roughness of the surface increases. As shown in other experimental and theoretical studies [B.3-B.10], the shape of the angular distribution is a complex function of roughness irregularity heights, height distributions, and spacings. All these properties cannot be boiled down to a single parameter. However, for a given type of surface, the single S_N parameter may be used to establish a relative measure of roughness heights. Therefore, we use the S_N value as a comparative estimator of roughness averaging parameters such as the root mean square roughness R_q or the roughness average R_a [B.11]. In addition to S_N, the system also outputs the values of M and I and the 20 intensity values of the array.

Two calibration checks should be performed on the SRI before using it with the IWS. These should normally be performed once a week, unless the SRI results are suspect. In that case, the IWS should be stopped and the SRI recalibrated. The first calibration is a procedure for nulling the dark current of each detector in the array. This is accomplished by holding a special light absorbing cell over the nosepiece of the detector head and following the manufacturer's instructions for the nulling procedure.

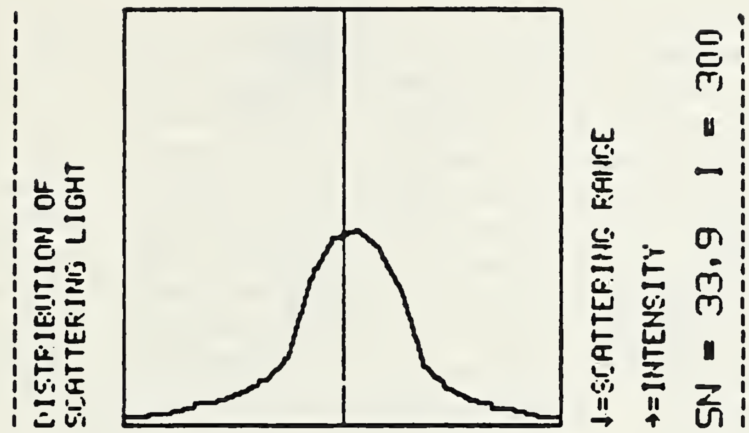

Figure 5. Typical scattering distribution as measured by the SRI

Second, a check should be made of the gauge response for a smooth surface. To accomplish this, a small mirror may be held against the nosepiece. The angular distribution and S_N reading are then recorded and compared with results from the manufacturer's setup procedure. After this, the SRI is ready to use.

For a flat surface the gauge may be easily aligned to yield an appropriate S_N reading. This can be shown by referring to Figure 6 and considering the three angular misalignment errors that can occur. If the gauge is misaligned by rotation about the x-axis (Fig. 6a), the misalignment can be sensed and corrected by rotating the gauge so that the peak of the distribution is at the center of the array. If rotation around the y-axis is the problem, the scattering pattern will move off the axis of the array (Figure 6b) and will result in a value of total intensity I that is less than the maximum. Therefore, the gauge orientation around the y-axis can be manually corrected to yield a maximum value for I. Finally, if the gauge is misoriented by rotation around the z-axis, the radiation pattern falling on the diode array will appear to be narrower than it actually is (Figure 6c). Hence, the gauge can be properly oriented by looking for a maximum S_N reading as it is rotated about the z-axis.

2. OPERATION

The robot begins the SRI procedure by picking up a part from the tray. Under the present manipulation constraints in the IWS, the robot always presents the bottom of the part, as it sits on the tray to the SRI for roughness inspection.

The axial alignment procedure then follows with the aid of the dial indicator (ADI) located near the SRI sensor and oriented parallel to it. The robot moves the part to a position about 25 mm in front of the ADI and then moves the part towards the gauge in 12.5 mm steps until the part contacts the gauge and a reading is made of the axial part position. Once this axial alignment is made, the part is moved in front of the SRI sensor to the optimum axial position about 2 mm from the nose piece.

After axial positioning, the angular alignments with respect to pitch, yaw, and roll are made. This is called tweaking.

The pitch correction is performed by first measuring the angular distribution of scattered light and storing the twenty diode values in the SRI Controller. Then the SRI program determines how far the peak of the distribution is located from the center of the array, and the robot makes a pitch correction of the part to bring the distribution on center.

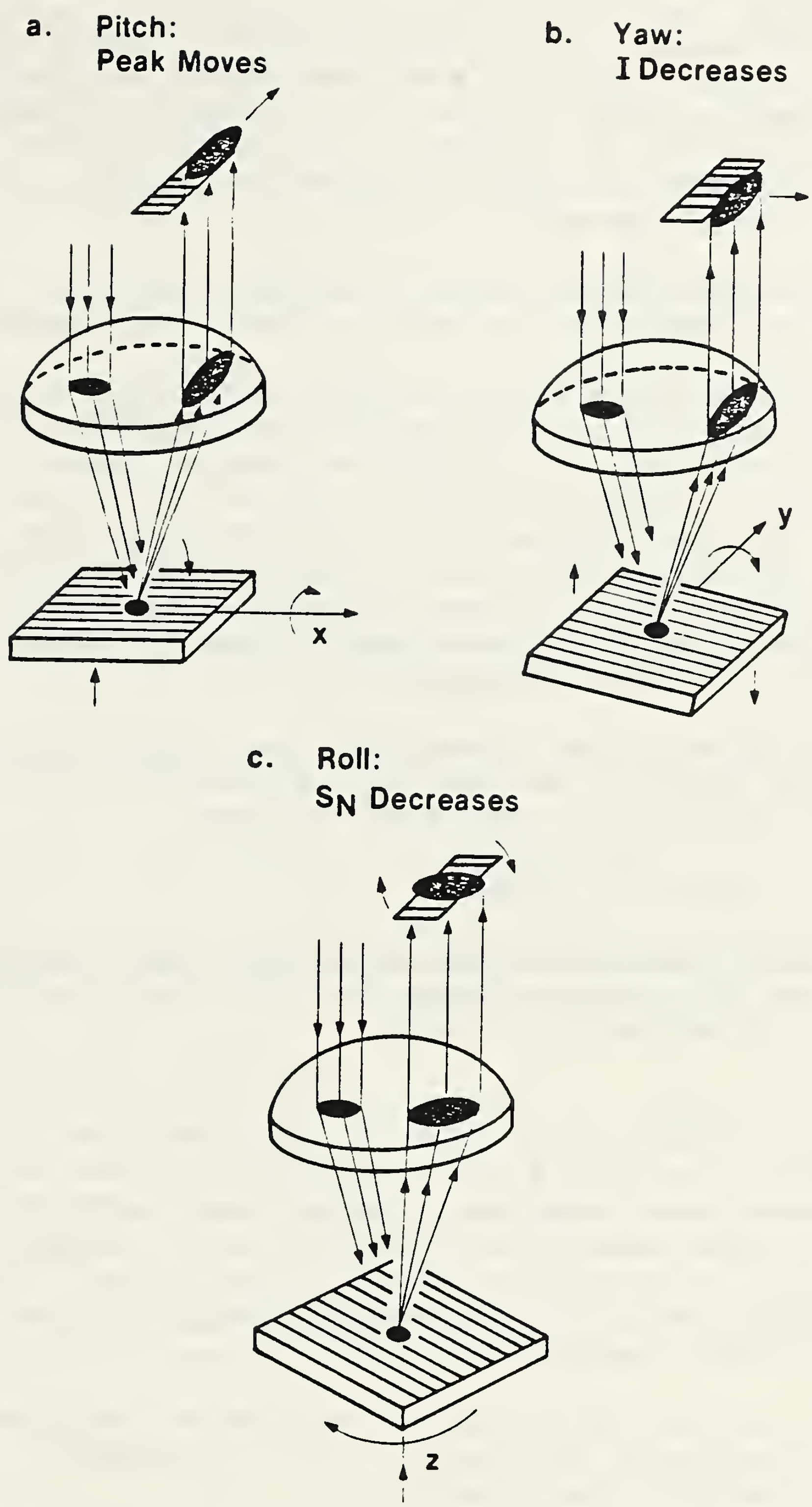

Figure 6. Details concerning optical alignment errors

The yaw correction is done next using a peak searching algorithm. The robot steps the part in a yawing mode in one-degree increments until a peak in the intensity signal I is located. This position should closely correspond to the optimum alignment in yaw.

Finally, the part is rolled about the z-axis as shown in Figure 6c under the direction of a peak-searching algorithm until a maximum value of S_N is found. This is done in two stages: first, in ten-degree increments to achieve a coarse alignment, then in one-degree increments in the neighborhood of the first maximum to achieve finer alignment.

After the three-fold alignment, the optimized value of S_N is stored as an indicator of the surface roughness condition.

Much of the data used by the SRI Controller for part alignment is displayed on the SRI console. This includes the S_N value, the total intensity I, a dump of the twenty intensity values of the diode array, a graph of these similar to Figure 5, and the array positions of the highest three intensity peaks in terms of the index i. In addition, two graphical indicators showing the rotation of the part in yaw and roll are also displayed. All of this information is updated each time the robot steps the part during the alignment procedure.

After the S_N value is recorded, the robot displaces the part sideways by about 1 mm, and the alignment procedure is repeated for a new position on the same surface.

3. RELATED RESEARCH

We are in the early stages of developing a database that will utilize the S_N readings from the SRI for specification of the roughness of mechanical parts.

Standard practice in roughness specification is the use of roughness average R_a [B.11], or alternatively the rms roughness R_q as ordinarily measured by contacting stylus instruments. In the future it is possible that the optical scattering parameter S_N itself may also become a standard one in engineering practice or that ongoing research to obtain geometrical roughness parameters, such as R_q, from the light scattering distributions in a rigorous manner will be successful.

At present we are performing comparator studies to relate S_N values as measured by the SRI with R_q results as measured by a Talysurf 6 stylus instrument.

The first set of results has been obtained for hand lapped stainless steel parts [B.12] with finishes similar to those that might be obtained on the cleaning and deburring workstation of the AMRF [B.19]. The results are shown in Figure 7 where R_q values as measured with a stylus instrument are plotted versus S_N values as measured with an SRI model identical to the one at the IWS. These data are represented by crosses (+'s). A best-fit curve to describe the correlation between R_q and S_N is also shown.

Two observations constrained the form of the function that we fitted for R_q vs. S_N. First, the curve has an asymptote at S_N = 100. An S_N value of 100 corresponds to a flat angular distribution having uniform scattering intensity at all angles. For a random surface finish, the angular distribution is a bell shaped curve having its maximum in the specular direction. The distribution generally becomes broader as the roughness increases, but it should approach a flat distribution only as the value of R_q becomes very large. Hence, the asymptote at S_N = 100.

Second, the geometrical spreading of the optical beam in the gauge is such that the value of S_N equals 5 when the rms roughness R_q of the surface is essentially equal to zero. This situation occurs when the SRI is tested with smooth optical surfaces. Hence, the function $R_q(S_N)$ should pass through the point (5,0).

In view of these constraints, the following formula for R_q was chosen:

$$R_q(\mu m) = (S_N-5)^{1/2}[a + b/(100-S_N)], \qquad (3)$$

having the parameters a and b. These were fitted to the data by a linear least-squares method. The resulting best-fit values for a and b, rounded to three significant figures, are

$$\begin{aligned} a &= 0.0138 \pm 0.0035\ \mu m, \\ b &= 0.257 \pm 0.066\ \mu m, \end{aligned} \qquad (4)$$

where the uncertainties in the fitted parameters represent estimates of one standard deviation for each parameter.

The square-root functional model fits the data points better than a linear model previously described [B.12] while still satisfying the two constraints.

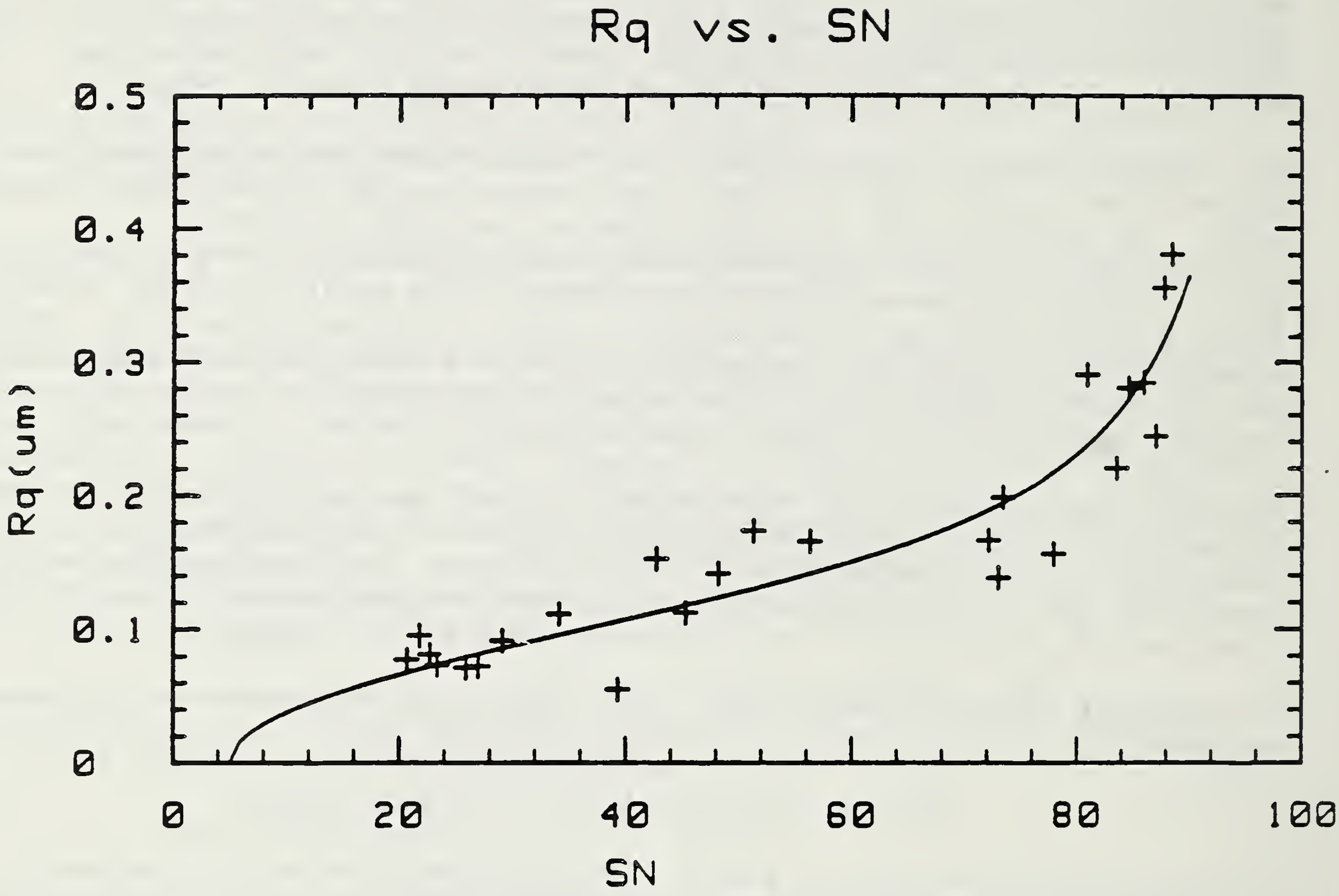

Figure 7. R_q values measured with a stylus instrument vs. S_N values obtained for the SRI.

Using the function described by Eq. 3 and shown in Figure 7, we calculated a coefficient of determination r^2 [B.13, B.14]. This statistic is similar to the square of the correlation coefficient and is a standard approach for expressing how well the variation in the R_q data is accounted for by the fitted curve. For the nonlinear model of Eq. (3), the formula for r^2 is given by:

$$r^2 = \frac{\sum_i \hat{R}_{qi} R_{qi} - n\bar{R}_q^2}{\sum_i R_{qi}^2 - n\bar{R}_q^2}, \qquad (5)$$

where n = 25, R_{qi} is the set of 25 measured R_q values, Rq is the mean of these data, and $\hat{R}_{qi}$ is the set of R_q values predicted by the fitted curve. The calculated value for r^2 was 0.87, representing a fairly good correlation between the S_N vs. R_q data and the fitted curve, considering that the data include points taken on four different stainless steel materials and with widely differing surface curvatures [B.12].

Based on the deviations between the data and the model, we also conclude that the S_N data from the SRI, together with the two parameter model given by Eq. (3), are appropriate for estimating the rms roughness of lapped stainless steel surfaces and most likely other lapped materials as well to an uncertainty of ±26 percent (1 standard deviation). This is a reasonable uncertainty for a comparator technique given the variability of both the stylus data and the optical data and the fact that standard values for specifying roughness are differentiated by factors of two [B.11].

It should be noted that the S_N values from the optical sensor of the SRI depend on the head geometry which is not standardized. Several types of heads are available with different illumination spot sizes and angular scattering ranges, shown as y' and ϕ respectively in Figure 2. The sensing head used in the IWS, with spot size of 1.8 mm and an angular range of ±15°, is the most common one.

IV. DATA STRUCTURES

1. LOCAL DATA

In the March 1987 implementation the data required for a surface roughness inspection of a part are stored locally in disk files on the SRIC itself. The SRIC is sent the command to 'LOAD_DATA' to tell it what part needs to be inspected. The LOAD_DATA command is packaged with two arguments--the part name and the name of the inspection plan (the latter is an integer). Upon receiving this command the SRIC prepares itself to access the proper data during the inspection.

Once the SRIC completes the command to 'LOAD_DATA', it waits for the command to 'INSPECT'. After receiving the INSPECT command, it directs the inspection of the part. As each state machine module runs, any data required by that module are retrieved from the local data files as they are required. It is necessary to access the data locally during the actual inspection to obtain the response time required.

The local data are stored in a flat file system; each relation is stored in a separate file. A relation contains key fields that are used to find the record required. Then, the data fields in that record are retrieved. The full specification for all the SRIC flat files is in Appendix D. The description of how the flat file system is implemented is in the IWS document <u>Implementation of the Execution Control System of the Inspection Workstation</u> [A.2].

2. AMRF DATA

In a future implementation the data required to inspect a part with the SRI will reside in the AMRF IMDAS. This data will be contained in two separate files. The first file is the part model file. This contains the geometry and topology data for the part, including the tolerance specifications. These data are in a neutral format, and are used by all processes throughout the AMRF. For a complete specification of the part model, see <u>AMRF Database Report Format: Part Model</u> [B.16]. Supplementary to the part model data, additional data are required to inspect a part. These data specify which points on each surface to measure as well as other data not included in the part model file. These data are included in the inspection data file.

Upon receiving the LOAD_DATA work order, the SRI Controller "task" module will direct the retrieval of the part model and the inspection data file from the IMDAS. It will then parse those files and transfer the data to the local data files described in the previous section. The structure for these local data files will remain the same, even when the data originates from the IMDAS rather than from the SRIC itself (as is currently the case).

V. TASK DECOMPOSITION

The state machine modules used to implement the SRI Controller are shown in Figure 8. Listed in their order of hierarchical task decomposition (from highest to lowest), those modules are irc_sri, task, surfaces, points, dial, and sri. (The modules dial and sri are at the same control level.) "Dial" contains the procedures needed to access the ADI. Likewise, "sri" contains the procedures necessary to control and monitor the SRI. These two modules are directly analogous to the machine module in the CMM Controller [A.3].

This section lists each of the state machine modules, including the two "machine" modules, dial and sri, and provides a general description of each.

1. irc_sri

The irc_sri module implements the University of Virginia (UVA) model [B.15] for interfacing the SRI Controller to the Robot Controller. This module accepts commands from the IRC and decomposes those into transition commands and order actions. It receives statuses from its subordinate, the "task" module, and returns statuses to the IRC.

2. task

The module, task, supervises the main functions performed by the SRI Controller, namely, to read the dial indicator, to retrieve the data to inspect a part (given the part name and the inspection plan name), and to supervise the inspection. The work orders for these functions are READ_DIAL, LOAD_DATA and INSPECT.

The READ_DIAL work order commands the SRI Controller to get the reading of the dial indicator and to send it back to the IRC. The command is sent down the task hierarchy through the "surfaces" module to the "points" module, which actually carries out the command.

The LOAD_DATA work order commands the SRI Controller to prepare itself so that it will use the proper local data files during the subsequent part inspection. Eventually, these data will be retrieved from the IMDAS. The data will then be parsed and stored in the above mentioned local data files in the same format as the data that are currently being used.

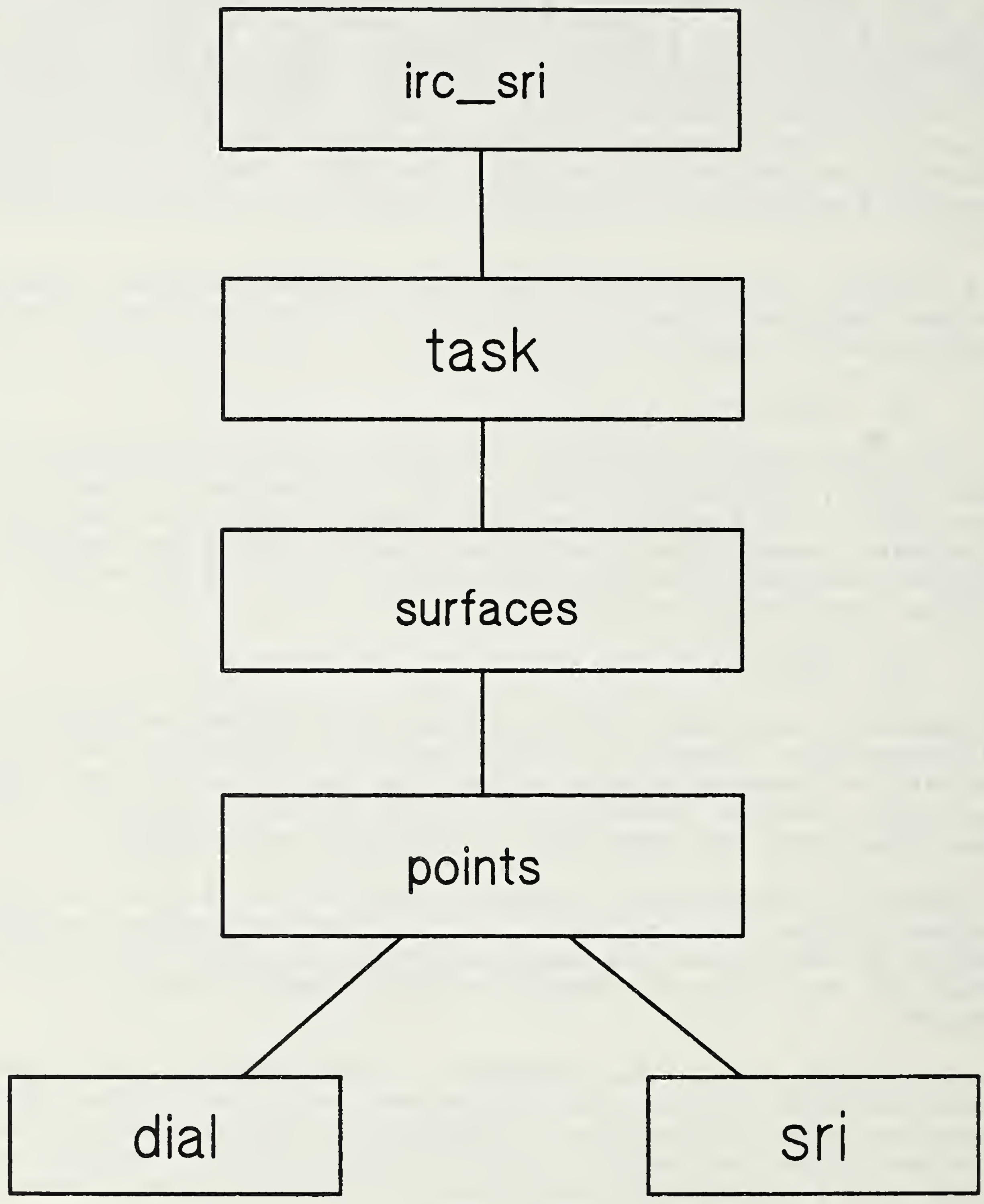

Figure 8. Control Levels for the SRI Controller

When the SRI Controller receives the work order INSPECT, it begins inspecting the first surface designated by the inspection data. When that surface has been completed, it continues on to the next surface until all surfaces in the inspection plan have been completed. It then signals a status of DONE back to the IRC, and consequently frees up the IRC to be commanded again by the Workstation Controller (WSC).

In practice (for the current implementation), only the bottom surface of each part (as it sits on the tray) is inspected by the SRI. The robot must reorient the part to present a new surface to the SRI, and that kind of manipulation has not yet been implemented in the IWS.

3. surfaces

The purpose of the "surfaces" module is to interact with the IRC to detect the edges of the surface to be inspected. Based on that knowledge, the physical location of the designated origin for that surface can be determined. Subsequently, this module sequences through the points to be measured on that surface.

Currently, only the sequencing operation is performed; the edges of the surface are not detected. The point on the surface that is immediately presented to the SRI is assumed to be the origin for that surface.

4. points

The main job for "points" is to post position requests to common memory as called for by the SRI inspection. In addition, "points" accesses the "dial" module procedure to read the automatic dial indicator, and posts that reading to common memory as well. It is up to the IRC to make use of the posted positions and dial readings to move the part accordingly.

The first time the module, points, is called for each surface, it is assumed that the point immediately in front of the SRI is the origin for that surface. "Points" then specifies the offset to the first point on the surface to be measured and waits until the IRC has acknowledged that the robot has moved the surface to that point.

A procedure called tweak_point (contained in the module, sri) is then called to determine the relative angular orientation from the current point required for the next reading. The purpose of tweak_point is to find the orientation that gives the proper SRI reading for each point. Once the robot moves to the requested orientation, tweak_point is called again, and the procedure is repeated. This is continued until the adjustment algorithm implemented in tweak_point signals the module, points, that it is done. "Points" has then completed the measurement for the current point and signals the surfaces module that it is DONE.

5. dial

The "dial" module is the machine level module for the ADI. It contains the procedures that service the ADI. The main function accessed during a normal run is get_dial_reading, which returns the dial reading as a real number. Additionally, this module contains several procedures that initialize the ADI as well as divide the get_dial_reading into its smaller component parts.

6. sri

The "sri" module contains the main procedures used to access the SRI from the "points" module. The main procedure contained in this module is tweak_point. This procedure implements the algorithm, discussed in sec. III.2, to determine the proper surface orientation to measure the current point with the SRI.

Tweak_point returns two variables, status and pt. If the status returned is WORKING, then the pt returned is the new point orientation requested by the SRIC. This orientation is always calculated relative to the point orientation before the tweak_point algorithm is first called for each point. When tweak_point returns DONE, then no further reorientations are necessary. The correct orientation has been found and the proper SRI reading taken.

VI. PROCEDURE MODULES

The procedure modules required by the SRI Controller (aside from "dial" and "sri") are described in this section.

1. sri_lib

This library module contains procedures from the HP library that are not used by the other controllers. The particular modules included here are used to interface the HP computer to the SRI and the ADI using the RS232 and GPIO boards, respectively.

2. graph_lib

This module contains all of the HP graphics modules that are required for displaying graphics on the HP monitor.

3. display

This module contains the procedures to interface the graphics demands of the SRI Controller to the HP graphics procedures (contained in graph_lib). Included are procedures to plot lines on the screen as well as to write text to specified positions on the screen.

Eventually, all IWS Controllers will contain the modules, graph_lib and display, and any text or graphics shown on an IWS monitor will pass through the "display" module on the appropriate controller.

4. sri_types

This module includes data structure types that are specific to the SRI Controller, and are referenced by state machine modules as well as other procedure modules throughout the SRI Controller program.

One data structure defined here is finish_statistics. This is the lowest level data structure used by SRIC that is independent of any particular SRI. It contains seven components. Five of these are related to the optical scattering patterns detected. These are S_N, I, peak offset, peak magnitude, and peak spread. The remaining two are computed values of roughness--R_q, the rms roughness, and R_a, the roughness average.

5. sri_prims

The sri_prims module contains all of the procedures that directly interface the HP computer to the SRI. Since this is the one module that needs to be modified to connect the SRIC to a different SRI, the details are discussed in Chapter 7, INTERFACE TO EQUIPMENT.

6. readsri

The main function provided by the "readsri" module is read_sri. This function takes the raw SRI data retrieved by sri_prims, processes them, and bundles them into the finish_statistics data structure described in section 4 above.

7. get_data

This module contains the procedures that search the locally stored data files to return the data values needed by the state machine modules as they are running.

8. rpt_funcs

This module exports the data structures and functions required for the SRIC to communicate the new part positions requested of the IRC during the SRIC inspection.

VII. INTERFACE TO EQUIPMENT

1. MODULES THAT INTERFACE TO EQUIPMENT

SRIC supervises both the SRI and the ADI. The only module that interfaces SRIC to the SRI is sri_prims. Likewise, the only module that interfaces SRIC to the ADI is "dial".

2. DETAILS OF THE CURRENT IMPLEMENTATION

In the sri_prims module, the following SRI functions are performed:

Initialize the SRI from a cold start, and prepare it to receive commands from the SRIC and return SRI data to it.

Return the scattering value (S_N).

Return the intensity (I).

Prepare to send the individual detector readings I_i--each one in order, upon command.

Return the value from each of the detector elements.

Additionally, this module specifies the number of elements in the SRI detector array and the angular spacing between them. The latter is called the pitch calibration factor in the program.

In the "dial" module, the following ADI functions are performed:

Initialize the ADI from a cold start.

Return the dial reading.

3. CHANGES REQUIRED FOR EQUIPMENT SUBSTITUTION

In order to substitute a different SRI or different ADI, any changes to the functions specified in Section 2 above must be implemented in the sri-prims and "dial" modules, respectively.

VIII. INITIALIZATION AND SHUT DOWN

1. START UP

When the SRIC program is first started, the SRI and the ADI are both initialized and are ready to receive commands. On receiving the WARM_STARTUP command from the IRC, variables related to the tweaking algorithm are initialized, and the SRIC is ready to receive work order commands.

2. SHUT DOWN

The SRIC reports back DONE when it receives the WARM_SHUTDOWN command. Nothing else is done. It can be warm started if it receives a new WARM_STARTUP command.

3. ABORT

The ABORT command is used for error handling. Currently, this command is not implemented. When the command is passed down from irc_sri to the next level, task, it is ignored.

IX. ERROR HANDLING

Currently, any error crashes the SRI Controller program, and the IWS must be restarted. Three types of errors have been observed with the SRI. We classify them as intensity errors, software errors, and detector errors.

1. INTENSITY ERROR

1.1. Description

The intensity error takes place when the total signal into the detector array becomes so large that the intensity value cannot be properly displayed on the SRI electronics. This error condition can occur when a highly polished, highly reflecting surface is measured by the SRI, and the condition immediately goes away when the signal decreases back to a measurable value. The error condition is displayed as a "UEL" on the SRI electronics display unit.

1.2. How Handled

At present this error condition can only be alleviated by manual reinitialization of the SRI electronics unit. Subsequently, the whole IWS must be restarted.

2. SOFTWARE ERROR

2.1. Description

The software error condition is displayed as "FFF" on the SRI electronics unit. This is a general condition to describe any one of a number of different error conditions sensed in the SRI operation, the key one likely being a breakdown in communications with the SRIC via the RS-232 interface.

2.2 How Handled

At present this error condition can only be alleviated by manual reinitialization of the SRI electronics unit. Subsequently, the whole IWS must be restarted.

3. DETECTOR ERROR

3.1. Description

The detector error is indicated as "F80." It usually indicates a change in the zero background calibration of the detectors.

3.2. How Handled

Recovering from an F80 requires at least a manual recalibration of the dark current null values in the detector array but may also require replacement of a fuse or a battery in the SRI electronics. Subsequently, the whole IWS must be restarted.

X. USER INTERFACE

1. STAND-ALONE OPERATION

In integrated mode, irc_sri is the highest level module in the SRI Controller. It receives commands, via the local network, from the Robot Controller. If the SRIC is to be run in stand-alone mode, the operator needs to enter commands directly to the SRI Controller and have those commands transferred to the irc_sri module. The interface that provides this connection between the user and the irc_sri module is the "sritest" module. "Sritest" simulates the Robot Controller, and allows the user to select commands for the SRI Controller.

2. USER COMMANDS

The commands available to the user are ABORT, SHUTDOWN, STARTUP, and EXECUTE. These are the transition commands. The first three commands do not have arguments. The arguments for the EXECUTE are the work orders and their respective arguments.

After turning on the equipment, the user must first choose STARTUP to bring the SRI Controller into the ready state. Next, the user selects EXECUTE and may select any of the three work orders: Get Dial Reading, Load Part, or Inspect. For each part, Load Part must be chosen before Inspect to select the data to inspect a particular part before the actual inspection may begin.

After a part has been inspected, data for a new part may be loaded and inspected, or else the SRI Controller may be shut down by issuing the transition command SHUTDOWN.

XI. FUTURE PLANS

The development of the SRI is still in progress. Much research still needs to be done to take advantage of all of its capabilities as a roughness sensor. Operational improvements should also be made as well. We discuss each of these two areas in the following subsections.

1. OPERATIONS

The automatic alignment procedure has been completed for flat or nearly flat surfaces. The alignment algorithm may be easily extended to convex surfaces, such as those produced by turning, and to surfaces that are slightly concave. For inspection of cylindrical bores, a different type of SRI head, presently available commercially, would need to be installed at the IWS in addition to the one presently used for flat surfaces.

The error recovery part of the SRI operation also needs to be automated. This will require hardware and software changes to allow external control of the SRI initialization by the HP Controller.

2. ROUGHNESS SENSING

Section III.3 discusses the first comparator study of optical roughness measurement performed for the AMRF. Studies on other types of materials and other finishing processes will be performed as part of the ongoing automated manufacturing research program at NBS. This research will enable us to develop mathematical curves such as that shown in Figure 7 for each type of finishing process.

As these studies are completed, a database will be accumulating for estimating rms roughness R_q, and perhaps roughness average R_a as well, for different machining processes. We also plan to include in the database knowledge of the correlations between surface roughness and product functions.

One limitation, that is apparent from our initial study on hand-lapped surfaces, is depicted in Figure 7. The range of the SRI for these types of parts is limited to about 0.3 μm R_q, that is, to fine lapped surfaces and probably fine ground ones as well. Therefore, rough ground surfaces are probably out of the range of the SRI. However, the range limitation depends on the wavelength of the radiation, fixed at 800 nm, and on the spacings of the surface irregularities. For roughly machined parts, such as those produced by facing, turning, or milling, the irregularities from the machining processes are much more widely spaced than those produced by grinding or lapping. This circumstance will tend to increase the range of measurable roughness for those rough machined components. Therefore, one of the principal results of the AMRF surface scattering research will be to determine the range of measurable roughnesses for various types of machining processes.

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C. GLOSSARY (and abbreviations)

ADI Abbreviation for the Automatic Dial Indicator.

Automatic Dial Indicator
Instrument used to measure the distance that a spring mounted stem is depressed.

controller
Supervises the operation of a mechanism, another controller, or both.

ECS Abbreviation for the execution control system.

Execution Control System
Computer program that runs on each controller computer and implements the AMRF design principles. This program loads and executes those modules which determine which controller is actually being run.

IMDAS Integrated Manufacturing Data Administration System [B.17, B.18].

Inspection Workstation
AMRF workstation that inspects parts for dimensional tolerance and surface finish.

IWS Abbreviation for the Inspection Workstation.

logical architecture
Specifies the direction of commands and statuses between controllers and between controllers and equipment.

physical architecture
Specifies the physical connections among the controllers and equipment.

ready state
The state in which a controller is ready to accept work order commands. This is the normal state of the controller during its operation.

SRI Abbreviation for the Surface Roughness Instrument.

SRIC Abbreviation for the SRI Controller.

Surface Roughness Instrument
Machine that measures the optical scattering from the surface of a part. The scattering can be correlated with its surface roughness.

state machine
Software control unit with outputs dependent on inputs to it plus its internal state. This is the building block for the IWS control software.

transition commands
Commands used to transfer the IWS to a new state (specified by the UVA model).

UVA Protocol
Model, proposed by research group from the University of Virginia and adopted by the AMRF, that specifies the start up and shut down sequence for the AMRF as a whole as well as every controller within the AMRF [B.15].

work element
The part of the work order command that specifies what main controller function to perform.

work order commands
A command accepted by a controller when it is in ready state. A work order command contains an action (i.e. execute, plan, cancel, or stop), a work element, parameters associated with the work element, an identification number, and an update number.

WSC
Abbreviation for the Workstation Controller.

D. FLAT FILE SPECIFICATIONS

This appendix contains the specifications for the flat files used by the SRI Controller and contained in local disk files. For details concerning the implementation of the flat file system, see the IWS document IMPLEMENTATION OF THE EXECUTION CONTROL SYSTEM OF THE INSPECTION WORKSTATION [A.2]. For a general description of what the flat files are used for, see Chapter IV, Section 2.

Each flat file is composed of ASCII characters that are broken up into records--each record containing one or more key fields and one or more data fields. Records are separated by a carriage return and a line feed. Fields are separated by one or more spaces.

Four types of flat files (also referred to as relations) are used for the SRI. The tabular information below describes each of these.

This information is presented in the following manner. The specification for each relation begins with the name of the relation. The name given here is the same as given in the computer program, except that in the computer program the name is prefixed by 'DS_'.

A brief description of the relation is specified next.

This is followed by the name of an example flat file that is actually used. The examples referenced here contain data to inspect the pipe clamp, one of the parts commonly manufactured at the AMRF.

The task module from which this relation is retrieved is specified next.

Following that are the descriptions of the key fields and data fields which contain the data actually found in the flat files. The key fields are used to find the particular record in the relation that is required. The names of these fields often include the underscore character, so that a name will clearly specify a single field, even if it has more than one word. However, these names are not necessarily the same as they appear in the computer program.

Additionally, the data types for the key fields are indicated after the name (or names) by ' : ' and then the identification of the type. Many of the fields are of type integer. Comments are also included in some cases below to elaborate on what the fields mean. These are distinguished by enclosing them between braces, '{' and '}'.

Following the names for the key fields are the names for the data fields. The names are specified in the same manner as those for the key fields. Data types and, in some cases, comments are added here as well.

1. Inspection_Plan

Description:
Given the inspection plan, return relevant inspection data.

Example file name: plan_clp

Retrieved from: task

Key field:
Inspection_Plan_Name : integer

Data fields:

```
Units : character      {measurement units for data -- 'I'
                        for inches or 'M' for mm}
Surf_Plan : integer    {specifies which surfaces to measure}
Num_Of_Surfs : integer
                     {total number of surfaces in Surf_Plan}
```

2. Surfs

Description:
Given the Surf_Name (from the Inspection Plan) and an index, get the next surface to inspect.

Example file name: sfs_clp

Retrieved from: task

Key field:
Surf_Plan, Surf_Index : integer

Data field:
Surface_Name : integer

3. Surf_Chars

Description:
Specifies the position coordinates to be measured for a particular surface.

Example file name: surf_clp

Retrieved from: surfaces

Key fields:
Surface_Name : integer

Data fields:
X_Org, Y_Org : real
{surface origin--in relation to initial location}
NumOfSurfPts : integer
{number of points to measure on current surface}

4. Point

Description:
Specifies the next point to be inspected relative to the origin specified in Surf_Chars. The components of the point are in SRI coordinates.

Example file name: pt_clp

Retrieved from: points

Key fields:
Surface_Name, Probing_Pt_Nbr : integer

Data fields:
X, Y : real {Two components of point on current surface. To the SRI, these two components are x, y. To the robot, the two components are z, y.}

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This document describes the theory and implementation of the Surface Roughness Instrument Controller (SRIC) program. This controller is part of the Inspection Workstation (IWS) in the Automated Manufacturing Research Facility (AMRF) in the Center for Manufacturing Engineering at the National Bureau of Standards. The SRIC supervises the surface roughness inspection of a part. The inspection is data driven.

The SRIC controls two pieces of equipment -- the surface roughness instrument (SRI) and the automatic dial indicator (ADI). The SRI monitors surface roughness by measuring the angular distribution of light scattered from the surface of a part. It does its job in coordination with the IWS robot. Using the SRI optical signals as sensory input, the robot properly aligns the part in front of the SRI so that a valid optical scattering reading is obtained. (The ADI is used to help the robot position the part in front of the SRI for its initial reading.) The SRIC uses the optical data obtained to compute an rms value for roughness and a roughness average.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

AMRF; data-driven control; dial indicator; inspection workstation; IWS; SRI; surface roughness

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