E6308

NASA Contractor Report 187144

# Versatile, Low-Cost, Computer-Controlled, Sample Positioning System for Vacuum Applications

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August 1991

Prepared for
Lewis Research Center
Under Grant NAG3-946

National Aeronautics and
Space Administration

# VERSATILE, LOW-COST, COMPUTER-CONTROLLED, SAMPLE POSITIONING SYSTEM FOR VACUUM APPLICATIONS

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E-6308

## ABSTRACT

A versatile, low-cost, easy to implement, microprocessor-based motorized positioning system (MPS) suitable for accurate sample manipulation in a SIMS system, and for other ultra-high vacuum (UHV) applications, has been designed and built at NASA Lewis Research Center. The system can be operated manually or under computer control. In the latter case, local, as well as remote operation is possible via the IEEE-488 bus. The position of the sample can be controlled in three linear orthogonal and one angular coordinates.

# INTRODUCTION

The use of energetic ion beams for the study and modification of materials is an area of current interest in basic and applied research.(1,2) The applications of ion beam techniques are numerous, and are well documented in the literature.(3) In these techniques, typically, a beam of ions is directed onto the surface of the sample to be analyzed. After a series of complicated processes, this bombardment process gives rise to the production of both charged particulate and uncharged radiation.(4) A number of analytical techniques have evolved over the years, whose name often reflects the type of radiation selected for detection. Hence, detection of emitted Auger electrons results in a technique known as Auger electron spectroscopy or AES;(5) detection of characteristic x-rays forms the basis of particle induced x-ray emission analysis or PIXE;(6) and so on. The use of mass spectrometric methods to detect the ionized fraction of atomic or molecular fragments (secondary ions) emitted (sputtered) from the sample as a result of ion bombardment, forms the basis of the technique known as secondary ion mass spectrometry (SIMS), which is one of several surface analytical techniques commonly used for materials characterization.(7-10)

Some of the major advantages of SIMS are its high sensitivity to very low atomic concentrations (typically in the ppm range), which make it unique among other surface analytical techniques for performing bulk (dynamic SIMS) as well as surface analysis (static SIMS) at the dopant or impurity level. Other characteristics are the ability to detect all elements and their isotopes (including hydrogen), and its capability to generate element-specific images of the sample surface, by correlating the secondary ion signal with the position of a finely focussed raster scanned primary ion beam.

Broadly speaking, the major components of a SIMS system are the source of primary ions, a secondary ion detector, and a suitable vacuum system designed to house the sample to be analyzed. A significant amount of research and development has been carried out to improve, optimize, and enhance this technique, and to explore its applications to a wide variety of disciplines. At present, highly sophisticated commercial and custom-built SIMS systems are available in research institutions and industry; some of these systems include recently developed approaches for ion signal enhancement or detection, such as *time-of-flight* or *post-ionization* techniques.(10) In most cases, these newer systems are equipped with a computer to perform the acquisition, display, storage, and processing of data, as well as to monitor and set experimental parameters, prior to, and during the run. However, their data systems, that is, the computer, the hardware interfaces and the software found in these SIMS instruments is generally not transportable from one system to another, due to inherent differences in the computers, the instrumentation, and the software developed for them.

Custom-built or earlier commercial instruments, often lack a data system to perform the above tasks. Although an attempt to automate to a level comparable with that of newer instruments may not be affordable or worthwhile in some cases, computer control of certain functions is nevertheless highly desirable, particularly in SIMS, where experiments require, at times, several hours of almost continuous acquisition of data.

We have recently developed a quadrupole-based SIMS system,(11) and have designed and implemented a versatile data system,(12) based on a personal computer (PC), standard plug-in boards and custom-designed circuitry to suit the needs for the acquisition, real-time display, storage, and processing of the experimental data. A schematic of our SIMS system is shown in Fig. 1. The ion source, the main chamber, and the mass filter (quadrupole) are clearly identified. Other components are also shown and labeled, including the sample manipulator (top of main chamber) used to control the position of the sample for analysis.

In our SIMS system, as is the case in many other instruments for surface analysis, including some of the newer ones, the position and orientation of the sample under investigation was originally not subject to computer control, but rather required manual operation. It was clear, however, that the optimization of the ion signal and the systematic study of the dependence of the signal on sample position and orientation, as well as system calibration, or stability measurements, could be enhanced in a variety of ways if these parameters were to be controlled by the computer. In particular, measurements could then be performed in a more reliable, faster and simpler manner.

Although motorized manipulators for these applications are available in the market,(13,14) in our case, they were unaffordable and often lacked the versatility that was required and desired for this application. In particular, some did not have the possibility of manual control; others did not offer the option of a GPIB(15,16) interface for communication with a host computer. As a result, we opted to develop our own custom system. In this work we describe the design, construction, and initial operation of a versatile computer-controlled motorized positioning system (MPS) adapted to an existing precision sample manipulator for use in UHV applications.

Major characteristics of the MPS are the following. When under computer control, the MPS can be operated in a stand-alone (microprocessor-controlled) or in a remote (PC-controlled) mode via the GPIB bus. The system can be operated manually, if so desired. The MPS uses four inexpensive stepper motors to control each one of the three linear and the rotational degrees of freedom available in the manipulator with the accuracy required in our application. Excluding the PC and the sample manipulator, at present retail prices (1991), the total cost of the parts for the system amounts to

800 USDlls, which is more than a factor of 10 below a comparable commercial system.(13,14)

The hardware and software design of the apparatus is discussed in Section II. Section III shows selected measurements made to characterize the performance of the MPS. Finally, Section IV presents our conclusions.

## THE APPARATUS

Figure 2 shows a cutaway view of the main chamber with the integrated MPS. A stepper motor is shown coupled to each micrometer head and to the shaft rotation drive. The controlling electronics and computer interface (GPIB) cable are also shown. In what follows, a description is presented of both the hardware and software design and implementation.

### Hardware

The MPS was designed to satisfy the following requirements. No alterations or modifications were to be made to the precision sample manipulator (Huntington, model PM600-TRC-1). It had to allow independent control of each of the four degrees of freedom (3 translational, 1 rotational) available. Manual operation was required. Computer control was to take place at two levels: local and remote. Local operation was to be accomplished with an intelligent (microprocessor-based) controller, while remote operation, would be done via the GPIB bus, for easy interfacing to the SIMS data system.

Figure 3 shows a block diagram of the motorized system as finally implemented. In our case, the computer is an IBM PC/AT, equipped with a GPIB controller board (Hewlett Packard, 82990A). For local control of the MPS, a suitable commercially available, inexpensive, dedicated microcomputer unit (MCU) was selected (Heath, ET3400A), for which a GPIB interface was custom designed and built.(18)

The MCU is based on the 8-bit Motorola MC6802 microprocessor; it has a 17-key keyboard and a 6 digit seven-segment LED display for standard input and output operations. It includes 2.5K bytes of RAM and ROM. External circuitry can be added to it via a 40-pin connector that makes most of the control, data and address lines of the microprocessor available to the user. Figure 3 also shows the architecture of the stepper motor controller. The latter includes the stepper motor drivers, 2K bytes of ROM, decoding circuitry, a GPIB interface, and its own power supply. The controller has two external LED indicators for remote (REMOTE) and half-step (HALF) operation. After independently powering the MCU and the controller, the MPS is activated with an external push button (RUN) on the controller box.

A full schematic of the circuit in the controller box (excluding only the power supply) is presented in Figs. 4(a) and (b). Figure 4(a) includes a 2716 EPROM, which contains both the program to control the manipulator when in the local mode, and the code needed to accept and execute GPIB commands when in the remote mode. The GPIB interface is based on the GPIA (MC68488) and allows implementation of the GPIB protocol with complete talker and listener capabilities. The circuit includes an octal transparent latch (74LS373) connected to an octal dip switch to set the GPIB address of the MPS, and four transceivers (MC3448A) to interface the controller to the bus via a standard 24-pin GPIB connector. Also show in Fig. 4(a) is the 40-pin custom connector which interfaces the controller box to the MCU.

Figure 4(b) illustrates the control of the stepper motor drivers (MC3479) by a peripheral interface adapter or PIA (MC6821). External connection to the motors is made via a 25-pin D-connector. The two LED indicators (REMOTE and HALF) and the RUN pushbutton are also shown. The stepper motors are compact, bi-phase motors, with 100 steps per revolution, and rated positional and step-to-step accuracies of ±5 percent (Minebea LTd, 17PS-C054-01). Timing belts and matching pulleys (Boston Gear) were used in order to increase both the resolution and the torque required to drive the micrometers in the manipulator. For the rotational mechanism, a 3.6:1 pulley ratio was used, and for the three linear micrometers, a ratio of 5:1 was chosen. This increased the resolution to $1^\circ$ per step, and 1 $\mu$m per step, respectively, in the full step mode. For simplicity, no switches, optical encoders or similar hardware for absolute positioning were included in the design of the system. As a result, at startup, the program needs to be given the initial coordinate settings for the sample position.

In mounting and coupling the stepper motors to the manipulator, particular attention was paid to the simplicity, accessibility, and rigidity of the design. Care was exercised to ensure that the relative position of the motor with respect to the micrometer heads remained fixed. The pulleys were attached to the end of the micrometer heads by replacing the original (speeder) knob with a longer one. An allen screw was used to fix the pulleys to the knob. Attachment of the top (rotational) pulley was done similarly, except that the latter required a small modification to prevent interference with the tilt mechanism of the manipulator. Our experience operating the system has shown that the final design satisfies the above requirements. Figure 5 shows a photograph of the system. The motorized micrometers for the horizontal and the vertical axes are clearly visible, as are the pulleys and timing belt for the angular coordinate.

## Software

The software for control of both the local and remote modes of operation of the motors is roughly 2K bytes in length and is resident in the controller's ROM. For easy visualization, a flow chart is shown in Fig. 6. A brief description of its operation is presented next.

Upon execution of MONITOR-2, the MPS ROM-resident program (pressing RUN on the controller box), several actions take place. In particular, both the PIA and the GPIA are initialized, the microprocessor unit GPIB address is read and displayed, and its keyboard keys are assigned specific control functions. By default, the program goes into the idle mode, and displays the present value of the angular coordinate. In this mode, input comes from the keyboard. If remotely controlled, input is in the form of arguments of previously defined GPIB bus commands.

If no input is detected from the keyboard or from the GPIB, the program continuously executes the IDLE branch. When a key is pressed, the LOCAL branch is entered. The local routine monitors the MCU's keyboard and takes an appropriate action, depending on the pressed key (see below for details).

When input from the PC is received via the GPIB, the REMOTE branch is automatically entered. The remote routine reads and checks for syntax errors in the received command, and takes the steps needed to execute it. Return to local mode can be done via the PC (by unadressing the GPIB device), or by simply pressing RUN on the controller box.

A diagram of the keyboard is shown in Fig. 7. As can be seen, except for two keys (MON RESET and 0) every key has assigned three different functions. Depending on the function being executed by the MPS, they serve as both command and data keys for either the standard built-in MONITOR program of the microprocessor unit, or for the MPS. To enter MONITOR, MON RESET is pressed. To enter MONITOR-2 pushbutton RUN is pressed. To move the sample in the x-direction, its corresponding key, the leftmost key in the second row, would be pressed. Then, single stepping in the positive (negative) direction would only require repeatedly pressing the second (third) key. An increase in the rate of change of any coordinate is obtained by maintaining the corresponding direction (±) key depressed. Real time updating of any coordinate value on the display is always done, unless its rate of change does not provide enough time for this task to be performed. When this occurs, the display is automatically blanked until this condition is no longer present. Half-step (full-step) operation is set with the middle (rightmost) key of the top row. Modification of the value of any coordinate is done by pressing its key, and then pressing the top leftmost key (CHANGE). The program then requests the new value for that coordinate. Care must be exercised when changing the value of a coordinate, as the program does not check for an erroneous input. It does, however, check for an attempt by the user to move to an out-of-range value during normal operation.

For remote operation, ASYST,(17) a FORTH-like high level language developed for PC-based data acquisition and control was used, thereby rendering the MPS compatible with the software previously developed for our data system. When operated in this mode, the keyboard is disabled (except MONRES) and any of two GPIB commands specifically defined for the MCU: STEP, and READ, can be used. The first one is used to single step, and the second one, to return position information from any one of the motors. Each command requires always a fixed number of arguments for its proper interpretation. For example, the syntax for the READ command is as follows: READ M,H,D,S,N. Here, M is the motor number, H the step size, D the direction of motion, S the stepping speed, and N the total number of steps. Upon reception of an invalid command, an error code is displayed by the MCU on the LED display to alert the user of the nature of the problem. Return to the local mode is done by pressing MONRES and then RUN, at any time.

## MEASUREMENTS

An important concern when using a system like the one described here is the degree of accuracy and reproducibility obtained when the sample position is changed. In order to get information on the MPS performance regarding these aspects, a series of measurements were made.

Two types of measurements were carried out. One to determine the backlash in every axis, resulting from the micrometer, pulleys, and timing belts. Another, to determine the degree of repeatability of the system; that is to measure how close to the original bombarded area the sample can be repositioned after a relatively complex movement. As shown in Fig. 2, with the origin of coordinates represented by the point of impact of the primary ion beam on the sample, the Z axis is defined by the initial direction of motion of the primary ion beam, the Y axis points upward, and the X axis away from the quadrupole assembly.

In the first case, measurements were restricted to movements in the XY plane. Recall that the Z axis is defined by the original direction of the primary beam, and changes in this coordinate are normally not required, once the geometry has been optimized for a particular experiment. A series of patterns were generated by bombarding a silicon sample with a 0.150-$\mu$A, 250-$\mu$m diameter beam of 15 keV oxygen ions. As shown in Fig. 8, a typical pattern involves bombarding the sample in eight different locations for a fixed time. These locations were selected so that movement along one axis was always in the same direction, while in the other, the direction of motion was reversed. An estimate of the backlash was then obtained by comparing the relative positions of the first three with respect to the last three spots. As can be seen from the Figure, the total backlash is of the order of 70 $\mu$m for the X direction. Similar results were obtained for the Y direction.

Figure 8 also shows the results of the measurements made to determine the backlash in the angular coordinate ($\theta$). The bombarding pattern consisted of sputtering the sample at spot 1, raising the sample 500 $\mu$m, rotating it -360° to reach spot 2, and sputtering again. In this manner, craters 1 to 5 were generated. For craters 6 to 10, the rotation was made through an angle of +360°. As can be seen, a backlash of about 80 $\mu$m is clearly visible when comparing the line generated by the edges of craters 1 to 5 with that one from craters 6 to 10.

The degree of repeatability of the system was measured by bombarding the silicon sample in one location, and moving it in a complex pattern on the XY plane so as to generate and remove backlash along both of these axes. The sample was then returned to its original nominal position, and bombarded again. The relative location of the two craters generated was observed. The pattern trace and the results are shown in Fig. 9. No difference can be observed among the various craters, except for a slight increase in diameter corresponding to the twice-bombarded crater (A). Finally, shown in Fig. 10 is a surface profile, taken with a stylus instrument, of crater A and a nearby one (B). As can be seen, crater A is deeper, which is consistent with the fact that it was bombarded twice. Repeated scans in various directions showed no offset between the craters generated by the first and the second bombardment process. Hence, the reproducibility of the system is satisfactory for our application, assuming backlash effects are properly taken into account and removed during movement of the sample.

## CONCLUSIONS

A motorized positioning system has been designed and built which fully satisfies our original expectations. The operation of the system has been completely satisfactory, and the accuracy and repeatability of the compounded system satisfy most needs of the surface analysis (SIMS) system for which it was developed.

Major characteristics of the system are the following. It can be operated manually or under computer control. In the latter case, it can be operated in a stand-alone or in a remote mode; the latter via the GPIB bus. It can be interfaced to any computer equipped with a GPIB controller board (or, as an option, to a serial port), and hence, can be easily integrated into the system, and controlled from a variety of programming or menu-driven environments. It has an open architecture, and hence can be easily modified or enhanced to accommodate new features or different hardware, as would be the case if stepper motors with higher resolution, speed, or torque were required. Its implementation requires no modifications or alterations to be made to the sample manipulator, other than the replacement of a few knobs.

All the electronic components required for implementation of the MPS are standard and, hence, should be easily available in the U.S. and most other countries. This may be an important consideration, as the availability of commercial systems in some countries is, at times, more limited. Finally, its cost (less than 1K USDlls) is at least 10 times lower than similar, and often less versatile, presently available commercial systems (10K to 15K USDlls), which makes the MPS appealing for institutions or laboratories with limited financial resources. The authors will gladly provide assistance and make available all the documentation (including the software) to readers interested in reproducing the system.

With a small amount of extra work, a similar system can be developed without resorting to the MCU utilized in this work. It must be pointed out, however, that with the present set up, interfacing of additional custom circuitry, if needed, can be easily accomplished, since the MCU provides access to the data, address, and control lines of the microprocessor.

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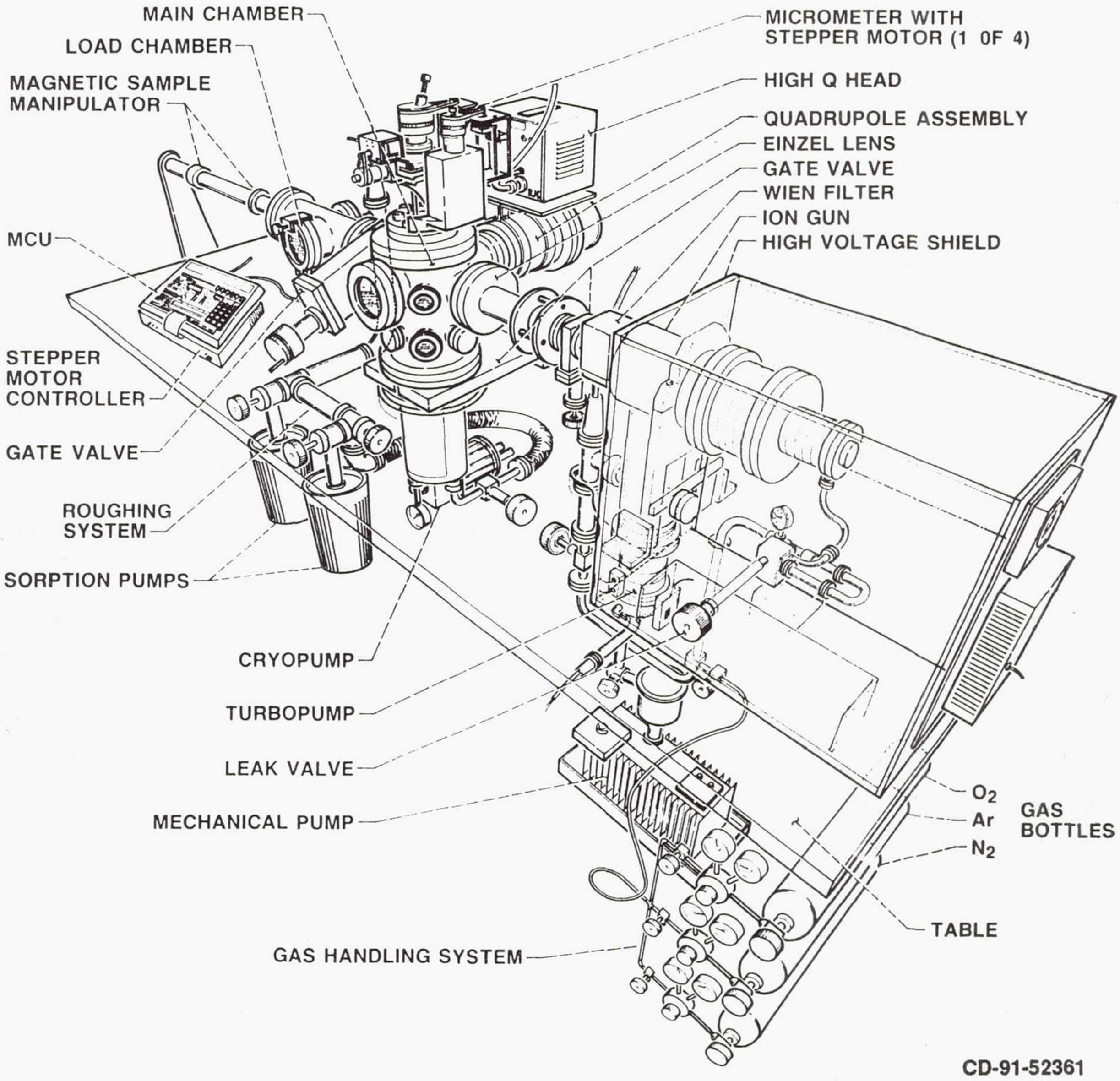


Figure 1.—Schematic of the SIMS vacuum system.

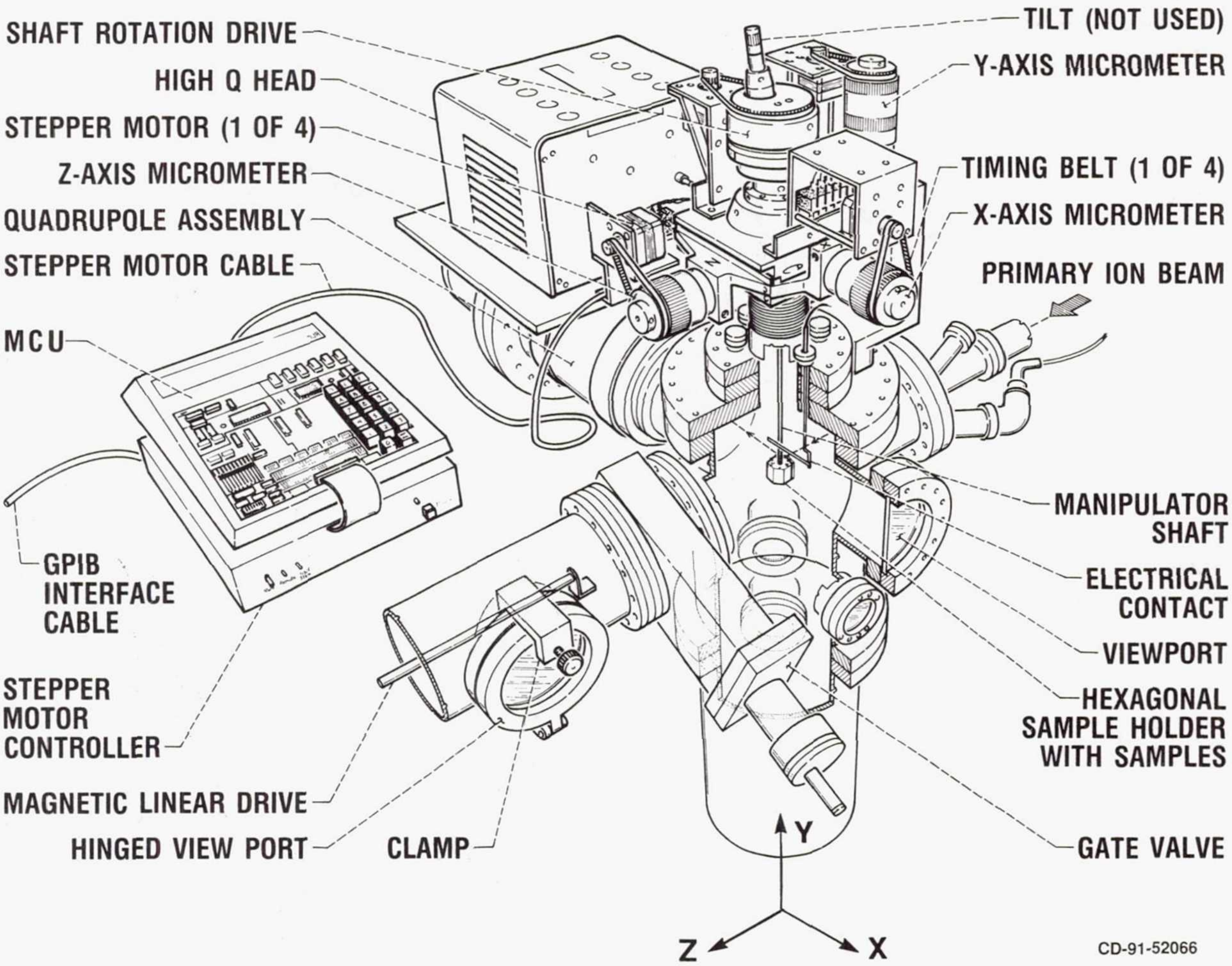


Figure 2.—Cutaway view of the main chamber with MPS. The components of the MPS can be identified: the MCU, the stepper motor controller, and the motors attached to the micrometer heads. For later reference, a coordinate reference frame is defined.

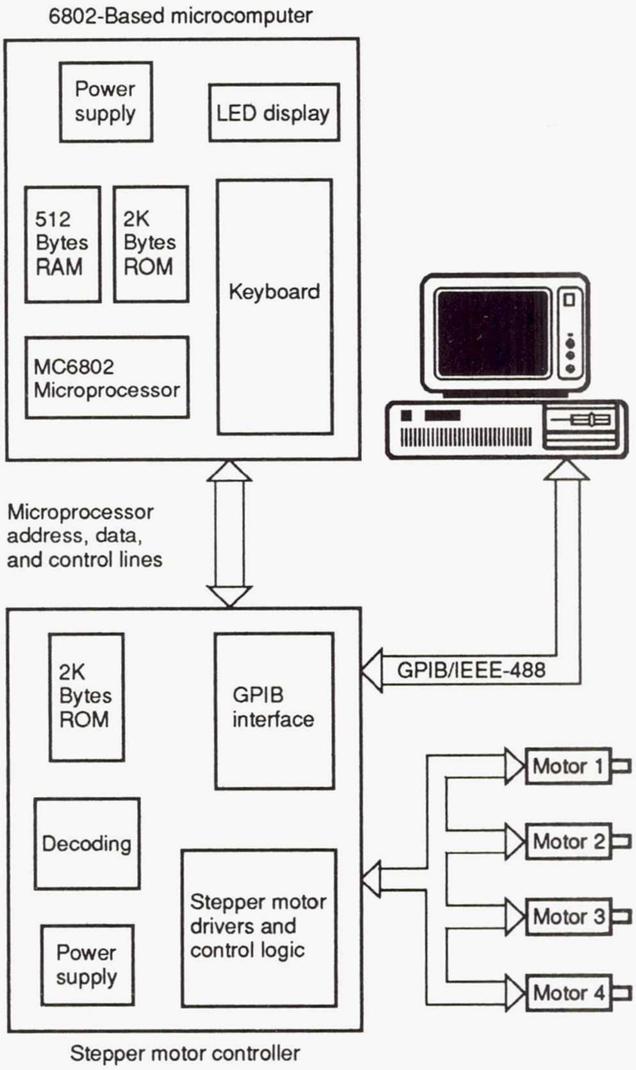
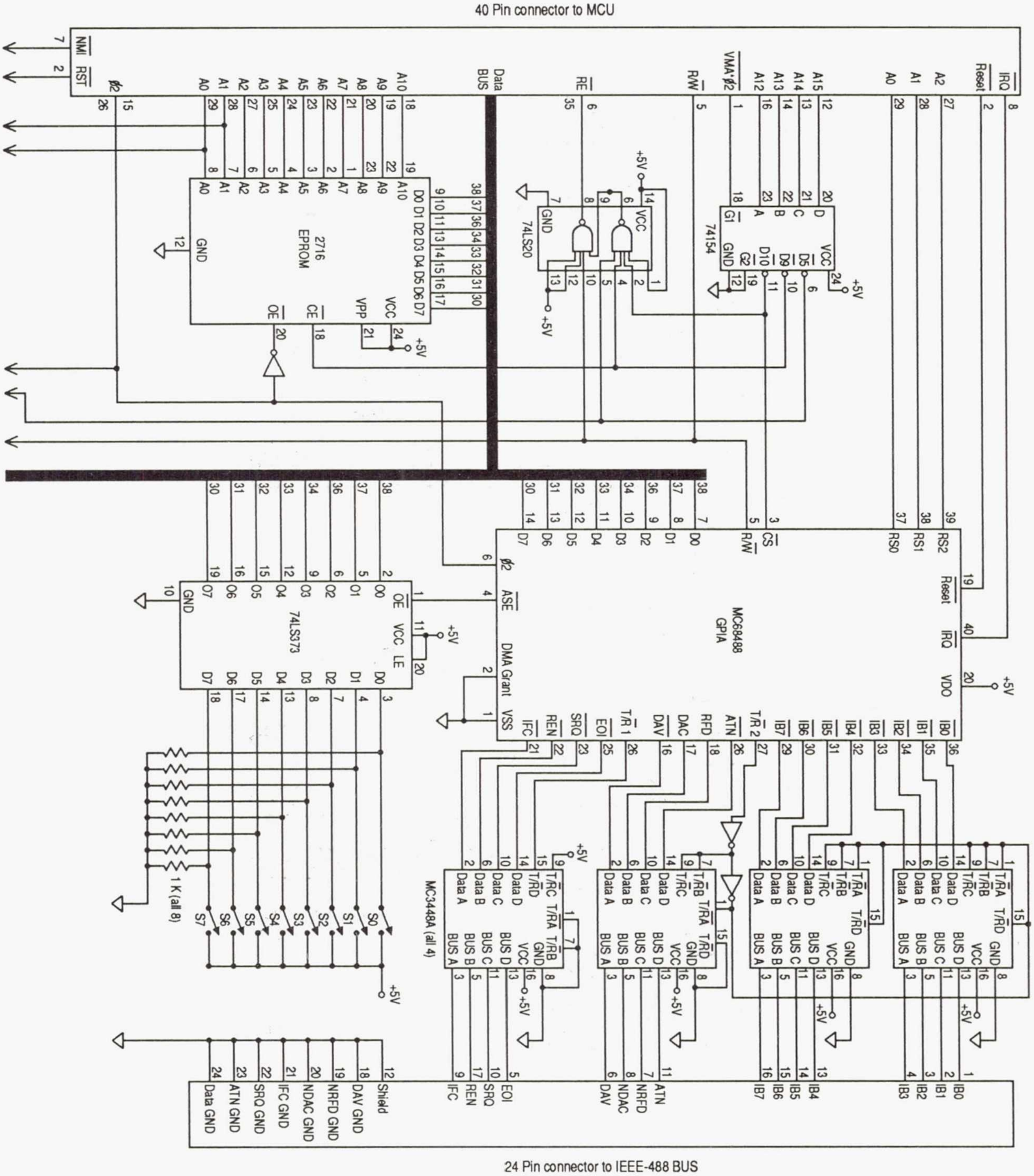
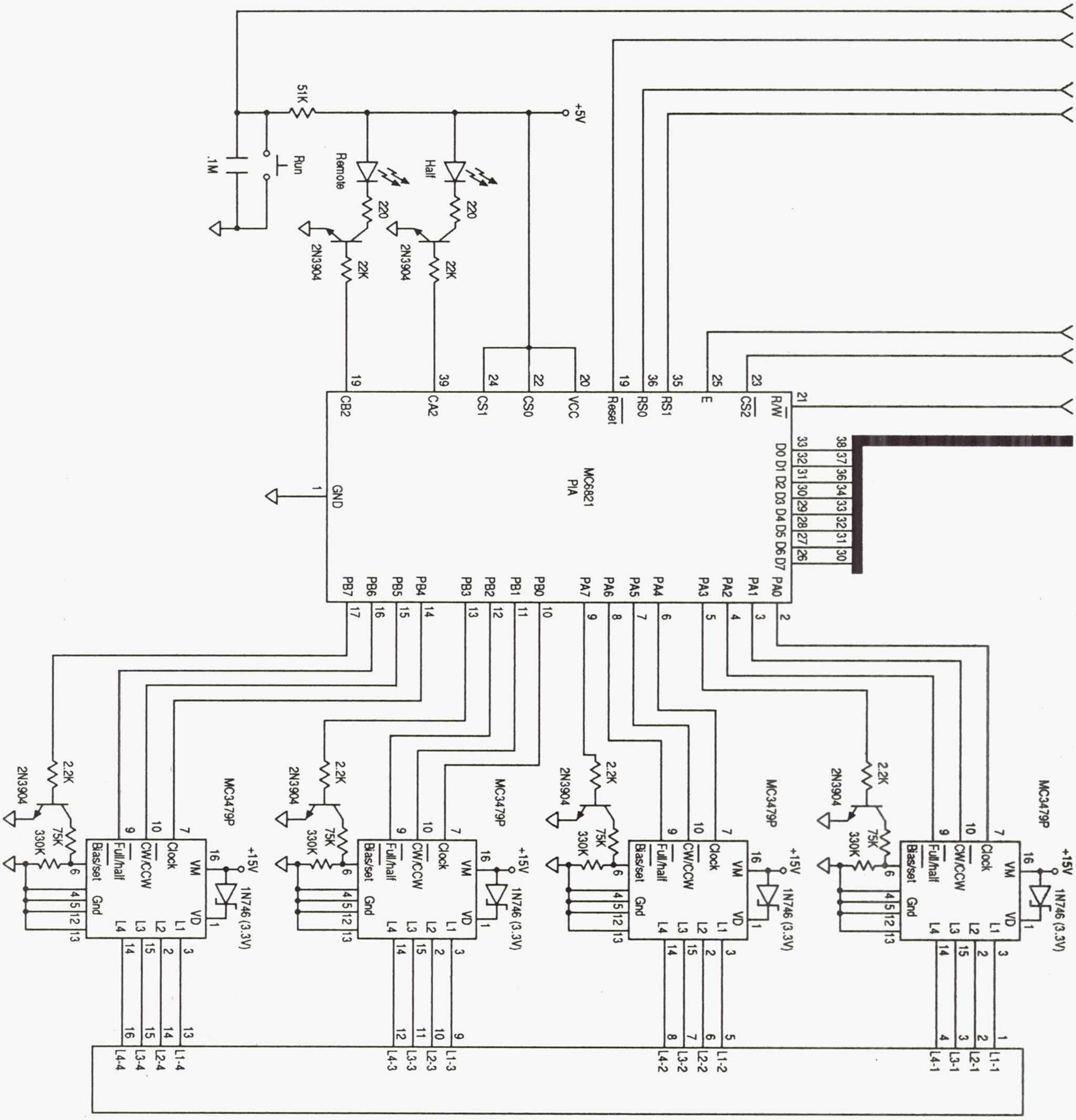


Figure 3.—Block diagram of the motorized positioning system (MPS). Shown: the PC, the MCU, the controller box, and the motors (sample manipulator is not included).



(a) First part of circuit, showing the GPIB interface and the non-volatile memory (EPROM).

Figure 4.—Circuit contained in stepper motor controller.



25 Pin connector to stepper motors

(b) Second part of the circuit, showing the PIA and the stepper motor drivers.

Figure 4.—Concluded.

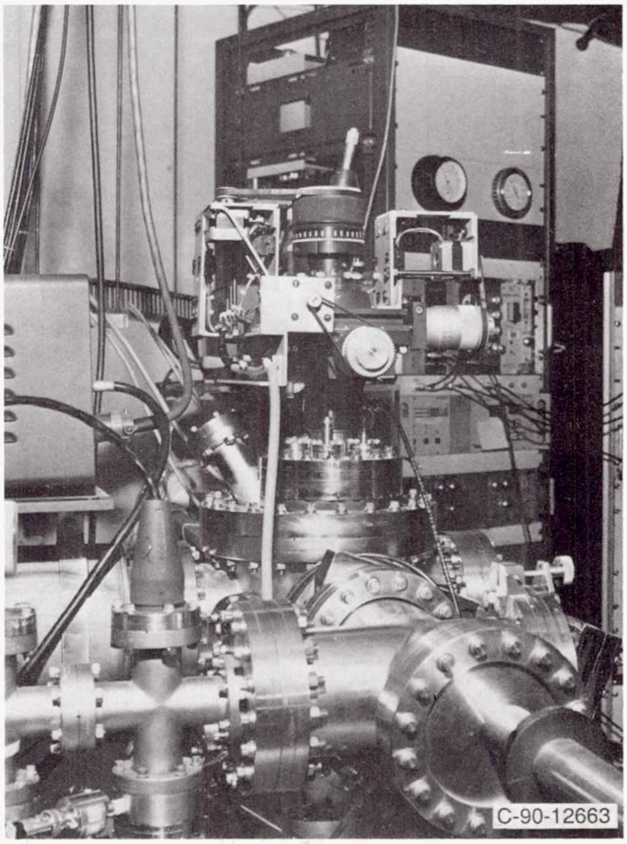


Figure 5.—MPS system showing some of the mounting details. The micrometers and the motors for the horizontal and the vertical coordinates are easily identified. Also visible is the belt and timing pulleys for the angular coordinate (top).

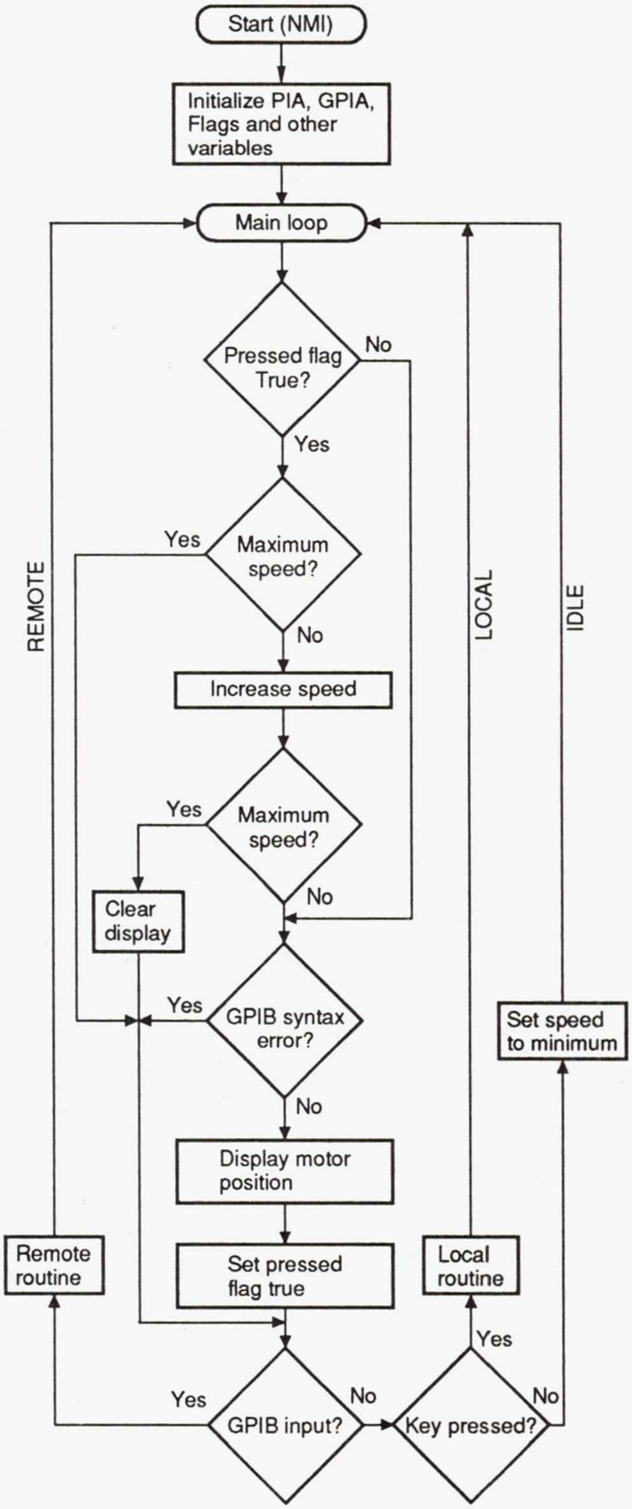


Figure 6.—Flowchart of the EPROM-based program. The three different branches are identified: IDLE (no input), LOCAL (MCU keyboard input), and REMOTE (PC input).

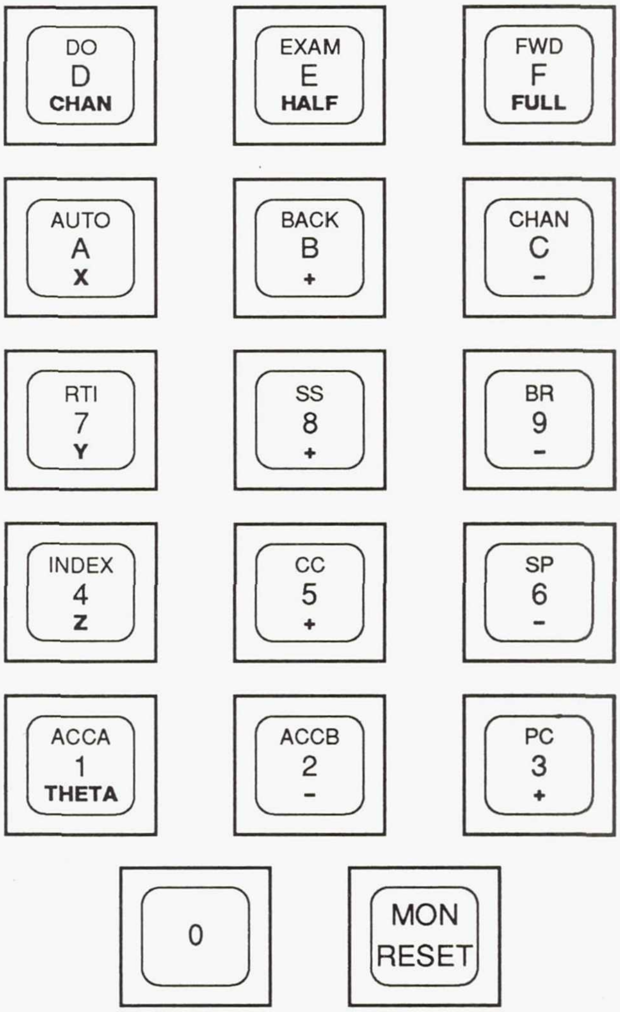
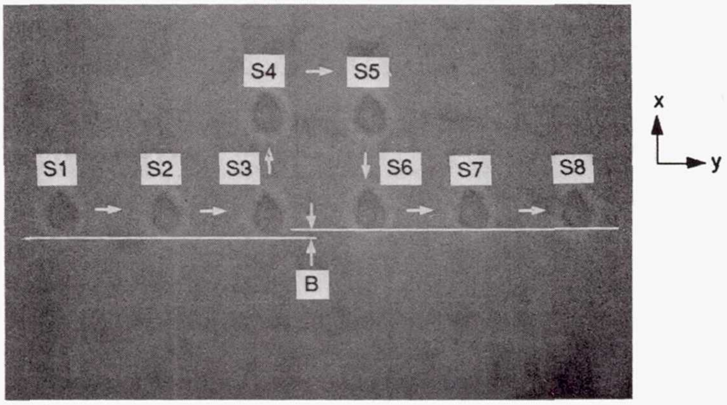


Figure 7.—MCU keyboard. For every key, the top two symbols represent its standard function, and the lowest symbol determines its role when used with the MPS.

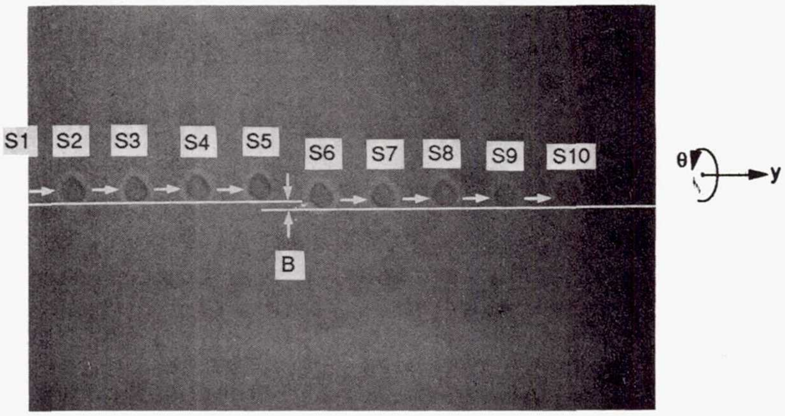
X measurement



Spot to spot = 500 µm
B = backlash ≈ 67 µm

S1 = $(X_0, Y_0)$
S2 = S1 + (0, 500 µm)
S3 = S2 + (0, 500 µm)
S4 = S3 + (500 µm, 0)
S5 = S4 + (0, 500 µm)
S6 = S5 + (–500 µm, 0)
S7 = S6 + (0, 500 µm)
S8 = S7 + (0, 500 µm)

θ measurement



Spot to spot = 500 µm
B = backlash ≈ 80 µm

S1 = $(\theta_0, Y_0)$
S2 = S1 + (–360°, 500 µm)
S3 = S2 + (–360°, 500 µm)
S4 = S3 + (–360°, 500 µm)
S5 = S4 + (–360°, 500 µm)
S6 = S5 + (360°, 500 µm)
S7 = S6 + (360°, 500 µm)
S8 = S7 + (360°, 500 µm)
S9 = S8 + (360°, 500 µm)
S10 = S9 + (360°, 500 µm)

Figure 8.—Bombarded silicon sample showing the effect of backlash in the X and θ directions. Also shown are the bombardment sequence followed, and the coordinates for each point.

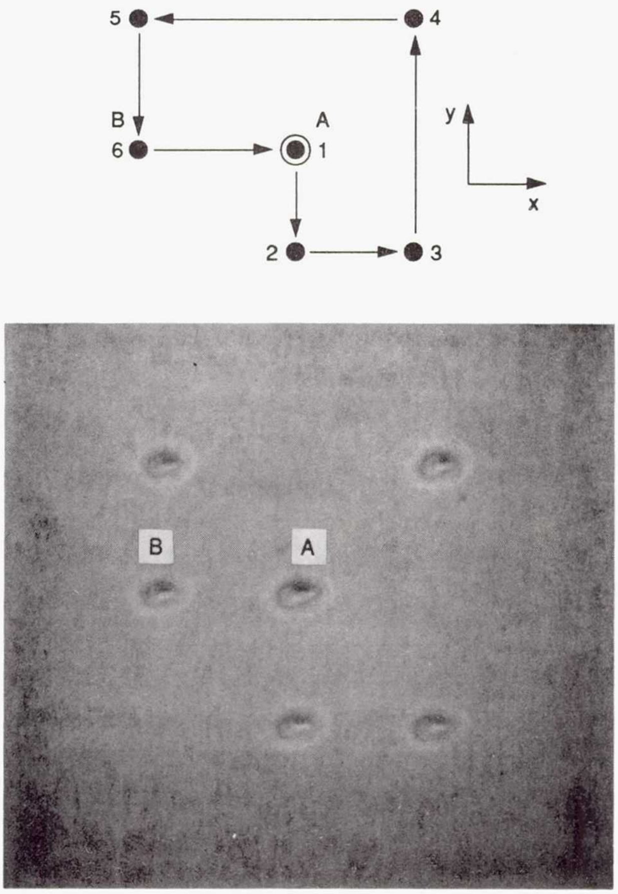


Figure 9.—Bombarded silicon sample showing the degree of repeatability of the system. The sequence followed and the coordinates for each point are also shown. The actual sample is shown at the bottom. Notice that with the pattern selected here, the backlash in both directions cancels out.

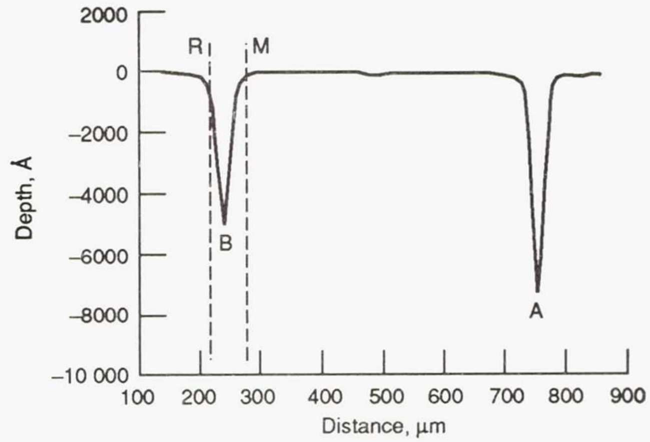


Figure 10.—Surface profile between craters A and B. Notice that the size of both craters is roughly the same. In this case, the only visible effect of the second bombardment process in crater A is its increase in depth. The width of the craters in both cases is about 50 μm.

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# Report Documentation Page

| | | |
|---|---|---|
| 1. Report No.<br>NASA CR-187144 | 2. Government Accession No. | 3. Recipient's Catalog No. |

| | |
|---|---|
| 4. Title and Subtitle<br>Versatile, Low-Cost, Computer-Controlled, Sample Positioning System for Vacuum Applications | 5. Report Date<br>August 1991 |
| | 6. Performing Organization Code |
| 7. Author(s)<br>Carlos Vargas-Aburto and Dale R. Liff | 8. Performing Organization Report No.<br>None (E-6308) |
| | 10. Work Unit No.<br>506-41-11 |
| 9. Performing Organization Name and Address<br>Kent State University<br>School of Technology<br>Kent, Ohio 44242 | 11. Contract or Grant No.<br>NAG3-946 |
| | 13. Type of Report and Period Covered<br>Contractor Report<br>Final |
| 12. Sponsoring Agency Name and Address<br>National Aeronautics and Space Administration<br>Lewis Research Center<br>Cleveland, Ohio 44135-3191 | 14. Sponsoring Agency Code |

15. Supplementary Notes

Project Manager, Sheila Bailey, Power Technology Division, NASA Lewis Research Center, (216) 433-2228.

16. Abstract

A versatile, low-cost, easy to implement, microprocessor-based motorized positioning system (MPS) suitable for accurate sample manipulation in a SIMS system, and for other ultra-high vacuum (UHV) applications, has been designed and built at NASA Lewis Research Center. The system can be operated manually or under computer control. In the latter case, local, as well as remote operation is possible via the IEEE-488 bus. The position of the sample can be controlled in three linear orthogonal and one angular coordinates.

| | |
|---|---|
| 17. Key Words (Suggested by Author(s))<br>Manipulators; Personal computer; Data acquisition; Control; Mass spectrometers; Ion spectroscopy; Positioning; Samples; SIMS | 18. Distribution Statement<br>Unclassified - Unlimited<br>Subject Category 31 |

| | | | |
|---|---|---|---|
| 19. Security Classif. (of the report)<br>Unclassified | 20. Security Classif. (of this page)<br>Unclassified | 21. No. of pages<br>24 | 22. Price*<br>A03 |

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