Session 1526

Integration of Enhanced Coordinate Measuring Machine Systems with Manufacturing Engineering Laboratories and Curriculum at Kettering University

Gwan-Ywan Lai

Kettering University

I. Introduction

Coordinate Measuring Machines (CMMs) are one of the most powerful and widely used metrological instruments in the manufacturing industry. There is virtually no workpiece whose dimensions cannot be measured with a properly equipped CMM system [1-6]. This National Science Foundation funded project (NSF-ILI: DUE-9851082) is to enhance two existing CMMs in the Metrology laboratory at Kettering University by acquiring two motorized probe heads, an automatic probe exchange system, a stylus changing probe and rack system, a laser digitizing system, and PC-DMIS CMM inspection software. The enhanced CMM systems allow for integration of modern, automated, and CAD-directed coordinate metrology as well as state-of-the-art laser digitizing technology into Manufacturing Engineering laboratories and curriculum at Kettering University. The project impacts students enrolled in the freshman course, MFGE-101 Manufacturing Processes and upper level courses such as Numerically Controlled (NC) Systems, Polymer Processing, and Computer Integrated Manufacturing (CIM) Systems.

II. Background

One important area of emphasis and expertise within the Industrial & Manufacturing Engineering and Business (IMEB) Department at Kettering University is metrology. In order to develop metrology education at Kettering University a team of IMEB faculty members with diverse interests and backgrounds was formed in 1995 and has been collaboratively working together to improve the metrology laboratory since then. The missions of the metrology laboratory are to provide students/faculty with opportunities of using modern metrological tools, integrate metrology into IMEB curriculum, support other manufacturing engineering laboratories, and provide an advanced undergraduate research environment for the Kettering University academic community. The team received an equipment grant award from Brown & Sharpe Manufacturing Company and acquired a direct computer controlled CMM in 1995. This

CMM has been actively used by students enrolled in a mandatory freshman course, MFGE-101 Manufacturing Processes since 1995. Students in this class use the CMM to inspect the dimensions of penholders manufactured from their casting and machining projects. This hands-on experience allows them to not only practice manufacturing processes but also inspect and verify the quality of their manufactured products. Students have shown increased interests in learning and practicing their machining skills because they can operate the CMM to verify the quality of their products.

Based on students feedback and this successful experience the team decided to further incorporate CMM metrology in upper level courses such as MFGE-384 Numerically Controlled (NC) Systems, MFGE-407 Polymer Processing, and MFGE-480 Computer Integrated Manufacturing (CIM) Systems. However, although the CMM with its MM4 inspection software, manual probe head, and few styli has served the freshman MFGE-101 class well, its availability and capabilities have limited its support and services to the upper level courses. Hence, the team targeted MTI Corporation and was successfully awarded a second CMM and a variety of metrological instruments including roundness and surface contour measuring devices, micrometers, height gages, slide calipers, and a toolmakers microscope in 1998. In addition, the team proposed and received this NSF-ILI grant to enhance the CMM systems and integrate CMM metrology into manufacturing engineering laboratories and curriculum in 1998. The team also received a temperature/humidity monitor for the Metrology laboratory from the Society of Manufacturing Engineers.

In addition to the aforementioned courses the project will also impact students enrolled in other Industrial and Manufacturing Engineering courses such as Statistics I & II, Sheet Metal Forming, Quality Assurance, Design of Experiments, and Robotics by providing inspection services and/or data for studies in machine capabilities, statistical analysis, gage repeatability & reproducibility, and quality control. The Metrology laboratory and the two CMM systems have been used to provide metrology experience to minority and female students participating in Kettering University's summer outreach programs such as Academically Interested Minorities, Engineering & Science for the 21st Century Woman, and Camp Kettering to introduce them to careers in engineering and science. They have also been used in Discover Kettering Day to demonstrate the operation and use of modern metrological instruments to high school students and their parents.

III. Development

In order to utilize the CMMs to effectively support the upper level courses (1) the CMMs have to be fully automated to allow for flexible inspection and integration in a CIM environment, (2) the CMMs must be electronically connected with NC, CIM, and Polymer Processing laboratories to allow for real-time inspection feedback to close the production loop of these processes via a properly selected CAD/CAM platform, and (3) a CAD-powered inspection system needs to be established to allow for intelligent inspection through the CAD/CAM system to verify design, combine tolerancing with soft gaging, simulate inspection procedures, and integrate the CMMs with new technologies in laser digitizing, reverse engineering, rapid prototyping, tooling, and manufacturing.

To achieve these tasks the team identified the capabilities and limitations of the two CMMs and determined that further enhancement and addition in CMM hardware including Motorized Probe Heads (MPH), an Automatic Probe Exchange System (APES), a Stylus Changing Probe and Rack System (SCPRS), and a Laser Digitizing Sensor (LDS) as well as software such as PC-DMIS inspection software and CAD software is needed.

Industrial CMM users in the automotive and aerospace industries have been using MPH and APES to increase CMM measurement capability and automate inspection procedures for years [1-5, 7-9]. However, SCPRS is a newly developed system that allows for quick, manual or automatic change of styli without additional complicated wiring or interfacing. SCPRS is easy to install and calibrate, and it provides an economic way to increase CMM inspection capability [14]. The combination of MPH/APES/SCPRS enables the two CMM systems to automatically execute complex inspection part programs without human intervention such as manually setting up probing directions and changing different size/shape probes and styli for various inspection needs.

LDS has received wide attention in recent years due to the need for quick scanning of objects with complicated shapes and sculptured surfaces. Different from conventional contact type measurement LDS uses a laser beam and two CCD cameras to obtain point cloud data of a scanned object in a non-contact fashion [15]. The scanned point cloud data can then be used to generate CAD models for applications in part qualification, quality assurance, design, reverse engineering, rapid prototyping and tooling, manufacturing, and CAE analysis. These tasks cannot be efficiently achieved by using the contact type CMM measurement techniques.

PC-DMIS is interactive graphics measurement software that can be linked to virtually any available CMM and CAD systems [16]. PC-DMIS has become the major inspection software of Brown & Sharpe CMM machines and has been adopted by companies such as General Motors. It allows CMMs to accept and utilize CAD models to efficiently generate inspection part programs, simulate inspection procedures, process and analyze inspection data, and perform quality analysis. CAD software such as I-Deas, Solid Works, and AutoCAD are available for this project.

IV. The Enhanced CMM Systems

The MPH, APES, SCPRS, LDS, and PC-DMIS systems were acquired, installed, and tested on the two CMMs in 1999 and 2000. The components and setup of the two enhanced CMM systems are described in the following.

The Brown & Sharpe CMM System

As shown in Figures 1 and 2, the Brown & Sharpe CMM (Microval PFx 454) system is equipped with a Renishaw PH9 motorized probe head, a SCPRS (including a TP20 touch trigger probe and an MCR20 stylus module changing rack), and a control computer with MM4 and PC-DMIS inspection software. The TP20 probe module is attached to the PH9 probe head mounted at the end of the Z rail. The probe can move in all axial directions, X (left to right), Y (front to back), Z (up and down), manually or automatically through the computer and MM4/PC-DMIS inspection software. Measuring range is 458 x 510 x 406 mm with a repeatability of 0.003 mm and a linear accuracy of 0.005 mm according to ASME B89.1.12M-1985 standards.

The MTI CMM System

As shown in Figures 3 and 4, the MTI CMM (BRT707) system is equipped with a Renishaw PH10M motorized probe head with a TP7M touch trigger probe module, an Automatic Probe Exchange System with TP20, TP2 and TP6A probe modules on the rack, and AutoCAD and Geomeasure 6000 inspection software. Measuring range is 700 x 700 x 600 mm with a repeatability of 0.004 mm and a linear accuracy of 0.003 mm according to ASME B89.1.12M-1985 standards. Figure 5 shows various probe extensions and styli available for both CMM systems. Figure 6 shows the Laser Digitizing System (LDS) installed on the MTI CMM. The PH10M motorized probe head is removed and replaced with a Kreon laser sensor. Figure 7 shows a part is being scanned by the LDS.

V. Laboratory Experiments

Pilot laboratory experiments have been developed and associated manuals are being developed for the two enhanced CMM systems. Some of the developed experiments are being used in MFGE-101 and some are being tested for other courses. Evaluations of student performance and satisfaction from these experiments serve as the first mechanism of project evaluation, and the results will be reported to the academic and industrial communities via publications and presentations when they become available. Some of the experiments are presented in the following. They demonstrate how the enhanced CMM systems can integrate metrology, CAD/CAM/CAE/CIM, rapid prototyping, and polymer processing facilities and curriculum at Kettering University.

A. MFGE-101 Manufacturing Processes

Experiment 1: Inspection of a Penholder through the two CMM systems using Teach, Off-Line, and CAD-Directed Programming [2 hours of CMM in a 6 hours structured laboratory].

Objective: Students learn the fundamentals of CMM hardware with MPH/APES/SCPRS and software (Geomeasure/PC-DMIS) by inspecting a penholder made from their machining projects.

Experiment Performed: Students will (a) machine a penholder according to its blue print, (b) use the learning mode of the CMM to teach and program the CMM to inspect the penholder, (c) use the CMM inspection programs created from Geomeasure or PC-DMIS (using off-line and CAD-directed programming) to inspect the penholder, and (d) evaluate the three CMM programming methods (teach, off-line, and CAD-directed) and the quality of their penholders.

Expected Results: Students will (a) learn the operating principles, hardware and software of the CMM systems, (b) discriminate the pros and cons of the three programming methods, and (c) determine the quality of their machined penholders from CMM inspection data and analysis.

B. Numerically Controlled (NC) Systems

Experiment 1: Introduction to CMM Hardware, Motorized Probe Head (MPH), Automatic Probe Exchange System (APES), Stylus Changing Probe and Rack System (SCPRS) and Geomeasure/PC-DMIS Software for Unmanned, Flexible CMM Inspection. [6 hours of structured and unstructured laboratory].

Objective: Students use Geomeasure/PC-DMIS software to program CMMs and automate inspection tasks via the MPH/APES/SCPRS systems to measure the parts made from their NC machining projects.

Experiment Performed: Students will (a) learn the fundamentals of CMM hardware, software, and the MPH/APES/SCPRS systems, (b) use the software to program the MPH to control the orientation of the probe head, (c) program the CMM to select proper probes/styli from the APES/SCPRS, (d) program the CMM/MPH/APES/SCPRS system to inspect the parts made from their NC machining projects without human intervention, (e) analyze and determine the quality of their parts, and (f) evaluate the reduction of inspection time and the increase of inspection accuracy and precision achieved by the CMM/MPH/APES/SCPRS system.

Expected Results: Students will (a) learn the operating principles of the CMM/MPH/APES/SCPRS, (b) determine the quality of their machining parts from CMM inspection data, and (c) appreciate the flexibility, productivity, automation, and economics of CMM.

Experiment 2: Reverse Engineering via CMMs with (1) the MPH/APES/SCPRS and Touch-Triggered Probes (TTP) system, and (2) the Kreon Laser Digitizing System and Polygonia software [6 hours]

Objective: Students learn reverse engineering using the CMM/MPH/APES/SCPRS/TTP system, the CMM/LDS system, and NC machining.

Experiment Performed: Students will (a) use TTP to digitize parts with standard geometric features such as circles, planes and angles, (b) use LDS to digitize complex parts with sculptured surfaces, (c) use the digitized geometry to create CAD models in Polygonia software, (d) generate NC machining codes in Mastercam and make replicas of the these parts, (e) use Geomeasure/PC-DMIS and the CAD models to program the CMM/MPH/APES/SCPRS/TTP and CMM/LDS systems to inspect the replicas, and (f) compare the quality of the replicas with the original parts, and evaluate the performance of the two CMM systems in reverse engineering applications for simple and complex parts.

Expected Results: Students will (a) duplicate parts without prints of these parts, (b) compare the quality of replicas with original ones, and (c) learn to integrate the CMM systems (contact and non-contact type measurements), CAD, and NC machines for reverse engineering.

C. Computer Integrated Manufacturing

Experiment 1: Integration of CMM and CNC with CAD/CAM Systems through CAD-Directed Inspection via PC-DMIS [6 hours of structured and unstructured laboratory].

Objective: Students use PC-DMIS to integrate CMM inspection and CNC production with I-Deas/Mastercam CAD/CAM systems in a CIM environment.

Experiment Performed: Students will (a) use I-Deas and Mastercam CAD/CAM systems to design and create CAD models with properly assigned tolerances, (b) verify the tolerances (GD&T) reflect the designer's intent and conform to design standards (ANSI Y14.5M or ISO 1101), (c) generate 3-D graphical representations of tolerance zones (softgages) and store them within the CAD models, (d) use PC-DMIS to generate Dimensional Measuring Interface Standard (DMIS) programs, (e) use PC-DMIS to simulate the CMM probing paths and perform 3-D collision detect, (f) use Mastercam to generate CNC machining codes and produce physical parts, (g) use the softgages and DMIS programs to direct the CMM to inspect the CNC machined parts, and (h) use PC-DMIS to compare the measured data against the original CAD design specifications.

Expected Results: Students will (a) learn system integration of CAD/CAM/CNC and CMM, and (b) integrate design, manufacturing, inspection, and quality control to close a production loop using the enhanced CMM systems and the PC-DMIS software.

D. Polymer Processing

Experiment 1: CMM Applications in Rapid Prototyping & Tooling for Injection Molding

Objective: Students learn the principle and practice behind reverse engineering, and rapid prototyping/tooling/manufacturing via the CMM systems (MPH/APES/SCPRS/TTP, LDS, and PC-DMIS), a Stereolithography Apparatus (SLA), and an injection molding machine.

Experiment Performed: Students will (a) scan physical parts using both TTP and LDS to obtain representative data points, (b) perform best-fit regression analysis available in PC-DMIS and/or Polygonia on the inspected data points to produce CAD models with smooth 3-dimensional splines and geometric features, (c) compare the difference and performance between the LDS and TTP, (d) export the CAD models to I-Deas or SolidWorks to generate STereoLithography (STL) files for SLA rapid prototyping, (e) use SLA to create prototypes and molds, (f) use the molds and the injection molding machine to make functional parts (g) use PC-DMIS to generate CMM probing paths based on the CAD models, (h) analyze the inspection data against the CAD models to study the shrinkage and warpage of the prototypes and molded parts

Expected Results: Students will learn (a) the operations of LDS and TTP, (b) the fundamentals of reverse engineering and rapid prototyping, and (c) the system integration of CMM, reverse engineering, and rapid prototyping/tooling/manufacturing, (d) a complete product realization cycle from design, manufacturing through inspection.

E. To Develop a New Course and Support Other Courses in IMEB curriculum

In addition to the above planned experiments, the enhanced CMM systems are used in developing a new course in metrology, GD&T, and quality. Students will learn functional design through GD&T, use CMM to measure standard geometric features (such as circles, planes, and angles) and non-prismatic features (such as sculpture surfaces), use MPH/APES/SCPRS/TTP/LDS/PC-DMIS to learn automated, CAD-directed inspection in a CIM environment, and use collected inspection data in statistical quality control and quality assurance. The CMM system will also help Industrial Engineering courses such as Statistics I and II, Quality Assurance, and Design of Experiments by providing data for students to study topics such as data collection & analysis, sampling distribution, quality control, and Gage Repeatability and Reproducibility (GR&R).

VI. Conclusion

This project has enhanced two CMMs with state-of-the-art hardware and software. The enhanced CMM systems help in bridging the gap between design and production, providing feedback from CMM inspection to refine design and manufacturing processes, providing inspection results for statistical process control and quality assurance, and integrating modern coordinate metrology in the IMEB curriculum. Several laboratory experiments have been planned and presented. These experiments are being tested for various courses. The enhanced CMM systems are also used to develop a new course in metrology, geometric dimensioning & tolerancing, and quality. This project has established a modern metrology facility and provides students with opportunities for conducting undergraduate research and independent study, and publishing theses and technical papers. The enhanced CMM systems have also been used in pre-college programs for junior/senior high school women and minorities. More experimental experiences, progress and results of this project will be presented when they become available in the future.

Acknowledgements

The equipment purchase for this project has been supported in part by the National Science Foundation (NSF-ILI: DUE-9851082). Dr. Tom Howell is the NSF Program Director for this project. A matching fund is provided by Kettering University. Additional support has been received from Brown & Sharpe Manufacturing Company, MTI Corporation, and the Society of Manufacturing Engineers. The author thanks the contributions made by the above organizations. He also expresses his appreciation to Professors Winston Erevelles and Stephen Aylor at Robert Morris College and Professor Laura Sullivan at Kettering University for their support and contributions in the starting stage of the project. He also thanks his graduate student, Mr. Venkateshwara Raju for his help in installing equipment and testing various laboratory experiments. Opinions expressed in this article are those of the author and not necessarily those of the NSF and companies mentioned.

Bibliography

1. Bosch, Coordinate Measuring Machines and Systems, Marcel Dekker, New York, NY, 1995.
2. Genest, "Seizing the Advantage with Flexible Gaging," Modern Machine Shop, November, 1993.
3. Coronato, "Software Helps Automate Inspections," Machine Design, 1994.
4. Genest, "Coordinate Measuring Machines," ASM Handbook, Vol. 17: Nondestructive Evaluation and Quality Control, ASM International, Materials Park, OH, 1993.
5. Genest, "Can We Make Automobiles without Using Models?", Quality Today, September, 1990.
6. Deitz, "Design for Quality Control," Mechanical Engineering, June, 1995.
7. Menq, H.-T. Yau, and G.-Y. Lai, “Automated Precision Measurement of Surface Profile in CAD-Directed Inspection,” IEEE Transactions on Robotics and Automation, Vol. 8, No. 2, pp. 268-278, April, 1992.
8. Menq, H.-T. Yau, G.-Y. Lai, and A. Miller, 1990, “Statistical Evaluation of Form Tolerances Using Discrete Measurement Data,” Proceedings of the Symposium on Advances in Integrated Product Design and Manufacturing, pp. 135-150, the 1990 ASME Winter Annual Meeting, November 25-30, Dallas, Texas.
9. J.-L.Wong, G.-Y. Lai, P. Smith, and C.-H. Menq, 1989, “Automatic Dimensional Inspection System Manual,” Technical Report to Edison Project, Ohio State Department of Development, and Ohio State University, Columbus, Ohio.
10. Kalpakjian, Manufacturing Engineering and Technology, 2nd ed., Addison-Wesley, New York, NY, 1992.
11. Kennedy, E.G. Hoffman, and S.D. Bond, Inspection and Gauging, 6th ed., Industrial Press, New York, NY, 1987.
12. Griffith, Measuring & Gauging Geometric Tolerances, Prentice Hall, Englewood Cliffs, NJ, 1994.
13. Anthony, Engineering Metrology, Pergamon Press, New York, NY, 1986.
14. Renishaw TP20 and MCR20 User’s Guide.
15. Kreon Laser Digitizing Sensor Manual.
16. PC-DMIS User’s Manual.

GWAN-YWAN LAI

Gwan-Ywan Lai, Ph.D. is a member of ASEE, APMI, SME and SPE. He has taught seminars in Injection Molding and Metrology, and has consulted in the areas of metrology, polymer processing, and materials for Callaway Golf, Knable & Associates, Medical Modeling, 3M, Dynisco and ErgoTech. He is the principal investigator of two NSF ILI Grants, a Brown & Sharpe Equipment Grant, and an internal Kettering Research Grant.

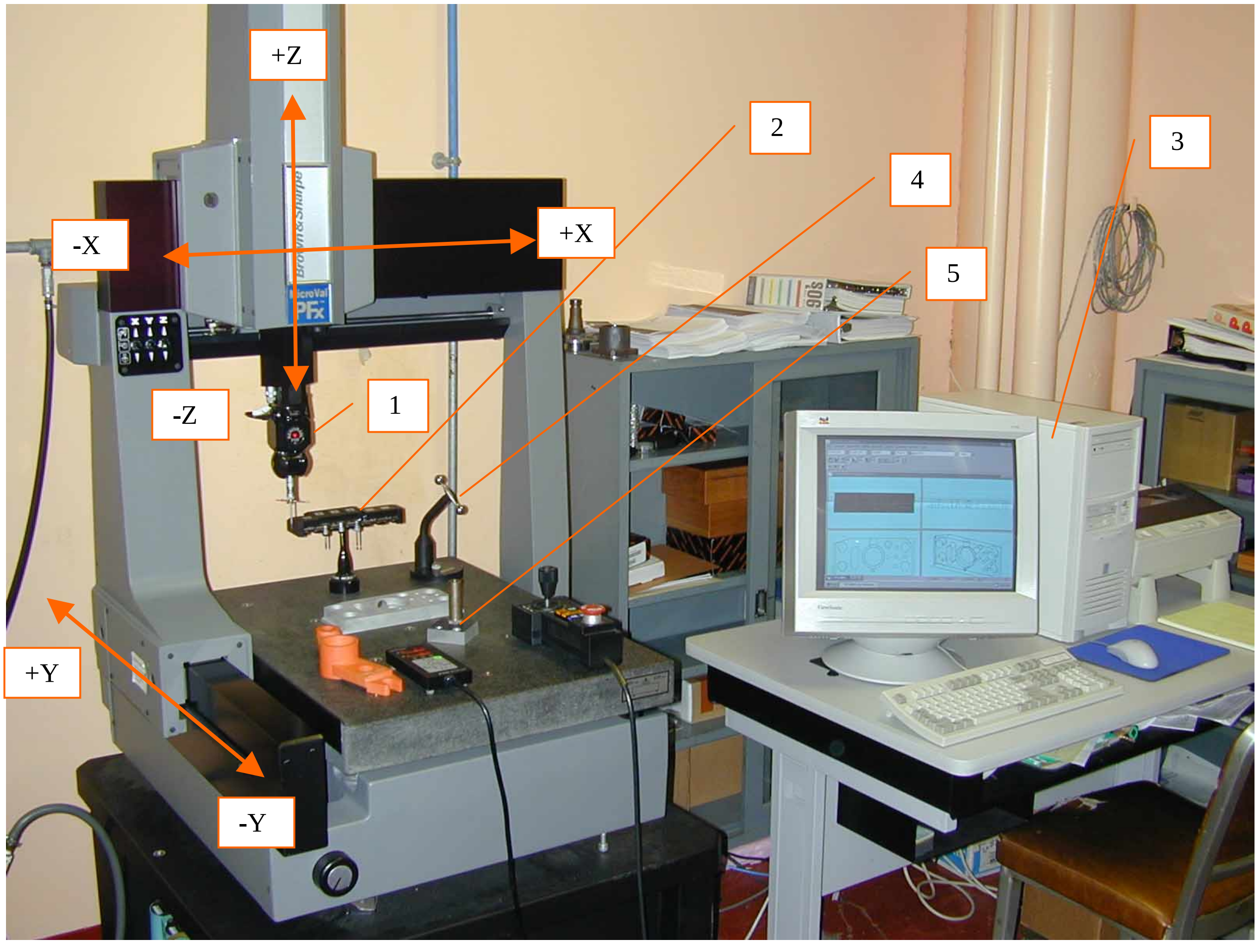

Figure 1. The Brown & Sharpe Micrioval PFx 454 CMM System: (1) PH9 Motorized Probe Head and TP20 Probe Module, (2) MCR20 Probe Module Changing Rack with Three Probe Modules, (3) Computer System with MM4 and PC-DMIS inspection software, (4) Qualification Spheres, and (5) Penholder from a Machining Project.

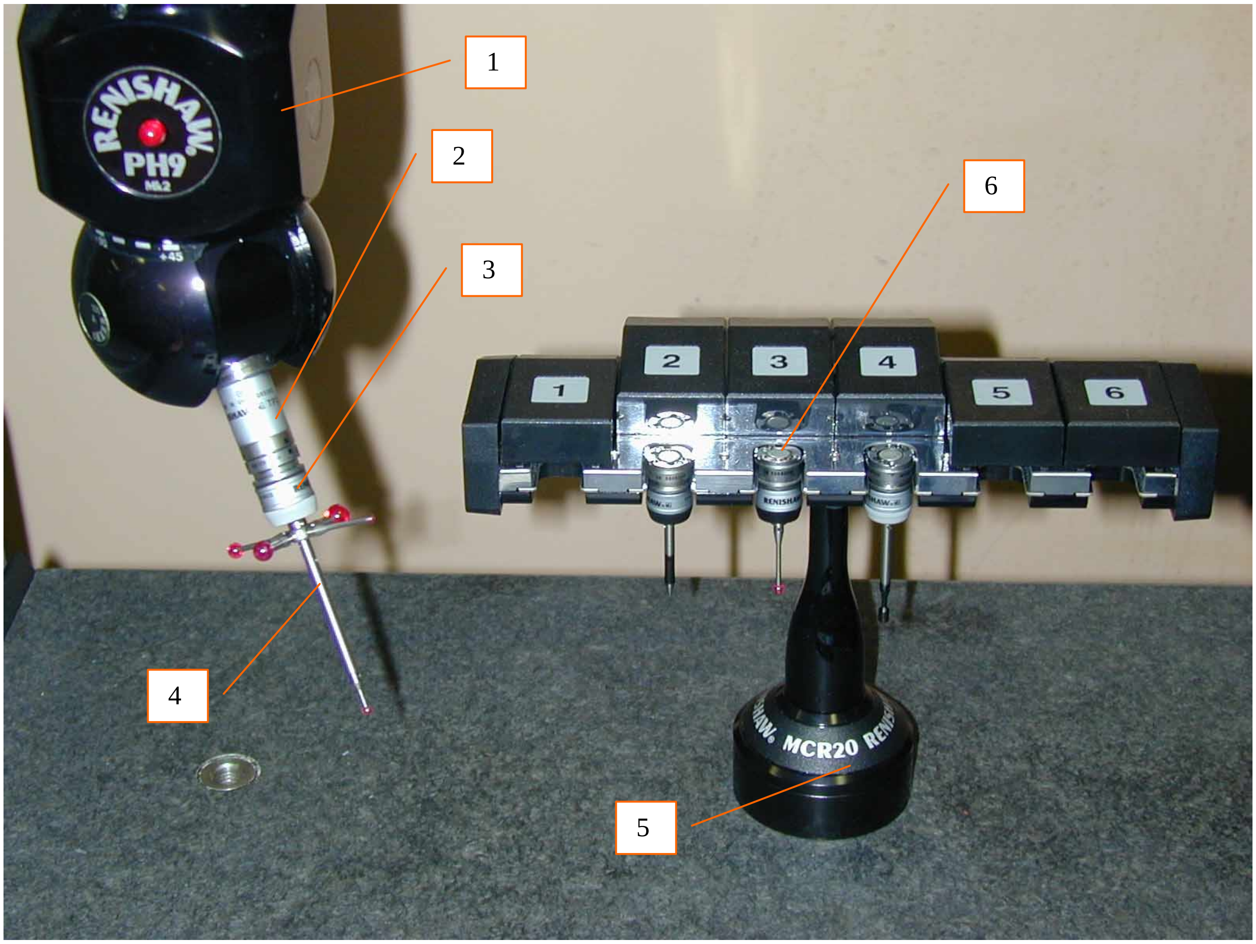

Figure 2. The MPH and SCPRS System: (1) PH9 Motorized Probe Head, (2) TP20 Probe Body, (3) Probe Module #1, (4) Styli, (5) MCR20 Module Changing Rack with Six Docking Stations, and (6) Probe Modules #2, #3, and #4.

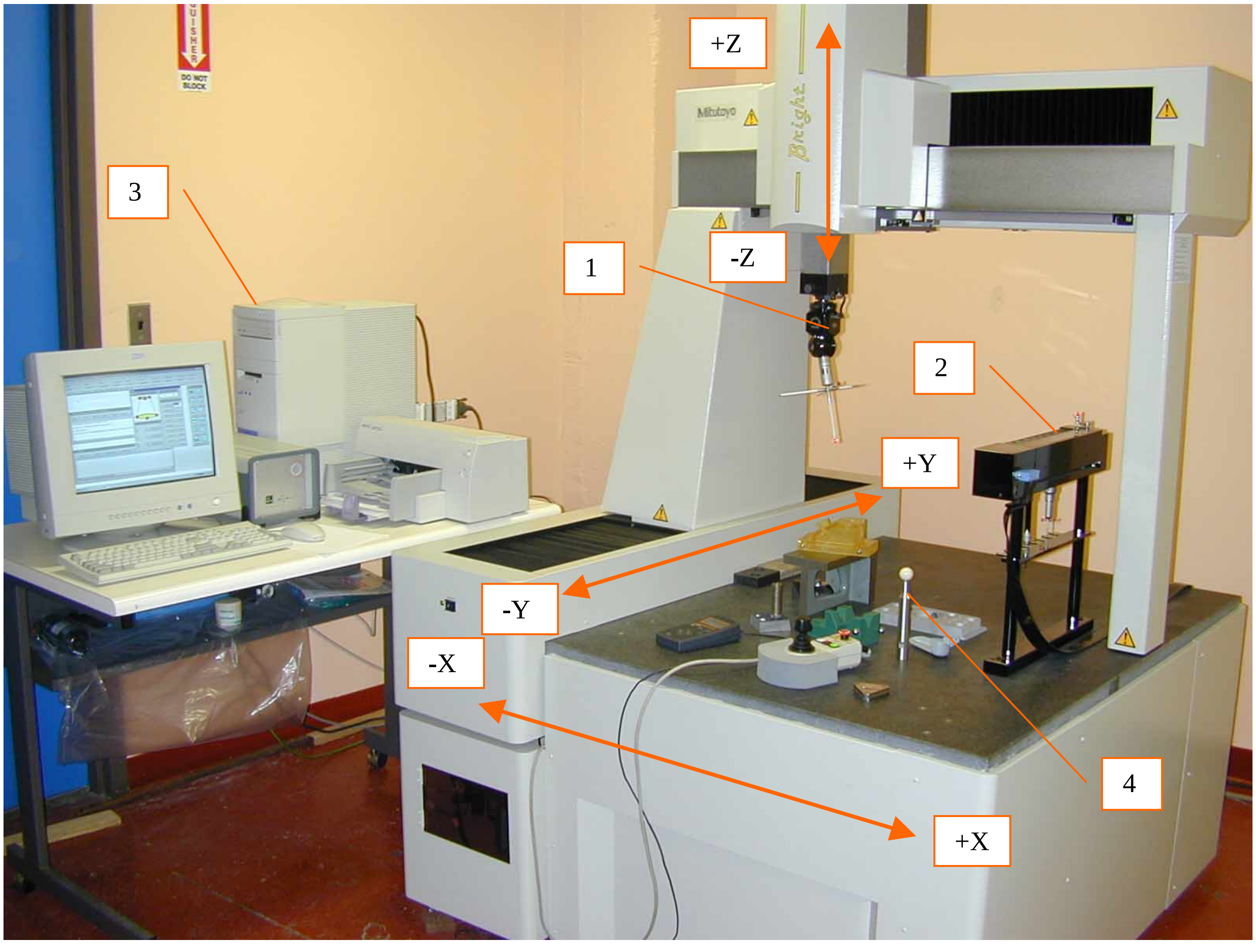

Figure 3. The MTI BRT 707 CMM System: (1) PH10M Motorized Probe Head with TP7M Probe, (2) ACR1 Automatic Probe Exchange System with Three Probe Modules and Styli, (3) Computer System with AutoCAD and Geomeasure 6000 inspection software, and (4) Qualification Sphere.

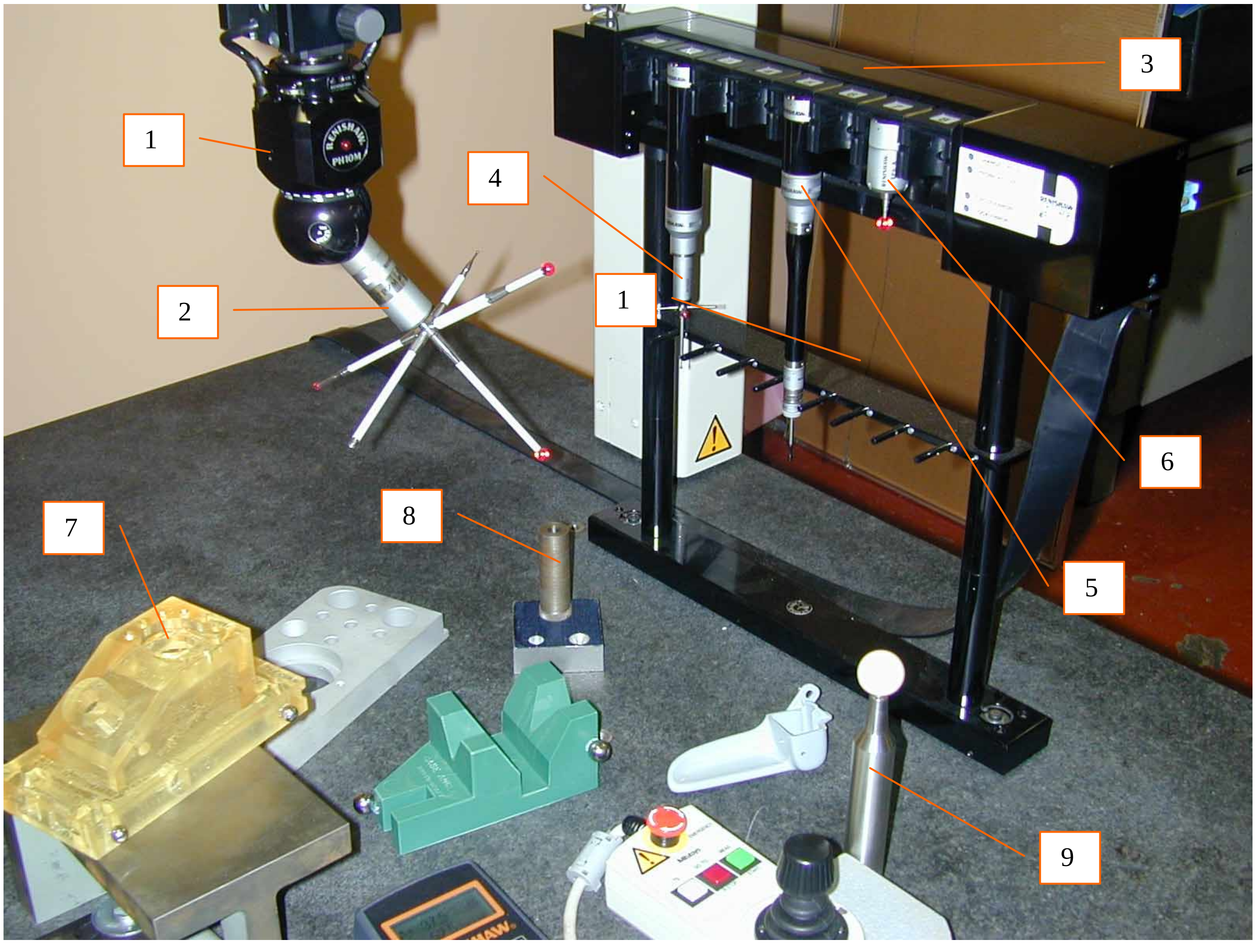

Figure 4. The MPH/APES System: (1) PH10M Motorized Probe Head, (2) TP7M Probe Module, (3) ACR1 Automatic Changing Rack with Eight Docking Stations, (4) TP2 Probe Module with a Star Set of Five Styli, (5) TP20 Probe Module with an Extension Bar and a Stylus, (6) TP6A Probe Module with a Stylus, (7) Epoxy Part from Stereolithography, (8) Penholder, and (9) Qualification Sphere.

Figure 5. Various Styli and Probe Extensions.

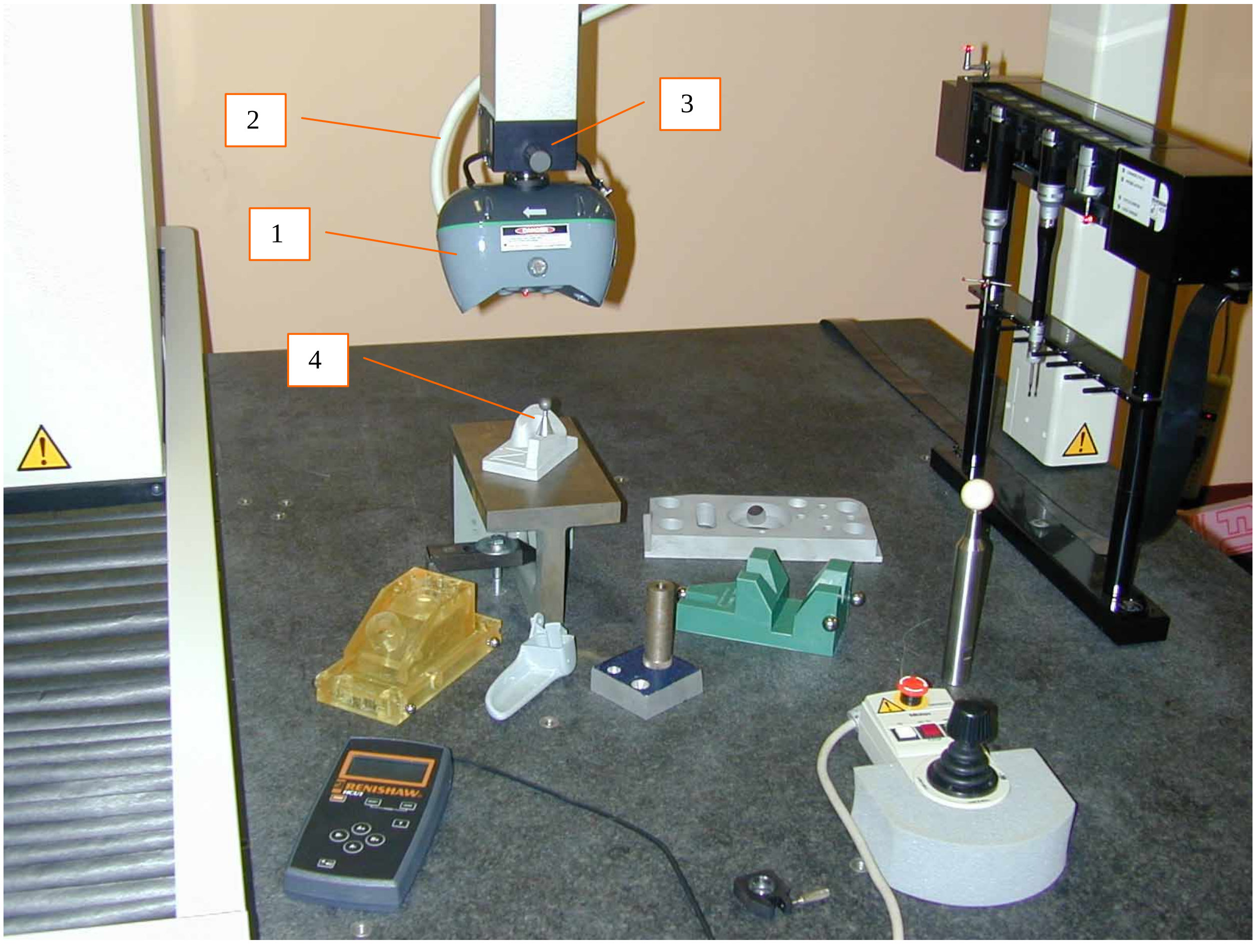

Figure 6. Kreon Laser Digitizing Sensor Installed at the End of MTI CMM Z-Rail: (1) Laser Digitizing Sensor, (2) Fiber Optic Cable Connecting the Sensor to its Electronic Control Unit, (3) Z-Rail, and (4) Part being Scanned.

Figure 7. Kreon Laser Digitizing Sensor is scanning a part along the X-axis. (1) The red line on the part is the laser beam. (2) Two CCD cameras capture the images of the red lines while the sensor is scanning.