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ADAPTIVE CONTROL SURVEY

This report contains the results of a survey of Adaptive Control Machining, conducted by Metcut Research Associates, Incorporated, Cincinnati, Ohio 45209, under Subcontract 65Y-35001V, with the Oak Ridge Y-12 Plant.

UNION CARBIDE CORPORATION
NUCLEAR DIVISION
OAK RIDGE Y-12 PLANT

operated for the ATOMIC ENERGY COMMISSION under U. S. GOVERNMENT Contract W-7405 eng 26

UNION CARBIDE

OAK RIDGE Y-12 PLANT
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ADAPTIVE CONTROL SURVEY

John F. Kahles, Metcut Research Associates, Inc

Oak Ridge Y-12 Plant

P.O. Box Y, Oak Ridge, Tennessee 37830

operated for the **U.S. ATOMIC ENERGY COMMISSION**
by **UNION CARBIDE CORPORATION-NUCLEAR DIVISION**
under Contract W-7405-eng-26

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ABSTRACT

A comprehensive survey has been made of the present status of adaptive control as it is applied to all types of machining processes. Included is a bibliography of 439 references, a summary of 15 plant visits, and the results of an extensively circulated questionnaire. This survey shows that industry has made little progress in applying adaptive control to the production of parts exhibiting high-quality surface finish and high accuracy. In particular, there is a need for research and development work in the fields of machinability and sensors for obtaining and monitoring very high surface finishes and accuracy.

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PREFACE

To continue the development of systems for exercising better control over metal-cutting processes, the Oak Ridge Y-12 Plant[a] has initiated an Adaptive Control Project for a numerically controlled lathe. This project is designed to determine the economic and technical feasibility of using adaptive control techniques with electronic geometric correction principles to produce a machined part of substantially higher quality than is possible using normal machining equipment and procedures. Quality is being defined as a weighted product of such physically evaluated part features as: size, shape, surface finish, and surface integrity. Machining economics, such as the material removal rate, extended tool life, and tool costs, are to be of secondary importance. Because of the scope of this project, it was decided to conduct a comprehensive survey in order to determine in what areas capabilities already exist for possible applications to the needs of the Y-12 Plant. A contract was signed with Metcut Research Associates, Inc of Cincinnati, Ohio to perform this survey, and the results of this study are the subject of this report.

(a) Operated for the US Atomic Energy Commission by the Union Carbide Corporation's Nuclear Division.

INTRODUCTION

The Fabrication Systems Development Department of Union Carbide Corporation-Nuclear Division's Y-12 Plant is presently conducting an adaptive control (AC) project of considerable magnitude. Because of the scope of this activity it was decided to conduct a comprehensive survey in order to determine in what areas capabilities already exist for possible application to Y-12's needs.

Y-12 interests in this study are engaged, primarily, in areas relating to sensing and control of accuracy, finish, and surface integrity rather than in adaptive control as normally applied to cost and production-rate considerations. Advances in the areas of tighter tolerances and high surface finishes are sought. Furthermore, these goals must be achieved in turning operations using water-base cutting fluids.

At the outset of this survey, a cursory evaluation of the literature and discussions with highly qualified men in industry and education indicated that very few significant accomplishments have been realized to date in the area of Y-12 interest. Hence, the design of this survey encompassed not only contacts already identified with AC, but also with those having an identifiable interdisciplinary relationship.

Since definitions and concepts regarding AC vary greatly, a few comments are in order concerning the way Y-12 views AC and how it fits into its program:

> "The Fabrication Systems Development Department is embarking upon an adaptive control project of considerable magnitude. This project consists of an attempt to control the cutting process in an optimum manner through the use of closed-loop feedback systems.
>
> "An adaptive system is one which is provided with a means for continuously monitoring its own performance in relation to a specified index of performance (IP) or optimum condition and a means for modifying its own parameters by closed-loop action so as to approach this optimum condition.
>
> "The adaptive system performs three essential functions: Identification, Decision, and Modification. 'Identification' is defined as the process by which the system is characterized or by which the IP is measured. The 'Decision' function comprises a comparison of system performance to the desired optimum and a selection of corrective strategy. 'Modification' is the process of changing the system parameters to gradually advance toward the optimum performance value along a course determined by the optimizing control strategy.

"Principal areas in which adaptive control can be beneficial are:

1. Increased part accuracy.

2. Improved surface quality.

3. Reduction or elimination of unsatisfactory production.

"Adaptive control of all practical machine characteristics and part/tool interaction will be attempted. The major objective is to optimize a combination of all major controlling parameters affecting the end product. Obviously, a thorough understanding of each factor is required, even though the final product will be fabricated under operating conditions which require a 'trade off' of the individual factors.

"<u>Technical Approach:</u>

An American tape controlled lathe has been obtained for the project. This machine has been retrofitted with a GE 7500 control and electro-hydraulic drives to upgrade its performance. A general purpose computer has been acquired to be used in conjunction with the interpolation capability of the existing numerical control (NC) unit so as to be representative, insofar as possible, of a full-sized computer-assisted NC-controlled machine shop installation. The necessary interface electronics will be developed to cause the appropriate computer-control unit-machine tool-process sensors communication and interaction.

"Improved laser interferometers have been installed and have been used for position feedback during the actual cutting conditions. Other hardware such as automatic error compensation devices and temperature, strain, and tool-load sensors will be procured or developed and interfaced with the machine tool control system. Software, including routines for real-time acquisition of process feedback data, operation of the optimization program, and updating of machine control information will be developed.

"The practicability of the devices and systems developed will be evaluated whenever possible using production-type parts to simulate actual problems due to shape and metallurgy."

With these objectives in mind, a survey plan was designed to uncover any possible assistance which the literature, plant visitations, and a questionnaire could offer.

The survey design included:

1. Plant visitations to:

   a. Present and potential manufacturers of AC machine tools.

   b. Present and high potential users of AC.

   c. Instrument and control companies.

2. Discussions with university personnel.

3. Review of the current literature.

4. Design, mailing, and evaluation of a comprehensive questionnaire.

SUMMARY

This report is a comprehensive survey of the present status of adaptive control as applied to material removal and as related to the specific interests of the Oak Ridge Y-12 Plant. Essentially, the survey plan comprised plant visitations, literature studies (both domestic and foreign), and a widely circulated questionnaire. The foreign literature study, less extensive by design, nonetheless is believed to accurately reflect the state of the art of AC in Germany, Italy, Japan, and several other countries.

The survey substantiated the belief that, generally, there is a strong interest in AC in the aerospace industry; but, presently, the potential market definitely requires encouragement in relationship to cost factors—and even more so for other industries. The first-generation AC machine tools were designed to use relatively complex multisensing systems. Problems encountered plus cost considerations, at the time of this survey, have essentially kept AC out of production machining. Presently, there is a definite, almost universal, trend toward the development and use of simpler sensing systems designed to take advantage of the monitoring of feed rates only and to adapt them to multiple spindle machines, particularly profile end mills. Overall, relatively few plants are very seriously considering any type of AC as applied to material removal at this time. Practically all of the present and potential industrial applications to date relate to AC for increasing productivity and reducing costs.

The Y-12 interest in adaptive control relates specifically to achieving a high surface finish and high accuracy in contrast with AC production and cost-type interests. Y-12 Plant personnel are also interested in the control of surface integrity. It is desired that these aims be fulfilled in turning operations using water-base cutting fluids.

At the outset of the survey, little existing capability was anticipated in the area of Y-12 interests. A review of approximately 550 documents (439 cited herein), mailing of 3,265 domestic and 272 foreign questionnaires (including an analysis of the 233 replies), and 15 plant visits and the interrogation of hundreds of people substantiate the belief that if significant progress is to be made, it will be necessary to enter into extensive research and development programs that give consideration to new machining techniques and the development of new types of sensors. Techniques must be developed to gain a high finish in alloys of interest with tool materials other than diamond, and this to be achieved by turning operations rather than by the conventional processes for producing a high finish. Considerably more basic knowledge is needed in relation to tool wear. Solution of the problems may require finding ways and means to monitor tool wear directly.

Some encouragement in this survey was noted in the area of signature analysis, including control, and in the potential application of adaptive learning systems already developed and being developed in fields other than material removal. These should be considered in Y-12's future planning, but priority consideration should be given to the machinability and sensor requirements.

INFORMATION ON ADAPTIVE CONTROL

PLANT VISITATIONS AND SEMINARS

Plant Visitations

Visits were made to installations of the following companies: Adaptronics, Inc, The Bendix Corporation, The Boeing Company, The Bunker-Ramo Corporation, The Cincinnati Milling Machine Company, Electro-Optics Associates, Federal Scientific Corporation, General Electric Company, Grumman Aerospace Corporation, IBM Corporation, McDonnell Douglass Corporation, Thermal Systems Inc, Twigg Industries, and United Detector Technology.

Pertinent information obtained through the visitation program can be summarized as follows:

1. There is keen interest in AC, especially with cost as the index of performance (IP). It is precisely this IP requirement, however, which in part is currently limiting more extensive application of AC. At the present time the great potential users of AC have no new production contracts with large material-removal requirements to justify the purchase of new AC systems. Instead, there is an interest in applying retrofit machines, particularly AC packages, to existing multispindle profilers. Even in retrofitting, there is a strong tendency to question the justification of costs of AC. Very little effort is being directed toward using part quality, defined as a weighted product of such physically evaluated part features as: size, shape, surface finish, and surface integrity, as the index of performance.

2. The technology of machine tool controls and computers is much more advanced and presents no deterrent to the expansion of AC applications at present. This conclusion was evident throughout the visitations. Some companies have very sophisticated control systems employing self-learning technqiues that should be considered to aid in an adaptive control of the machining process. However, these systems have not yet been applied to this process.

3. A great need was expressed during some visits with companies applying AC to end milling for: (a) force data in relationship to feedrates, and (b) data on chip load versus surface finish.

4. It was thought that available technology for taking stereo pairs of aerial transparencies and producing orthographic projection photographs and altitude charts with very high accuracies might be applicable to surface finish sensing. A visit was made to a company possessing this technology.

The results of this visit indicated that this technology might be adapted to measure part surface finish, but not without requiring considerable basic effort. Even with this effort, sensing could not be accomplished during the actual cutting process. Other companies indicated that surface-finish monitoring using optical means is feasible; however, considerable research and development is necessary.

5. Many complex AC systems are not cutting material in production. Some of the deterrents are:

   a. Need for more development, including modification of AC equipment including the machine tool, sensors, and controls. Dissatisfaction has been expressed concerning some of the sensor and controls systems used to equip first-generation AC machines.

   b. Lack of justification for the use of single spindle machines equipped with AC compared with non-AC multiple spindle machines.

   c. Some companies are in the process of redesigning their AC units with feed control only instead of a combination of feed and speed.

6. Sensing of cutter deflection at the spindle nose and cutter torque in the spindle is being accomplished to adaptive control milling machines. Experience indicated that in some instances measurement of motor current or torque was too insensitive for some systems when applied to milling.

7. Some excellent background work has been done and some sophisticated units have been developed for signature analysis of the machining process. These units, known as spectrum analyzers, may provide the ability for measuring tool wear during the cutting process. Changes of the signature derived during the cutting may indicate tool wear and other changes in the machining process. One company had utilized signature analysis for detecting tool wear.

8. Control of the feedrate based upon machine component loading was most predominate.

9. A trend was noted toward simpler AC systems by modifying only one programmed variable such as feedrate. Lack of available sensing equipment and control algorithms seems to have prompted this trend.

10. Some companies indicated continued interest in thermal sensing for application to adaptive control. Overall interest in this area of sensing is mild.

11. Several companies have expressed the need for data showing the effect of tool geometry and finish of the cutting edge on workpiece finish and rate of tool wear.

12. Visits to many of the companies revealed the highly competitive aspects of AC. Some of the companies were reluctant to discuss some aspects of their activities unless further agreements were entered into with Union Carbide.

Adaptive Control Seminar

An Adaptive Control Seminar was held in Atlanta, Georgia on February 24 and 25, 1970. The program included the following papers (also included in the Literature Survey section of this report):

Title	Author
What is Adaptive Machine Tool Control?	Robert H. Raible, Associate Professor of Electrical Engineering, University of Cincinnati
A Survey of Adaptive Control Machining	Mikell P. Groover, Assistant Professor of Industrial Engineering, Lehigh University
Why Adaptive Control for Electrochemical Grinding?	Les V. Colwell, Professor of Mechanical Engineering, University of Michigan
Adaptive Control of Forces in the Profile Milling Process	Clive P. Hohberger, Principal Engineer, Bunker-Ramo Corporation
Adaptive Controlled Profile Milling	Richard A. Mathias, Metal Cutting Research, Cincinnati Milling Machine Co
A Trainable Adaptive Machine Control System	Jerry M. Idelsohn, Project Engineer, Bendix Research Laboratories
Retrofit of Adaptive Control to Profilers	Randolph T. Hanger, Group Engineer, The Boeing Company

The important conclusions reached in attending this meeting were:

1. Economics was one of the most important indices of performance. However, no definitive data were supplied by any of the papers relative to cost within such constraints as finish, size, and surface integrity.

2. Agreement was essentially manifest concerning the great importance of sensing "feed" at this point in time.

3. The Boeing representative described his company's adaptive retrofit for profilers. He believes that deflection sensing is good enough for now to get AC on the road. Current problems are: chip control, tooth breakage, and burning of the cutter. Currently, Boeing is looking at drastic ways to alter the cutter, and they feel that there are great opportunities in applying new cutter designs.

4. None of the papers and none of the seminar registrants who were contacted informally were able to provide data in the area of Y-12 interest.

An Analysis of the Seminar (by R. H. Raible, who presented one of the papers and also served as a consultant to Metcut Research Associates, Inc for this meeting) - Of the seven presentations made at this seminar, a majority included surveys and definitions of the concept of adaptive control. Five different systems were included in the presentations, and three of these were described in sufficient detail to allow for a technical discussion. The speakers represented those concerned with basic and developmental research efforts at three universities, three major machine tool manufacturers, and one major user of modern machine tools. Those in attendance at the sessions were mostly concerned with direct manufacturing problems, and most of the questions and follow-up discussion were related to the applicability of various techniques.

The following remarks and observations are drawn from an overall view of the seminar.

1. General Technique - The traditional description of an adaptive system which includes the steps of identification, decision, and modification is used by most workers in system development. The most frequent implementation in machine tool applications uses direct measurement of certain parameters and use of a fixed formula (empirical, in part) to control directly certain other parameters, although a searching procedure was described by one speaker and referred to by two others as being of considerable interest.

2. Index of Performance - The only IP considered at length was the production rate, usually represented by the metal-removal rate with a suitable weighting factor to account for the tool-wear rate and tool changes. Attributes of the machined product such as accuracy and surface quality were treated as constraining conditions on the setup and operation of the system, within which the adaptive control could act to optimize production. The primary consideration here was the difficulty of an on-line measurement of the

workpiece, although one speaker mentioned the possibility of improving surface finish in grinding by a "trainable" adaptive system.

3. Measured Variables - By far the greatest interest centered on the measurement of cutting forces, usually by measuring spindle deflection or torque sensors. The potential increase in production (on the order of 20%, or more in certain instances) by a simple feedback of cutting forces, and the relative ease with which this can be done, might tend to preclude the development of still more elaborate control schemes to achieve what might be only a small additional improvement. Tool-wear rate and tool-tip temperature are also considered important, but are difficult to measure. Gaging methods and surface analyzers were not discussed.

4. Control Parameters - Feed and speed were the only control parameters discussed in the metal-cutting applications (one paper on electrochemical grinding was the exception). One author pointed out that the relatively easily attainable control of feedrate only could produce a substantial proportion of the total improvement in performance available by this technique, assuming the cutting speed was fixed at an appropriate value.

5. Numerical Control - The importance of numerical control in modern machine tool technology has at least two implications for adaptive control designers: (a) the adaptive control scheme must be compatible with the NC technique; (b) machine tool controls will be more and more oriented toward digital and computer control, and the computation workload required of the more elaborate adaptive schemes might be carried by a computer already dedicated to the NC system.

LITERATURE SURVEY

The literature survey consisted of a detailed examination of the domestic literature (Appendix A). A less extensive state-of-the-art survey of the foreign literature was made by Max Kronenberg (Appendix B).

The primary sources for the AC literature were two information centers, namely: the Air Force Machinability Data Center (AFMDC), Cincinnati, Ohio, and the Machining and Gaging Information Center (MAGIC), Oak Ridge, Tennessee. Other centers were also contacted. In addition, bibliographies were requested from technical societies and publishers of periodicals. All articles obtained from primary or secondary searches were reviewed for additional references.

The sources for the literature search were as follows:

Information Centers (other than AFMDC and MAGIC)

Aerospace Materials Information Center (AMIC) - This center is an AFMIC[b] located at Wright-Patterson AFB, Ohio, Air Force Materials Laboratory. The center collects, interprets, organizes into retrievable form, and disseminates technical information on such topics as materials and metals, various types of manufacturing procedures, and methods of materials evaluation.

Aerospace Research Applications Center (ARAC) - This center is located at the Indiana University Foundation, Indiana University, Bloomington, Indiana. It is a NASA-sponsored center which disseminates to civilian-oriented industry the results of the nation's governmental research and development programs to and in the development of new and improved products, processes, and materials for commercial markets, and precludes duplication in industrial research and development programs of work already done in whole or part in government programs.

Defense Metals Information Center (DMIC) - An AFMIC located at the Battelle Memorial Institute, Columbus, Ohio, which collects, interprets, and disseminates technical information about special metals used in aircraft, missiles, and other military systems.

Electronic Properties Information Center (EPIC) - An AFMIC located at the Hughes Aircraft Company, Culver City, California, which collects, indexes, and abstracts the world's literature on the electrical, magnetic, and optical properties of materials of value to the defense community. This center also evaluates, compiles, and publishes the experimental data from this literature. As yet, there appears to be no apparent endeavor in AC in the areas listed.

Instrumentation Information Center - This center is operated by the US Department of Commerce, NBS, Washington, DC and operates as a reference service in the subject field of instrumentation, chiefly for the NBS. However, it also serves other governmental agencies on request.

Machine Tool and Manufacturing Technical Information Center (MIC) - This facility is located at the University of Cincinnati, Cincinnati, Ohio, and is

(b) AFMIC denotes Air Force Materials Information Centers sponsored by the Air Force Materials Laboratory, Wright-Patterson AFB, Ohio.

funded in part under the State Technical Services Act. Its work is devoted primarily to information services in relationship to machine tools.

National Referral Center for Science and Technology - This center is located at the Library of Congress, Washington, DC and is supported by the National Science Foundation. It is designed to advise where and how to obtain information on specific topics in all fields of science and technology and areas relating to them. It is also concerned with all kinds of information resources in government, industry, and in the academic and professional areas.

Science Information Exchange - This information source is located at the Smithsonian Institution, Washington, DC and is a national registry of current planned or in-progress research in all basic and applied fields of the life, social, physical, and engineering sciences.

Periodicals

Automation - A Penton publication that is designed to aid production functions in manufacturing plants in all industries.

Control Engineering - A Reuben H. Donnelly publication in the field of control and information systems.

Instruments & Control Systems - A Chilton publication in the field of instruments and devices for measurements, inspection, testing, analysis, computing, and automatic control.

Societies

American Automatic Control Council - An intersociety federation formed to promote cooperation among US technical and scientific societies which have an interest in automatic control.

Instrument Society of America - A group located in Pittsburgh, Pennsylvania that is organized to advance the arts and sciences connected with the theory, design, manufacture, and testing of instruments in the various sciences and technologies.

Numerical Control Society - A group located in Princeton, New Jersey that was founded to serve the unique requirements and integrated responsibilities created by the concept of control via symbolic data, to provide a central information source and information exchange, and to be a focal point for the exploration of new ideas to serve the user and potential user of numerical control equipment.

The reference list, Appendix A, totals 439 documents. The main list (Items 1 - 320) is cited alphabetically in numerical order by author; all annonymous articles (Items 321 - 423) are listed at the end of the bibliography list by title. In addition, literature acquired after the main body of acquisitions was frozen is contained in a supplement (Items 424 to 439). Since the bibliography is rather extensive, a Subject Index, Appendix C, was prepared covering the following major categories:

1. Material Removal Operations

2. Sensors

3. Systems Analysis

4. Controls

5. Direct Digital Control

6. Economics

7. General Literature

Analysis of the literature substantiated the fact that there is an extensive interest in adaptive control. The major AC interests relate to cost and production factors. The literature also leads one to believe that much more production application has been made of AC than was noted in the plant visitations of this survey. The literature indicated that the major serious activity in material removal in AC is end milling.

The literature does not reflect some of the strong trends toward the use of simpler AC systems, as noted in making the plant visitations. With respect to AC-related information, considerable interest is manifest in the application of direct digital control to material removal. Because of their pertinence, some of the references were included in Appendix C.

The AC literature also contains many articles providing announcements and trends. Many of these were eliminated, but some were included especially since MAGIC had originally listed in bibliographies supplied to Metcut. These articles are helpful in that they reveal the extent of interest in AC and may even be of possible value in identifying sources for assisting Y-12 in their AC program. This literature study did not identify the information that was directly applicable to the quality adaptive control interests of Union Carbide. However, the subject index has been constructed so as to obtain existing related information to

Union Carbide's needs by consulting such descriptors as size, tool wear, finish, and sensors. These sources provide a springboard for entering into more activity with technical people.

ADAPTIVE CONTROL QUESTIONNAIRE

Included in this section of the report is a copy of the transmittal letter and accompanying questionnaire used in gathering additional survey information (Pages 38 through 42). This questionnaire was sent to companies identified directly with AC and also to many companies working in fields considered interdisciplinary with AC. It was hoped that some companies might already have valuable information even though they were not as yet identified with AC.

Sources Selected for Questionnaire Mailing

The majority of questionnaires were addressed to specific individuals in companies from the following sources:

Literature Contacts - The Bibliography, Appendix A, was used to collect names of individuals and companies.

Aerospace Firms - Two sources were noted:

1. World Space Directory. Vol 7(2), Spring 1969. Washington, DC, American Aviation Publications, Inc.

   Section B Industrial - Major Space and Oceanology Manufacturers, Parts B10 through B330 were scanned for contacts. This part included Pages 61 - 180.

2. An inventory of Profile/Contour Machines. Washington, DC, Aerospace Industries Association of America, Inc, November 1966.

   A list of companies was extracted from Pages 10 - 12 of this report.

Manufacturers - Various types of manufacturing companies provided source material.

Machine Tools -

1. Air Force Machinability Data Center

An inquiry was directed to AFMDC requesting a search on special term - MACHINE TOOL-DIRECTORY Contacts were extracted from these sources.

2. Aviation Week & Space Technology, Marketing Directory Issue. Vol 91(26). Mid-December 1969. New York, McGraw-Hill.

   Terms used in locating companies for contacts are as follows: Chemical Milling, Drilling, Lapping Service, Machine Tools, Masers, Metal Finishing/Polishing, Metal Forming Machines, Metal Removal Machines, Reamers, Roll Forming Machines, Shot Peening, Taps, Tools (machines), Ultrasonic Equipment.

3. Directory of Machine Tools 1969, Washington, DC, National Machine Tool Builder's Association.

   Section I, Pages 1 - 46, contains a list of the companies indexed in this directory.

4. Machine and Tool Directory. Vol 18. 1969. Wheaton, Illinois, Hitchcock Publishing Company.

   The following three sections were used in selecting contacts from this book:

   a. Electrolytic Machines (ECM, EDM, ELG), Pages 93 - 108.

   b. Numerical Control Systems, Pages 37 - 45.

   c. Numerically Controlled Machine Tools, Pages 47 - 92.

5. Machine Tools and Related Products 1968. Washington, DC, National Machine Tool Builders' Association.

   The complete directory was used for contacts.

6. Numerical Control Guidebook 1970. Modern Machine Shop, Cincinnati, Ohio, Gardner Publications, Inc.

   The section on Machine Tools from Pages 170 - 262 was scanned and appropriate companies selected.

7. Numerically Controlled Machine Tools and Related Products 1968. Washington, DC, National Machine Tool Builders' Association.

A list of companies from this directory was extracted from Pages 1 - 18.

8. Numerical Control Multi Operation Machine Tools, Metalworking. Vol 23(9): 67-70. September 1967.

   This directory supplied company names from the pages listed.

9. Selector Guide NC Systems. American Machinist. Vol 111(24): 121-136. November 29, 1967.

   This directory supplied company names from the pages listed.

10. Thomas' Register of American Manufacturers. 59th edition (1969). New York, Thomas Publishing Company.

    All basic machining operations were checked along with Machine Tools and Nonconventional Machining.

Controls -

1. Aviation Week & Space Technology. Marketing Directory Issue Vol 91(26). Mid-December 1969. New York, McGraw-Hill.

   The following terms were used as guides to sources: Control Equipment-Electronic, Control Equipment-Nonelectric, Environmental Control Systems, Fluidic Controls, Logic and Control Modules, Positioning Controls.

2. Design News, Annual 1970. Vol 1. Denver, Colorado, Cahners Publishing Corporation (1970).

   The following two sections were scanned:

   a. Section 3: Switching Control & Regulation on Pages 194 - 195. These were used in correlation with the advertisers' index.

   b. Section 10: Testing & Measurement on Page 625. This was also used in correlation with the advertisers' index.

3. Instruments & Control Systems. Philadelphia, Pennsylvania, Rimbach Publications Division of Chilton (1970).

The Product Index section was checked for contacts.

4. Machine and Tool Directory. Vol 18. 1969. Wheaton, Illinois, Hitchcock Publishing Company.

   The following terms contained in Pages 311 - 316 were used:

   Controllers-Pressure, Controls-Electrical, Controls-Feedback, Controls-Hydraulic, Controls-Liquid Levels, Controls-Machine Gage, Controls-Mechanical, Controls-Pneumatic, Controls-Speed and Torque, Controls-Temperature, Control Systems-Fluidic, Control Systems-Pneumatic.

5. NC Guidebook, Modern Machine Shop. Cincinnati, Ohio, Gardner Publications, Inc (1969).

   The following areas were checked:

   Adaptive Controls, Contouring Controls-Direct Computer Control Systems, Control-Systems, Fluidic Controls-Logic and Control Modules, Positioning.

6. Thomas' Register of American Manufacturers. 59th edition (1969). New York, Thomas Publishing Company.

   The following terms were checked from Pages 1791 - 1860:

   Controls-Automatic, Controls-Electric, Controls-Electric Motor, Controls-Electronic, Controls-Feeder, Controls-Fluidic and Static, Controls-Lathe, Controls-Machine, Controls-Machine Tool (electrical), Controls-Temperature, Controls-Numerical, Controls-Pneumatic, Controls-Proportioning, Controls-Pyrometer, Controls-Speed, Controls-Torque, Controls-Miscellaneous, Controls & Regulators, Control Systems.

<u>Sensors</u> -

1. <u>Aviation Week & Space Technology</u>. Marketing Directory Issue. Vol 91(26). Mid-December 1969. New York, McGraw-Hill.

   The following areas were checked:

   Detectors, Dynamometers, Electrical Impulses (registers), Environmental Control Systems, Fiber Optics, Fluidics-Sensors, Gages, Gaging, Optical Systems & Equipment, Sensors/Transducers, Synchros-Resolvers, Thermocouples, and Accessories.

2. Design News, Annual 1970. Vol 1. Denver, Colorado, Cahners Publishing Corporation.

   In the product index the following areas were checked:

   Instruments and Controls Section-Electric Actuators, Sensing Devices (transducers, thermocouples, photocells), Solenoids, Synchros.

3. Instruments and Control Systems. Philadelphia, Pennsylvania, Rimbach Publications Division of Chilton (1970).

   Product index was checked under appropriate headings.

4. Machine and Tool Directory. Vol 18. 1969. Wheaton, Illinois, Hitchcock Publishing Company.

   Areas checked are as follows:

   Gages-Automatic Size Control, Gages-Bore, Gages-Depth, Gages-Machine Control, Gages-Special, Gages-Surface, Gages-Taper, Gages-Temperature, Gages-Tool Setting, Gages-Ultrasonic, Inspection Instruments-Dimensional, Inspection Instruments-Electronic, Inspection Instruments-Numerically Controlled, Inspection Instruments-Optical, Inspection Instruments-Ultrasonic, Lasers, Surface Finishing Measuring Equipment, Thermocouples.

5. Thomas' Register of American Manufacturers. 59th edition. 1969. New York, Thomas Publishing Company.

   The following areas were checked:

   Accelerometers, Controls and Regulators, Detectors, Fiber Optics, Thermocouples, Torques, Transducers.

Instruments -

1. Aviation Week & Space Technology. Marketing Directory Issue. Vol 91(26). Mid-December 1969. New York, McGraw-Hill.

   Areas checked are listed as follows:

Indicator Instruments, Inspection Equipment, Instrument-Testing, Resolvers, Synchros.

2. Design News, Annual 1970. Vol 1. Denver, Colorado, Cahners Publishing Corporation.

   The following sections were checked:

   Section 3-Switching Control and Regulators, and Section 10-Testing and Measurement. The product index was also checked under Instruments and Controls.

3. Instrument and Control Systems. Philadelphia, Pennsylvania, Rimbach Publications Division of Chilton Company (1970).

   The product index section was checked under the appropriate headings.

4. Machine and Tool Directory. Vol 18. 1969. Wheaton, Illinois, Hitchcock Publishing Company.

   The following sections were checked:

   Inspection Instruments-Dimensional, Inspection Instruments-Electronic, Inspection Instruments-Numerical Controlled, Inspection Instruments-Optical, Surface Finishing Measuring Equipment.

5. Thomas' Register of American Manufacturers. 59th edition. 1969. New York, Thomas Publishing Company.

   The following areas have been checked:

   Instrument Accessories, Instruments-Acoustic Measuring, Instruments-Calibrating, Instruments-Digital, Instruments-Electric Measuring and Testing, etc, Instruments-Electrochemical, Instruments-Electromechanical, Instruments-Electronic, Instruments-Measuring, Instruments-Program Control, Instruments-Speed Indicating, Instruments-Ultrasonic.

Computers -

1. Aviation Week & Space Technology. Marketing Directory Issue. Vol 91(26). Mid-December 1969. New York, McGraw-Hill.

The following areas were checked:

Computer Components, Computers-Analog, Computers-Digital, Computers-Hybrid, Memories-Computer.

2. Data Systems News. Information Source Directory, Vol 10. December 1969. New York, United Business Publications, 1969.

   Section on computers was taken from Page 12.

3. Design News, Annual 1970. Vol 1. Denver, Colorado, Cahners Publishing Corporation.

   Index to advertisers under Systems and Assemblies-Computers on Page PS-22 was taken.

4. Machine and Tool Directory. Vol 18. 1969. Wheaton, Illinois, Hitchcock Publishing Company.

   Computer section on Page 302 was taken.

5. Thomas' Register of American Manufacturers. 59th edition. 1969. New York, Thomas Publishing Company.

   The following areas were checked:

   Computers-Analog and Digital, Computers-Process Control, Computer Service-Electronic Analog and Digital.

Universities -

1. Air Force Machinability Data Center.

   An inquiry was submitted to AFMDC for all inquirers on Adaptive Control and Direct Computer Control. These inquirers were added to the list of contacts.

2. World Space Directory. Vol 7(2). Spring 1969. Washington, DC, American Aviation Publications, Inc.

   Section on Colleges and Universities from Pages 435 to 486 was included.

Centers -

1. All the centers originally contacted for adaptive control information were used.

2. Various library sources available for center contacts were used.

Research Organizations, Institutions, Societies, Associations-

1. World Space Directory. Vol 7(2). Spring 1969. Washington, DC, American Aviation Publications, Inc.

   Major nonprofit research organizations and professional associations and organizations from Pages 487 to 507 were used.

2. List of registrants from the Adaptive Control Seminar in Atlanta, Georgia, February 24-25, 1970, sponsored by the Society of Manufacturing Engineers.

Aerospace Industries Association - The Aerospace Industries Association mailed questionnaires to their Manufacturing Committee.

Fortune Magazine - Fortune's Directory of the Largest Industrial Corporations. Fortune. Vol LXXIX(6):166. May 15, 1969.

This listing was used as a means of verifying pertinent companies.

Foreign - Max Kronenberg reviewed the foreign literature for contacts on a cursory basis.

Summary of the Responses to the Questionnaire (For details see Appendix D.)

Following are the mailing statistics:

Number of Questionnaires Mailed	3,537
Domestic	3,265
Foreign	272
Number of Questionnaires Returned as Nondeliverable	44
Domestic	37
Foreign	7
Percent of Questionnaires Delivered	98.8
Total Number of Questionnaires Delivered	3,493

Total Number of Replies	233
Percent of Replies	6.7
Number of Questionnaires Containing Applicable Information	102
Domestic	95
Foreign	7
Number of Questionnaires with Limited Application	15
Percent of Replies Containing Applicable Information	43.8

It is apparent that a high percentage of the letters were delivered but that the percent of total replies as well as applicable replies was low. Ordinarily, a good return is considered to be about 15 - 20 percent. Apparently, the low total percentage was the result of the attempt to seek information by making an extensive mailing to people not yet closely involved with AC. It was decided to forgo a followup mailing. Indications are that the percentage of replies would have increased but no more applicable replies would have been obtained.

No accounting was made of the percentage of returns from AC-oriented companies, but an examination of applicable replies indicates that the response was very satisfactory; and, furthermore, that the replies contained some significant information and data.

Appendix D contains the addresses of those who submitted applicable replies. This list is an excellent source of contacts for Y-12. Appendix D also contains an analysis of the applicable replies to each question. The questionnaire was considered to be of value to this survey and to the Y-12 AC project even though it did not isolate sources of information on sensing and control in the area of Y-12 interest.

METCUT RESEARCH ASSOCIATES INC.

3980 ROSSLYN DRIVE, CINCINNATI, OHIO 45209 / Teletype: 810-461-2840 / Telephone: (513) 271-5100

March 1970

ADAPTIVE CONTROL SURVEY FOR
UNION CARBIDE CORPORATION—NUCLEAR DIVISION
SUBCONTRACT NO. 65Y-35001V

The Fabrication Systems Development Department of the Union Carbide Corporation Nuclear Division is beginning an adaptive control project of considerable magnitude and is using the services of Metcut for preparation of a comprehensive survey. Specifically, the purpose of this survey is to collect and analyze information concerning systems for controlling accuracy, surface finish, surface integrity, vibration, chatter and tool wear which are applicable for turning various parts on machine tools. It will also include cost control aspects, instrumentation and interpretation. In addition, there is considerable interest in the feasibility of using adaptive control to produce surface finishes substantially better than 10 microinches and to attain accuracies in the order of plus or minus 0.0001 inch.

We invite your participation by completing the enclosed questionnaire. This questionnaire will provide us with some important information as well as an indication of your interest in having one of our representatives visit you.

We hope you will accommodate us by filling out as much of the questionnaire as possible. We are looking forward to receiving your reply by April 10, 1970.

METCUT RESEARCH ASSOCIATES INC.

John F Kahles

John F. Kahles, Vice President

JFK/mn

Enc.

QUESTIONNAIRE - ADAPTIVE CONTROL SURVEY

Metcut Research Associates Inc.
Cincinnati, Ohio 45209

for

Union Carbide Corporation
Nuclear Division
Oak Ridge, Tennessee 37830

Subcontract 65Y-35001V

IT IS EXPRESSLY UNDERSTOOD AND AGREED THAT ANY INFORMATION FURNISHED BY THE RECIPIENT OF THIS QUESTIONNAIRE WILL NOT BE CONSIDERED AS BUSINESS CONFIDENTIAL.

The following questionnaire has the general purpose of determining the level of interest and activity of your organization in an area of machine control which is sometimes referred to as adaptive control. If the applicability of a particular question to your own situation is ambiguous, please make suitable corrections or explanations and respond in light of the overall objective.

More specifically, the purpose of this questionnaire is to help increase the effectiveness of a comprehensive analysis of the present state of the art of adaptive control. An attempt is being made to collect and analyze information concerning systems for controlling accuracy, surface finish, surface integrity, vibration, chatter and tool wear which are applicable for turning various parts on machine tools using cutting fluids. The survey will also include cost control aspects, instrumentation and interpretation. A special effort will be made to ascertain the feasibility of adaptively controlling very high surface finish and accuracies.

1. In which of the following activities is your organization engaged?

   1.1 Basic research in machining processes ( )
   1.2 Basic research in machine tool control ( )
   1.3 Manufacture of machine tools ( )
   1.4 Use of machine tools for production ( )
   1.5 Planning and specification of machining systems for outside customers ( )
   1.6 Instrumentation for machine tool applications ( )
   1.7 Other (specify ______________________) ( )

2. Has your organization become involved in adaptive control to the extent that you believe your organization could provide helpful guidance, professional services or hardware to Union Carbide Corporation Nuclear Division? Yes ( ) No ( )

3. Are your organization's adaptive control activities proprietary to the extent that you are not in position to assist us? Yes ( ) No ( )

4. Has your organization already designed and/or built components or complete adaptive control systems which are already in operation or which will be shortly? Yes ( ) No ( )

5. Is your organization using an adaptive control system which you have purchased? Yes ( ) No ( )

6. To which of the material removal operations is your adaptive control system being applied?

1 Turning ( ) 4 Tapping ( )
2 Milling ( ) 5 Grinding ( )
3 Drilling ( ) 6 Other ____________

7. Please list the relationship between the controlled parameters and controlling processes by using the table below. (Insert code numbers listed below.)

CONTROLLED PARAMETERS	Type Sensors Used	Sensors Sampling Rate	Logic Scheme
Dimensional Accuracy			
Positional Accuracy			
Contour			
Surface Finish			
Tool Chatter			
Deflection			
Var. of Feed			
Cutting Forces			
Spindle Growth			
Tool Tip Temperature			
Chip Size			
Tool Wear Rate			
Metal Removal Rate			
Other			

Sensors:

1. accelerometers
2. strain gages
3. optical systems
4. lasers
5. resolvers
6. thermocouples
7. thermocouple effect
8. capacitance gages
9. eddy current
10. induction gages
11. other (specify: ______ ______________)

Sensor Sampling Rate:

1. continuously
2. milliseconds
3. seconds 1-60
4. minutes 1-30
5. minutes 30-60
6. other ________
7. hardly ever
8. never

Logic Scheme:

1. standard formula
2. tabulated data
3. machine learning process
4. trial and error

8. Is your adaptive machining process monitored and/or controlled in any way by automatic equipment such as digital computer ( ), modified numerical control unit ( ), or other special controller ( )?

9. Do you believe that our present technology (understanding of machining processes, sensors, and controls) is sufficiently advanced to apply adaptive control for developing accuracies and surface finishes substantially better than 0.0001 inch and 10 microinches? Yes ( ) No ( )

If your answer is No, please indicate the general areas which you believe need basic research study:

____

____

10. Which surface finish measurement techniques (other than stylus-profilometer type) are presently available or are presently being developed (reflectance type, fiber optics, etc.) to adaptively produce finishes substantially better than 10 microinches:

____

____

____

11. Are you acquainted with any measurement techniques using short range transducers (0-0.005 inch) to measure tool wear? (for example, capacitance, inductance, or eddy current probes) Yes ( ) No ( )

12. What criteria do you use to measure machine performance in order to justify application of adaptive control to specific material removal tasks? (Possible criteria include accuracy, surface finish, cost and/or production rates, etc.)

____

____

13. Has your organization literature available covering your adaptive control system and/or activities? Yes ( ) No ( )

Literature is enclosed ( )
Literature is being sent under separate cover ( )

14. Do you believe a personal visit to your organization by representatives of Metcut Research and Union Carbide would contribute to this questionnaire or to our survey in general? Yes ( ) No ( )

(over)

15. Can you recommend additional contacts in the field of adaptive control? Please list names and addresses.

____
____
____
____
____
____

16. If you have any additional information or comments, please include them.

____
____
____
____
____
____

Your assistance in reviewing this survey is most appreciated.

Submitted by:

Name ______________________

Title ______________________

Organization ______________________

Address ______________________

____

Please return questionnaire to:

Metcut Research Associates Inc.
3980 Rosslyn Drive
Cincinnati, Ohio 45209

March 1970

ACKNOWLEDGEMENTS

The authors wish to extend their appreciation to all those who participated in this survey, including manufacturers and users who shared their information during plant visitations as well as those who answered the Adaptive Control Survey Questionnaire.

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APPENDIX A

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APPENDIX B

FOREIGN LITERATURE STUDY (Including Bibliography)

All literature referenced is available at the Air Force Machinability Data Center or in Max Kronenberg's Library, except as noted.

Requests for all publications should be directed to the Air Force Machinability Data Center.

STATE-OF-THE-ART SURVEY OF FOREIGN LITERATURE ON ADAPTIVE MACHINE TOOL CONTROL IN FOREIGN COUNTRIES INCLUDING A SELECTED BIBLIOGRAPHY OF FOREIGN LITERATURE

Dr. Max Kronenberg, Consultant
Cincinnati, Ohio

This report is based on information obtained during visits to Eureopean institutes and on foreign literature available in my library.

Visits

In the summer of 1969 I presented a paper on machining problems before the Technical University of Stuttgart and met on this occasion Professor G. Stute who heads the recently established "Institute for Control Technique of Machine Tools" at that university. I received from him two booklets used by students of his department. A few examples taken from the booklets are attached hereto as Ref 45 of the Bibliography. Stute is also the author of a report on adaptive control prepared for the German Machine Tool Builders Association (Ref 46). He is the editor of the new German Engineering Journal "Steuerungstechnik" (Control Techniques) and contributed to a new handbook (Ref 35) published by W. Simon, professor at the Technical University of Berlin, West Berlin.

In 1966 I participated as a United Nations Expert in the "International Symposium on Metalworking Industries in Developing Countries"held during four weeks in Moscow, USSR. I had an opportunity to visit "Stankin University" which is specializing in production methods and machine tools. In one of the laboratories a spline shaft grinding machine with adaptive control was demonstrated. The in-feed of the grinding wheel was automatically reduced when the sparking increased beyond a certain limit and vice versa. Details of the design were not given. Walking around the machine I noticed a large box which may have contained the control device.

Machine Tools Built

Although many scientific investigations into adaptive control have been undertaken in Europe and in Japan, little information has been disclosed on the design and actual performance of machine tools with adaptive control. No data are given on the surface finish obtained on these machines and few on dimensional accuracy. The lack of information may be due to patents applied for or to other proprietary reasons or most probably to the fact that little attention has been given to surface finish resulting from adaptive control. A patent search may give some clues since patent applications are published in some European countries.

From a French publication (Ref 1) it follows that the Gildemeister Machine Tool Co of Bielefeld, West Germany, has developed a lathe with adaptive control in cooperation with the Siemens Electric Co, which corresponds to the Westinghouse Corp in this country. A description of the machine is given in an anonymous article (Ref 4). The A/C unit, termed "sinumerik 320" is based on horsepower control adapting feed rate and depth of cut. The torque is measured at the main spindle with strain gages and compared with data computed from scientific formulas for the machining of metals. The difference between the actual horsepower and the desirable horsepower serves as the input signal. In the same publication (Ref 4), it is indicated that several devices for control of parameters, such as torque, horsepower, etc, will be on exhibit at the forthcoming Machine Tool Show in West Germany in the fall of 1970.

In a lathe developed by the Royal Aircraft Establishment in England, the cutting speed is controlled by the temperature at the cutting edge which acts as the sensor of the system (Ref 29). The metal removal rate is increased 45 percent and the surface finish improved (no details). Changes in the machinability, changes in the weight and size of the chips, and changes in the thermal conductivity of the workpiece are likewise used for adapting the cutting speed to the wear rate and temperature.

In two German-language publications by a Hungarian author (Refs 5 and 6), detailed information is given on the design of a vertical milling machine with adaptive control. The machine was built by the Csepel Machine Tool Co in Hungary (patented). The discussion refers to the spacecraft and missile industries and their requirements in surface finish and dimensional accuracy. A value of 0.2/μm (= 0.000 008 inch) is mentioned with regard to dimensional accuracy. These conditions can be satisfied in practice only by reducing vibration and elastic deformation of machine tools, which in turn depend on cutting force, torque, cutting speed, etc, and on their mutual interdependence expressed by metal cutting equations. By converting these equations (Refs 18 and 19) into electric circuits, it was possible to stabilize the torque at the milling arbor and to control the feed. It proved possible to increase accuracy and production rate by simultaneous application of two electric circuits with transistors and a hydraulic step motor.

Although not concerned with the machining of metals, but rather with stone, the design of a milling machine (Ref 7) will be of interest. In the event that the stone has hard spots overloading the motors or if the stock to be removed exceeds a predetermined quantity, an electric device reduces the feed rate of this Swiss-built machine.

A comparison of European and American machine tools with adaptive control is outlined in a paper by F. Kuplent (Ref 20). In the case of the Keller milling machine, which is equipped with a Bendix control, and likewise in the case of the Cincinnati milling machine, equipped with the Acramizer control, the adaptive control regulates the feed rate and the spindle rpm although different quantities are measured. The Keller machine measures the torque at the main spindle, its vibration, and the temperature at the cutting edge. The Cincinnati machine also measures the torque and the horsepower in addition to measuring the deflection of the main bearing in two planes.

The European machine tools considered include the Gildemeister lathe (see also Ref 1), the Csepel milling machine (Hungary, see also Refs 5 and 6), and a lathe designed by the University of Pisa (Italy). The cutting speed and the depth of cut are adaptively controlled in the Gildemeister lathe. On the other hand, the distance from the tool to the table is controlled (in addition to the cutting speed) in the case of the Csepel vertical miller. It is equipped with an adaptive control developed by the Hungarian Academy of Science. Only the rpm is adaptively controlled in the Pisa lathe. The torques are measured in the Gildemeister and Csepel machine tools in addition to the horsepower (Gildemeister). The incremental change in the distance between tool and table, that is the deflection of the machine column (Csepel), is measured instead of the horsepower. Vibration, horsepower, and tool temperature are determined in the case of the Pisa lathe.

While the American machine tools mentioned aim at minimum machining cost, the target of the Gildemeister design is maximum metal removal and automatic adjustment of the depth of cut; that of the Hungarian miller is constant deflection and that of the Italian lathe constant tool temperature. The Sinumerik path control (Gildemeister lathe) has reduced the machine time by 20 percent and the programming by 60 percent.

Research

Research into adaptive control of machine tools is carried out at several universities in Europe and at the plants of machine tool manufacturers. Professor G. Spur heads the machine tool laboratory at Berlin Techn University. In one of his papers (Ref 39), the criteria of adaptive control have been analyzed independently, ie, without a definite design. A number of possibilities are discussed for the evaluation of the metal cutting processes as a means for determining the modifications of the parameters. The same author has published papers on adaptive control in 1967 and 1968 (Refs 40 and 41). He is also co-author of a book on V/C machine tools (Ref 35) which includes several chapters on adaptive control. I had no opportunity to see his laboratory this time, but saw that of the Stuttgart University (see page 90 of this report).

Two types of adaptive control are distinguished in a paper by K. Maier (Ref 21). In the first type, the so-called disturbing influences (changes in hardness, etc) are balanced automatically, while in the second type the cutting parameters are corrected for these factors so that optimum cost or production rates are obtained (see also Ref 15).

In a doctoral thesis by U. Degenhardt (Ref 11), it is indicated that tool wear is the most significant criterion for adaptive control. The relationship between wearland, cutting speed, feed, tool life, etc, is expressed mathematically and related to the condition for minimum cost and maximum production rate. Tool life for minimum cost can best be obtained by speed control. The depth of cut has a minor effect on tool wear.

In a paper by S. Stöckmann (Pittler Machine Tool Co, Ref 43), it is said that the most important metal cutting quantities are the cutting temperature, the cutting forces, vibration, the horsepower, torque, and tool wear. In the case of finishing, the surface quality must be taken into consideration. In his opinion, cutting force measurements are not satisfactory as a basis for adaptive control. This statement caused opposition from the audience. In the discussion, it was said that very good results were obtained when the pulsating nature of the cutting force was taken into consideration. Stöckmann is also of the opinion that the cutting temperature is a useful criterion only in the case of high speed steel tools but not with carbide tools because a wide range of temperatures is associated with the same tool life of carbides.

In publications by S. Spizig (Refs 37 and 38) it is reported that a honing machine with adaptive control was exhibited at the 1968 Leipzig Machine Tool Show in East Germany. No details are given.

In a British paper by Porter & Summers (Ref 32) dealing with adaptive control research, the conclusion is drawn that maximum benefit from adaptive control requires the use of more sophisticated strategies than those that are presently considered adequate in the machine tool industry. The metal removal in cubic inch per dollar is taken as the performance index for comparing various data which include also the USAF Machinability Reports, Vol 1, 1950 (available from the Air Force Machinability Data Center, Cincinnati, Ohio).

Sensors and Measuring Devices

Seven different types of sensors are discussed by Nenntwig (Refs 26, 27, and 28), namely:

1. Contacts
2. Resistance sensors
3. Photoelectric sensors
4. Ray sensitive sensors
5. Capacitance sensors
6. Inductance sensors
7. Piezo electric sensors

His discussion is limited to the designs and the differences in these sensors without outlining their use in adaptive control of machine tools. The main advantage of electronic sensors is their high sensitivity, their reliability, accuracy, and the fact that they have a low inertia and thus fast response. Photoelectric sensors have gained wide application in recent years because they render it possible to utilize light without mechanical contact.

Upon correspondence with Nenntwig, the following names of German manufacturers of sensors were obtained:

AEG Telefunken GmbH, Halbleiterwerk, D 71 Heilbronn, W Germany

Falkenthal & Presser GmbH D 744 Muertingen, W Germany

Siemens AG D 8 Muenchen 1, Oskar von Miller Ring.

Valvo GmbH 2 Hamburg 1, Burchardstr. 19

Heimann GmbH D 62, Wiesbaden - Dotzheim, Weher Koeppel 6

Details of the photoelectric sensors made by AEG Telefunken are given in Ref 8.

A handbook on technical controls was published by Oppelt (Ref 30). Various types of sensors are also discussed by Mitthof (Ref 25).

A company by the name of H. Ruf - Mannheim is quoted in Refs 13 and 14 as a manufacturer of contact-free sensors. In the same reference, the following companies are listed as active in the field of measuring instruments: Hahn & Kolb, Stuttgart; Dr. Ing. Perthen Hannover; E. Leitz, Wetzlar (also manufacturer of the Leica camera); and Carl Zeiss, Oberkirchen.

At the Convention of German Engineers 1969, several papers were presented (Ref 33): one by Rohrbach on measuring of moving parts, one by Buschmann on a minature device for measuring rapidly varying torque and one by Wächter on optical - electric motion converters permitting contact-free measuring of motion. Manufacturers names are not given. S. Bumiller (Ref 9) reports on self-adapting vibration dampers and on compensation of machining errors caused by tool wear. "Light curtains" for measuring purposes is the topic of a paper by Sick and Walter (Ref 34).

A tool life sensor was developed in Japan (Ref 48) utilizing the variation in the cutting force as related to tool wear. The feeler of an electric micrometer head is mounted on the tool post and in contact with the transient surface machined by the side cutting edge. As the wearland increases, the transient surface shifts toward the tool axis resulting therefore in a corresponding displacement of the sensor and an electric signal. In order to compensate for thermal expansion of the tool, a primary sensor is used. Tool wear can also be projected on a screen. Another Japanese contribution to adaptive control will be found in Ref 49.

Inductive sensors have been developed in Sweden according to Zilling (Refs 52 and 53).

In Switzerland, the Novomatic Co at Neuchâtel is engaged in the development of automatic devices for control of machine tools (Ref 23).

In Hungary, the Hungarian Optical Works is likewise working on equipment for measuring and controlling machine tools (Ref 2).

In the Soviet Union, an exposition was held in Moscow in 1969 covering the progress in the field of automation. According to an advertisement (Ref 3), sensors were on exhibit there. A paper was read by Ye V Dneprovski on "Active Inspection Systems for Automatic Lathes and Control Processes" and published in IZD-Vo Nauka, p 69. ff.

Synopsis

From visitations and from foreign literature available in my library, it is evident that considerable work is under way in the field of adaptive control of machine tools. This applies to Europe as well as to Japan.

No data on surface finish have been published judged by the literature perused. Dimensional accuracy of 0.000008 inches is mentioned in Ref 5 as a target for the aircraft and spacecraft industries in Hungary.

Names of individuals and of companies active in adaptive control of machine tools are identified in the reference list, and the best sources for sensors are indicated. A search for foreign patents and of additional publications in foreign countries may disclose further information on the state of the art of adaptive control. Although no direct reference is made in a number of these publications to adaptive control of machine tools, it may assumed that they may be considered as potential users or suppliers of implements for adaptive control.

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APPENDIX C

SUBJECT INDEX

Numbers are reference numbers in the main bibliography.

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*Denotes untranslated documents from AFMDC. For foreign review of AC see Appendix B of this report.

APPENDIX D

ANALYSIS OF THE QUESTIONNAIRE

Following is a summary, question by question, of the Survey Questionnaire which was used as a part of this AC survey effort. The overall analysis of the questionnaire and its impact in the area of Y-12 interest may be found on Pages 24 and 25. This summary includes all directly applicable replies (102) plus those with limited applicability (15). The bracketed numbers included with each question indicate total response to each specific question or category.

1. In which of the following activities is your organization engaged?

   1.1 Basic research in machining processes (25)
   1.2 Basic research in machine tool control (28)
   1.3 Manufacture of machine tools (28)
   1.4 Use of machine tools for production (54)
   1.5 Planning and specification of machining systems for outside customers (25)
   1.6 Instrumentation for machine tool applications (61)
   1.7 Other (12)
      1.7.1 Computer (3)
      1.7.2 Grinding Specialists (1)
      1.7.3 Research & Development (6)
      1.7.4 Surface Finish & Texture (1)
      1.7.5 Vibration (1)

2. Has your organization become involved in adaptive control to the extent that you believe your organization could provide helpful guidance, professional services, or hardware to Union Carbide Corporation-Nuclear Division? Yes (66) No (51)

3. Are your organization's adaptive control activities proprietary to the extent that you are not in position to assist us? Yes (18) No (94)

4. Has your organization already designed and/or built components or complete adaptive control systems which are already in operation or which will be shortly? Yes (70) No (30)

5. Is your organization using an adaptive control system which you have purchased? Yes (15) No (102)

6. To which of the material removal operations is your adaptive control system being applied?

   6.1 Turning (34)
   6.2 Milling (34)

6.3 Drilling (20)
6.4 Tapping (11)
6.5 Grinding (25)
6.6 Other (7)
  6.6.1 Boring (3)
  6.6.2 ECG (1)
  6.6.3 ECM (1)
  6.6.4 Grinding (1)
  6.6.5 Honing (1)

7. Please list the relationship between the controlled parameters and controlling processes by using the table below. (For details of the original question, see Page 40). This analysis is by R. H. Raible, University of Cincinnati, Consultant:

Examination of the responses to Question 7 can be used to measure the potential for application of adaptive control even in those instances where the technique is not actually applied at present. The following are specific observations extracted from the questionnaire data.

(1) In order of frequency, the following process parameters were mentioned as actually being measured by one method or another:

Positional Accuracy	(33)
Dimensional Accuracy	(29)
Surface Finish	(16)
Deflection	(16)
Contour	(15)
Chatter	(15)
Variation of Feed	(12)
Tool Tip Temperature	(12)
Tool Wear Rate	(11)
Cutting Forces	(9)
Metal Removal Rate	(8)
Chip Size	(4)
Spindle Growth	(0)

The high frequency of positional and dimensional accuracy measurement is to be expected. The relatively high occurrence of surface finish, chatter, and variation of feed is interesting in that these are more or less directly related to the quality of finish of the process. Deflection (of workpiece, spindle, and/or tool) and cutting forces are directly related to each other and the data above show considerable interest in this type of process parameter. Tool tip temperature and tool wear rate, admittedly difficult parameters to measure, nonetheless are used in a substantial number of applications. Metal removal rate was mentioned relatively infrequently considering its obvious importance in indicating production volume.

Adaptive control based upon various attributes of the machining process, both quantity and quality, will require automatic methods of measuring most of the items listed above, and there appears to be considerable technology available in this direction.

(2) The various types of measuring techniques used and their specific applications included the following:

Resolvers:	dimensional and positional accuracy, contour, variation of feed
Optics (including lasers):	dimensional and positional accuracy, contour, surface finish, deflection, chip size, tool wear rate, metal removal rate
Induction gages:	dimensional and positional accuracy, surface finish, tool chatter, deflection
Accelerometers:	surface finish, tool chatter, variations in feed
Strain gages & piezo-electric:	tool chatter, deflection, variation of feed, cutting forces, tool wear rate, metal removal rate
Thermocouple effect:	tool tip temperature

In addition, a wide variety of other methods was mentioned less frequently, including capacitance gages, digital encoders, audio methods, air-electric gages, drive motor power sensors, thermistors, tachometers, linear "E-I" transformers. Certain other special purpose devices were mentioned by name with no description.

(3) If adaptive control is to be used to offset unpredictable variations in the process, an important parameter related to the rate at which this adaptation can be accomplished is the bandwidth or otherwise the sampling rate of the measuring equipment. The results of the

questionnaire indicated continuous methods of measurement for each of the variables listed, and methods which operate at 1,000 measurements per second or faster in most cases. This ability would appear to be adequate for most of the anticipated applications of adaptive control.

(4) Part of Question 7 was directed at finding out how the various process parameters were being set (or controlled). As one would expect, a majority of responses indicated the use of standard formulas and/or tabulated data, implying some sort of setup procedure based on past experience, which is then left at the predetermined setting during operation. However, in the case of almost every parameter listed, there was a significant number of responses indicating learning or trial-and-error procedures. This information indicates that some followup or "trim" of the original settings has been found to be desirable, as well as practicable. Adaptive control might be accomplished by automating these procedures.

7.1 Dimensional Accuracy

Type Sensors Used

Optical devices	(7)
Resolvers	(6)
Induction gages	(9)
Miscellaneous (CAP, Null)	(7)

Sensor Sampling Rate

Continuously	(16)
1,000/second	(2)
1-60 seconds	(2)
1-30 minutes	(2)
End of work	(1)

Logic Scheme

Standard formula	(14)
Tabulated data	(3)
Learning	(3)
Trial & error	(1)

7.2 Positional Accuracy

Type Sensors Used

Optical	(10)
Resolvers	(10)
Induction gages	(4)
Digital encoders	(3)
Miscellaneous	(6)

Sensor Sampling Rate

Continuously	(16)
1,000/second	(4)
1-60 seconds	(2)
1-30 minutes	(2)
Other (end of work)	(2)

Logic Scheme

Standard formula	(19)
Tabulated data	(1)
Learning	(4)
Trial & error	(2)

7.3 Contour

Type Sensors Used

Resolvers	(5)
Optical	(4)
Miscellaneous (audio, encoder)	(6)

Sensor Sampling Rate

Continuously	(8)
1,000/second	(2)
1-30 minutes	(1)

Logic Scheme

Standard formula	(5)
Tabulated data	(3)

7.4 Surface Finish

Type Sensors Used

Accelerometers	(2)
Optical	(5)
Induction gages	(2)
Miscellaneous (audio, air-electric)	(7)

Sensors Sampling Rate

Continuously	(7)
1,000/second	(3)
1-30 minutes	(2)
Final piece	(1)

Logic Scheme

Standard formula	(3)
Tabulated data	(3)
Learning	(2)
Trial & error	(2)

7.5 Tool Chatter

Type Sensors Used

Accelerometers	(4)
Strain gages	(4)
Induction gages	(3)
Miscellaneous (CAP, optical)	(4)

Sensors Sampling Rate

Continuously	(6)
1,000/second	(2)
1-60 seconds	(1)
Other (when necessary)	(2)

Logic Scheme

Standard formula	(2)
Tabulated data	(2)
Learning	(3)
Trial & error	(3)

7.6 Deflection

Type Sensors Used

Strain gages	(6)
Optical (laser)	(3)
Induction gages	(2)
Miscellaneous (hydro pressure, Digitol, CAP)	(5)

Sensors Sampling Rate

Continuously	(7)
1,000/second	(3)
1-60 seconds	(3)
When necessary	(1)

Logic Scheme

Standard formula	(7)
Tabulated data	(3)
Learning	(3)
Trial & error	(1)

7.7 Variation of Feed

Type Sensors Used

Accelerometers & drive motor power	(3)
Strain gages	(1)
Optical	(1)
Resolvers	(3)
Miscellaneous	(4)

Sensors Sampling Rate

Continuously	(5)
1,000/second	(1)
1-60 seconds	(1)
When necessary or final workpiece	(3)

Logic Scheme

Standard formula	(7)
Tabulated data	(3)
Learning	(3)

7.8 Cutting Force

Type Sensors Used

Strain gages (piezo)	(7)
Drive motor power	(2)

Sensors Sampling Rate

Continuously	(11)
1,000/second	(1)
1-60 seconds	(1)

Logic Scheme

Standard formula	(5)
Tabulated data	(5)
Learning	(3)
Trial & error	(1)

7.9 Spindle Growth (no response)

7.10 Tool Tip Temperature

Type Sensors Used

Accelerometers	(1)
Thermocouple & thermocouple effects	(9)
Miscellaneous (Thermistor)	(2)

Sensors Sampling Rate

Continuously	(7)
1-60 seconds	(1)

Logic Scheme

Standard formula	(4)
Tabulated data	(2)
Learning	(2)
Trial & error	(1)

7.11 Chip Size

Type Sensors Used

Optical	(2)
Indirect (Linear E-Mag & Tachometer)	(2)

Sensors Sampling Rate

Continuously	(1)
1-30 minutes	(1)
When necessary	(1)

Logic Scheme

Standard formula	(3)
Tabulated data	(2)
Learning	(1)

7.12 Tool Wear Rate

Type Sensors Used

Strain gage	(2)
Optical (lasers)	(5)
Thermocouple effect	(1)
Miscellaneous	(3)

Sensors Sampling Rate

Continuously	(2)
1-60 seconds	(2)

Logic Scheme

Standard formula	(7)
Tabulated data	(1)
Learning	(2)
Trial & error	(3)

7.13 Metal Removal Rate

Type Sensors Used

Strain gage	(1)
Optical	(2)
Resolver	(1)
Induction gage	(1)
Miscellaneous (CAP, tachometer, motor power)	(3)

Sensors Sampling Rate

Continuously	(4)

Logic Scheme

Standard formula	(6)
Tabulated data	(1)
Learning	(3)

8. Is your adaptive machining process monitored and/or controlled in any way by automatic equipment such as digital computer (23), modified numerical control unit (21), or other special controller (31)?

9. Do you believe that our present technology (understanding of machining processes, sensors, and controls) is sufficiently advanced to apply adaptive control for developing accuracies and surface finishes substantially better than 0.0001 inch and 10 microinches? Yes (35) No (57)

If your answer is No, please indicate the general areas which you believe need basic research study:

9.1	Actuators	(1)
9.2	Contour	(2)
9.3	Deflection	(1)
9.4	Direct Digital Control	(1)
9.5	Dynamic Cutting Force Control	(1)
9.6	Holography: Laser Development	(1)
9.7	Machine Tool and Fixture Design	(6)
9.8	Sensors	(16)
9.9	Surface Finish	(3)
9.10	System Stability (beyond present limit of 0.0005")	(1)
9.11	Temperature Growth	(1)

9.12	Tool Chatter	(1)
9.13	Tool Control Systems	(3)
9.14	Tool Torque	(1)
9.15	Vibration	(1)

10. Which surface finish measurement techniques (other than stylus-profilometer type) are presently available or are presently being developed (reflectance type, fiber optics, etc) to adaptively produce finishes substantially better than 10 microinches:

10.1	Air Servoed, Air Gages	(1)
10.2	Fiber Optics	(1)
10.3	Indirect Techniques: Precise Position & Speed Control of Both Axis	(1)
10.4	Interferometry	(2)
10.5	Light Sensor Used for Thread Cutting	(1)
10.6	Optical: Reflectance	(8)
10.7	Real Time Holography	(1)
10.8	Standard Glass Beads Development	(1)
10.9	Transducer Design (proprietary)	(1)

11. Are you acquainted with any measurement techniques using short-range transducers (0 - 0.005 inch) to measure tool wear? (for example, capacitance, inductance, or eddy current probes) Yes (27) No (67)

12. What criteria do you use to measure machine performance in order to justify application of adaptive control to specific material removal tasks? (possible criteria include accuracy, surface finish, cost and/or production rates, etc)

12.1	Accuracy	(29)
12.2	Cost* and/or Production Rates	(72)
12.3	Continuous Process Control	(1)
12.4	Power	(2)
12.5	Programming Simplification	(1)
12.6	Reproducibility	(2)
12.7	Surface Finish	(16)
12.8	Torque	(1)

* Cost factors cited include: Inspection, Scrap Reduction, and Tool Costs.

13. Has your organization literature available covering your adaptive control system and/or activities? Yes (33) No (64)

14. Do you believe a personal visit to your organization by representatives of Metcut Research and Union Carbide would contribute to this questionnaire or to our survey in general? Yes (46) No (55)

    The (No) answers are primarily from companies interested in AC but ones who believe they are not sufficiently advanced to assist Y-12 at this time.

15. Can you recommend additional contacts in the field of adaptive control? Please list names and addresses.

    Additional contacts recommended were checked against our existing file and those not appearing were mailed a survey.