DO NOT MICROFILM
COVER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

**Thermo
Electron**

CORPORATION

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TE660-406-82

DOE Report No. 90024-1

**PRELIMINARY ANALYSIS
OF THE STATE OF THE ART
OF ROBOTICS AND PRECISION ENGINEERING
AND EVALUATION OF POTENTIAL FOR IMPROVED
ENERGY UTILIZATION IN THE PULP, PAPER,
AND RELATED ENERGY-CONSUMING PROCESSES**

MASTER

NOTICE
PORTIONS OF THIS REPORT ARE ILLEGIBLE.
It has been reproduced from the best
available copy to permit the broadest
possible availability.

Final Report
Prepared for
U.S. Department of Energy
Office of Energy Systems Research
Washington, D.C.

AC02-81CS 90024

January 1982

✓ **Thermo Electron Corporation
Washington Operations Office**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

My
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

<u>Chapter</u>		<u>Page</u>
	EXECUTIVE SUMMARY	1
1	INTRODUCTION	4
	1.1 PURPOSE.....	4
	1.2 BACKGROUND.....	4
	1.2.1 Robotics.....	4
	1.2.2 Precision Engineering.....	6
	1.3 STUDY METHODS.....	6
2	ROBOTICS	7
	2.1 RESEARCH AND DEVELOPMENT ACTIVITY	7
	2.1.1 General	7
	2.1.2 Universities	10
	2.1.3 Laboratories.....	10
	2.1.4 Industrial Growth.....	11
	2.1.5 Vision Sensing.....	12
	2.1.6 Tactile Sensing	15
	2.1.7 "Hearing" Sensing	16
	2.2 TELEPRESENCE	17
	2.3 ROBOTICS IN THE PULP AND PAPER INDUSTRY... ..	17
	2.3.1 Industry Status	17
	2.3.2 Prospects for Improvement	22
	2.3.3 Requirements.....	23
	2.3.4 Energy Conservation Potential.....	26
3	PRECISION ENGINEERING.....	28
	3.1 INTRODUCTION	28
	3.2 PRECISION ENGINEERING PERSPECTIVE	28
	3.3 MACHINE MATERIALS.....	31
	3.4 PRECISION ENGINEERING AND ENERGY CONSERVATION.....	33
	3.5 PRECISION ENGINEERING AND THE PULP AND PAPER INDUSTRY	39
4	CONCLUSIONS AND RECOMMENDATIONS.....	42
	4.1 ROBOTICS	42
	4.2 PRECISION ENGINEERING.....	43

TABLE OF CONTENTS (cont'd)

<u>Chapter</u>	<u>Page</u>
APPENDICES	44
APPENDIX A - REFERENCES	45
APPENDIX B - REPRINTED SECTIONS OF REFERENCE 4, "Impact on Energy Conservation of Auto- matic Control Systems Utilization in the U.S. Pulp and Paper Industry," Fam, Sherif S., Report DOE/CS/40150-1, 1978.	48
APPENDIX C - MANUFACTURERS LIST	55

EXECUTIVE SUMMARY

This study was undertaken to conduct a preliminary analysis of the state of the art of two technologies, robotics and precision engineering, and to evaluate their potential for improved energy utilization in the pulp, paper, and related energy consuming processes.

As defined herein, a robotic system is a series of automated mechanical actions wherein some level of machine intelligence is incorporated which allows the machine to interpret certain control inputs that are made and to also interpret in conjunction with those, feedback from the operations it is performing. It combines those with input from overall plant control in a hierarchy of inputs. The system has the logic to interpret the hierarchical order of inputs and cause a decision to be made in the absence of a man. The elements of a robotic system are the sensing of a condition in the environment, an interpretation associated with that sensor, and a mechanical action resulting from the interpretation.

Activity in this field is growing rapidly, although most activity is related to the development of smart robots rather than to systems as defined above. There is a broad base of support, both in industry and the universities, for upgrading robot machine capabilities. A large part of that support is associated with visualization and tactile sensors which facilitate assembly, placement, inspection, and tracking. Progress in this area is relatively rapid and development times are short for specifically engineered applications.

The critical path in the development of robotic systems lies in the generation of reliable sensor signals. Robotic systems require a broad spectrum of sensors from which hierarchical logic systems can draw decision making information. This requirement, recognized two years ago by DOE's Office of Industrial Programs, resulted in the establishment of a program at the National Bureau of Standards which is attempting to develop

a spectrum of sensor capabilities in areas such as real time gas chemical analysis, multiphase flow in liquids, moisture content in solids, and erosion-corrosion measurement.

Such sensors are applicable to robotic system automatic process control in a variety of energy-intensive industries. The pulp and paper industry, for example, has immediate use for some of these sensors in recovery boiler control. Estimated boiler efficiency improvements as high as 30 percent are thought by the industry to be achievable with reliable, accurate, real time sensing of appropriate boiler parameters combined with available computer capability. An additional contribution to energy productivity would be derived from an increase in capacity which would result from operating systems closer to the safe limits of process equipment.

Precision engineering is defined as the generation or manufacture of components wherein geometry, dimension, and surface finish are controlled to within several hundred Angstroms in single point turning operations.

Investigation into the state of the art of precision engineering in the United States finds that this capability exists in several national laboratories and is intended to be used exclusively for the development of weapons. There is an attempt at the present time by Lawrence Livermore Laboratory to expand its capability into industry. Several corporations are now beginning to develop equipment to support the precision engineering field, but as of this time no attempt has been made by anyone in the United States to determine the needs, requirements, and potential energy savings in fuel, materials, and manpower that may be gained through the application of precision engineering into manufacturing technology.

Figure 1. Process for Identifying Energy Conservation R&D Opportunities for Precision Engineering

1. INTRODUCTION

1.1 PURPOSE

This study was undertaken to conduct a preliminary analysis of the state of the art of two technologies, robotics and precision engineering, and to evaluate their potential for improved energy utilization in the pulp, paper, and related energy consuming processes. The effort is recognized as essential in development of a comprehensive advanced technology research activity in support of the needs apparent to the energy consuming industrial sector.

1.2 BACKGROUND

1.2.1 Robotics

A revolution is occurring in industrial automation as a result of the accelerating installation rate of versatile programmable machines popularly called robots. A robot, as defined by the Robot Institute of America, is a reprogrammable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks.

As used here, robotics refers to a device or system that provides automated mechanical action with some level of machine intelligence for sensing and directing. The robotic system is in many ways the technological equivalent of the human system having components such as sensors (eyes), actuators (muscles), and a computer (brain) which allows the system to perform mechanical functions by reacting to needs in its environment that it perceives and interprets.^{(23)*} A robotic system consists of three essential elements:

- Sensing of a condition or situation

*Numbers in parentheses identify references in Appendix A.

- Interpretation of signals from sensors by properly designed algorithm in conjunction with machine intelligence comprising microprocessors and appropriate software.
- Mechanical action.

The mechanical actions are controlled by appropriate software and hardware. Feedback and feedforward are provided to the microprocessors of the various stages. The system has the logic to interpret the hierarchical order of inputs and causes decisions to be made using self-contained logic.

Regardless of the definition used, today's robots result generally from the marriage of industrial automation, computer capability, and teleoperator technology.

The teleoperator came into being in response to the needs created by the nuclear weapons program and nuclear power industry. Development was pioneered by the Argonne National Laboratory in support of the Manhattan Project. As originally designed, this device did not overlap robot technology. It simply duplicated the hand and arm motions of its operator on a one-to-one basis using a mechanical linkage. As it has evolved, the human operator remains as an integral part of the control loop. However, the operator's motions and applied forces can be multiplied by factors greater or less than one, and linkages can be other than mechanical with electrical interfaces.

The teleoperator mechanical arm is, in many respects, the precursor of the robot arm. Both devices attempt to duplicate the capabilities of the human arm and hand. In their most recent incarnations, each incorporates microprocessors in various joints and junctions to enhance "feel" and expand capability. Each has a capability limit imposed by the technological limit of existing sensors.

1.2.2 Precision Engineering

Precision engineering is a generic term having numerous meanings. In the context of this discussion precision engineering involves the generation or manufacture of components wherein geometry, dimension, and surface finish are controlled to within several hundred Angstroms in single point turning operations. The purpose of this discussion is to explore the value of precision engineering and related sciences to energy conservation (fuel savings) in the paper and pulp industries.

1.3 STUDY METHODS

Discussions with designers, producers, and users of robotic and precision engineering equipments in academia and industry were the primary source of the information from which opinions were formed and recommendations developed. Technical papers, reports, and periodicals were also used. Sources are identified in Appendix A.

The Energy Policy and Conservation Act (EPCA) mandated the creation of the Industrial Energy Efficiency Improvement Program. This program included compulsory reporting of energy use by the 10 most energy intensive manufacturing industries and developed for them 1980 energy efficiency improvement targets. The paper industry (including pulp), 1 of the 10 reporting industries, fell short of its 1980 target,⁽²⁴⁾ the last year for which data are published. Because this industry used processes and equipment that could be made to yield significant energy savings, a detailed discussion of it is included in Section 2.3 and Appendix B.

2. ROBOTICS

2.1 RESEARCH AND DEVELOPMENT ACTIVITY

2.1.1 General

Robots are finding increasing acceptance in industry. The majority of industrial robots in the United States have operating costs of less than \$5 per hour. This figure includes the base price of the equipment and is calculated over a two shift, 12-month year. Since first shift labor costs average about \$17 an hour, the industrial robot will easily cost less in the long run than manual labor.

Robots also save labor costs by eliminating the equipment needed to protect the safety of human workers. Using industrial robots for parts handling can sizeably reduce costs of shielding, guarding, ventilating, and lighting. It also reduces the insurance costs and the liability risks associated with human labor.

One must bear in mind when calculating how much manpower is replaced with robots, that a robot can work more than one shift and each robot can replace more than one worker. A robot can also replace more than one man per shift where two or more workers may be needed to move a heavy workpiece. In addition, a normal production worker will grow tired during the course of a typical work shift. However, as a general rule in industry, in 95 percent of the applications, industrial robots take more time than manual labor to perform a task. Nevertheless, on the average over the course of an entire work shift in nearly every case reported, robots produce a higher total number of finished parts. This occurs as a result of fatigue of personnel and the downtime for human needs. It is not uncommon for a manager to justify a robot installation fully on the direct replacement of first shift manpower. However, it is not clear that a machine replaces a person. The amount of personnel does not seem to change. In fact, in those industries where robots or robotic systems have been installed, the manning level of the plant has not been seen to drop. In some cases, it has risen. ⁽¹⁵⁾

Very few robotic systems, as defined in this survey, are in use today, primarily due to sensor limitations. An industrial robot, like most machines, can repeat the same task for prolonged periods with great precision. Unlike most machines, it can be reprogrammed for new tasks and can change tools, called end effectors, to extend its range of capabilities. It is reliable, untiring, and relatively unaffected by hostile environments. It has no ability to coordinate "hand and eye,"⁽⁶⁾ to react to unforeseen circumstances or changing environments. A robotic system may or may not have a mechanical arm involving "hand and eye" coordination, but will react to unseen circumstances or changing environments by making decisions and commanding action in the absence of a human. See Table 1 for an estimate of the present world robot population.⁽⁹⁾ The number of robots in use is expected to increase at an annually compounded rate of 30 to 35 percent.^(15,23)

The majority of tasks assigned to robots are of the "pick and place" type, where the machine simply moves an object from one place to another. Variations of this machine type include spot welding and spray painting tasks. The task determines the type of tool or end effector that is used. Machine control is essentially the same. The operating arm is moved so as to place the tool at a predetermined location using an appropriate coordinate system. The tool is actuated, the arm moved as required according to a predetermined schedule, and the tool deactivated at a programmed location. The workpiece must be located in a predetermined spot and orientation which can result in expensive jigs and tooling.

An early step toward smarter machines introduced switches and interlocks to notify the robot of workpiece arrival and feedback task completion. Improving the quality of position information, for both the workpiece and the end effector, has direct payoff. Throughput increases while tooling costs drop and the equipment becomes adaptable to a greater variety of tasks. Research is, therefore, intensifying in sight, touch, and sound sensing, the areas with the most potential for near-term results.

TABLE 1
ESTIMATED INDUSTRIAL ROBOT POPULATION IN 1980 - ALL INDUSTRIES**

Region	Country	A	B	C	D	E	
Asia	Japan	5,150		12,050		50,510	67,710
	Australia	14	*	*	*	*	14
Subtotal							67,724 (80.1%)
Western Europe	West Germany	440	293	200	200	5,000	6,133
	Sweden	720	180	300	*	*	1,200
	Italy	300	50	100	50	*	500
	France	320	60	150	*	*	530
	Norway	20	20	100	30	30	200
	United Kingdom	146	117	54	54	*	371
	Finland	20	10	70	10	20	130
	Belgium	42		82	3	7	134
	Spain	29	*	*			29
Subtotal							9,227 (10.9%)
North America	United States	2,485	439	1,377	*	*	4,301
	Canada	54	5	10	*	*	69
Subtotal							4,370 (5.2%)
Eastern Europe	Poland	70	40	200	50	360	720
	U.S.S.R.	100	50	200	150	2,000	2,500
Subtotal							3,220 (3.8%)
Grand Total							84,541 (100%)

*Data not available.

**Source: "Automation Levels in Automobile Manufacturing," unpublished report prepared for DOT/TSC by Tanner Associates, Farmington, MI, January 1981, updated August 1981.

As noted by Charles Rosen and David Nitzan of SRI: ⁽¹⁸⁾

A major limitation of these manipulators is their primitive sensory feedback. In particular, commercially available industrial robots have neither contact sensors (force, torque, and touch sensors) as aids to manipulation, nor noncontact sensors (visual and range sensors) as aids to recognition, inspection, or manipulation of workpieces. Extensive research in machine intelligence, a branch of computer science, has provided tools, techniques, and concepts that are directly relevant to this class of problems. This work originated in a number of 'hand-eye' and robot programs that developed and demonstrated fairly complex systems of integrated effectors and sensors to guide a manipulator by using computer-processed contact and noncontact sensory feedback.

To substantially increase the capability of machines, automated systems and process equipment will require major improvements in their ability to derive information from their environment and react appropriately.

2.1.2 Universities

In the United States, those universities that were prominent through the early phase of artificial intelligence investigations in the 1960's continue to be prominent in robotics technology. Included here are MIT, Carnegie Mellon, Stanford, Yale, and the University of California at Berkeley. Most recently the University of Texas at Austin, Rhode Island, Louisiana State, the University of Florida at Boca Raton, the University of Cincinnati, George Washington University, the University of Central Florida, and Rensselaer Polytechnic Institute have initiated programs in software and hardware. There are six universities in Japan with significant programs, while there are two in Great Britain. ⁽⁵⁾

2.1.3 Laboratories

The Marshall Space Flight Center has been involved since 1971 in the application of robotic techniques in aerospace systems. The Jet Propulsion Laboratories and SRI have extensive programs.

The National Science Foundation supports a cooperative program with industry at SRI; the program is in its ninth year. The Department of Energy's Office of Industrial Conservation is supporting a program on sensor development at the National Bureau of Standards. Boeing Aircraft is completing a two-year Air Force funded program conducted by the Wright-Patterson Laboratory on a fully automated robotic system for aircraft parts production.

Foreign research centers include the Fraunhofer Institute for Production and Automation in Stuttgart, Swiss Institute in Lausanne, and the Mihailo Pupin Institute in Belgrade. The first of these receives about half of its support from the government while the second receives about one-third.

2.1.4 Industrial Growth

The number of industrial concerns, both large and small, with dedicated programs in this technology is rapidly expanding. Small companies, usually formed from mutual industry-university interest, spring up monthly.⁽⁵⁾ Increasingly, large companies are using in-house resources to generate robots and systems which respond to their own needs. When successful, these become marketable products. Some of the large companies with significant programs are Westinghouse, IBM, Texas Instruments, General Motors, General Electric, United Technologies, General Dynamics, McDonnell Douglas, Lockheed, Boeing, and Honeywell. The better known smaller companies with robots as their principal product line are Autoplace, Automatix, Cincinnati Milacron, DeVilbliss, Industrial Automates, Planet, Prab Conveyors, and Unimation.⁽¹⁷⁾

There are about 30 consulting firms which serve a rapidly developing market in applications engineering. These firms adapt a production, off-the-shelf robot, to a customer's specific needs. Components and peripherals are also developing markets. These things in combination begin to provide a source of robotic systems. However, this evolutionary process is responsible for the existence of a growing problem in the

industry. Because there are no standards, an industrial "tower of Babel" is emerging. Equipment from different suppliers, sometimes from the same supplier, cannot be interfaced directly because inputs and outputs or control languages (software) don't match.

Foreign industrial interest is strong in Italy, France, West Germany, Sweden, and particularly in Japan. Current estimates put the number of Japanese robotics manufacturers at about 200.

As a technology begins to emerge, societies and professional groups form to encourage information exchange. There are two such groups in the United States: The Robotics Institute of America and the Production Engineering Research Association, which is a subset of the Society of Engineering Manufacturers. Great Britain has the British Robot Association. France, Italy, and Japan each have an industrial robot association. The Japanese Industrial Robot Association was formed totally with government support and is chartered to promote the use of robots in industry. Sixty percent of its budget comes from the Ministry of International Trade and Industry.⁽⁵⁾

There have been 11 annual international symposia. The most recent was held in Japan in November 1981.⁽¹⁶⁾ The first European Automated Manufacturing Exhibition, known as Automan #1, was held in the United Kingdom in May 1981 in Brighton, England.

2.1.5 Vision Sensing

Vision research is one of the most active single areas of robotics research. It is the sensory capability that has been most anticipated by potential industrial users, and the one which most users feel will significantly increase the role of robotics in manufacturing. Research into robot vision covers a wide range of problems ranging from relatively simple pattern recognition problems to the most ambitious efforts in artificial intelligence. Several commercial robot vendors supply vision systems with their machines. They are two-dimensional systems which use tubes or solid-state,

linear arrays as detectors. With various sighting techniques and computer video processing, decision-making information for machine process control is generated.

Vision systems for industrial applications are in use today in a few restricted applications. Autoplace Corporation markets a robot vision system called Opto-Sense which uses a solid-state camera to automatically inspect transmission separator plates for missing holes. The Delco Electronics Division of General Motors uses a vision system called SIGHT-1 for the inspection of transistor chips used in car and truck ignition systems. This system is an outgrowth of research conducted at the GM Research Laboratories and is the first vision system to be used in U.S. automobile production. (21)

The SIGHT-1 system uses image enhancement to outline the part on the conveyor belt. The system determines the position and orientation of the part using edge analysis techniques. The part is rejected if it fails to meet programmed criteria.

Cincinnati Milacron has also introduced a vision system called CONSIGHT for use with its industrial robot. CONSIGHT is employed for picking parts off a moving conveyor.

Despite these examples of industrial vision systems currently in use, robot vision is still in the research and development stage. One of the major centers of robot vision research is SRI International. Vision work there has emphasized part identification, orientation, and inspection; and the use of vision for manipulator control.

The SRI industrial automation program, which receives support from the National Science Foundation, has had successes. One of the program's achievements is a hardware/software module for sensing and processing visual images. The module can determine the identity, position, and orientation of parts and holes. It consists of three components: a solid-state

TV camera; a microcomputer; and an interface preprocessor. Lockheed California Company at Burbank, one of SRI's industrial partners, has used the vision module in conjunction with experimentally designed equipment to automate drilling and riveting of aircraft structures.⁽¹²⁾ Experimental work has included use of a robot for multiaxis manipulation of the workpiece for positioning as well as handling. This installation uses microcomputers, computer vision, a robot, and a machine tool coordinated through hierarchical control. The system drills holes and installs rivets using visual control after being given the starting location, the number of rivets desired, the rivet spacing, and the distance from the edge of the part.

In a project funded by the Department of Energy's Office of Industrial Programs, Honeywell has developed a robotic system that uses a linear array video detector to locate and classify surface defects in steel slabs as they exit the rolls. Programming is such that the system makes the determination if corrective action is required and controls the corrective process. Traditionally, inspection required cooling to room temperature for human examination and reheating for repair. Automatic control of arc welding is viewed as an opportunity for large productivity gains. Vision sensing appears to have the most promise for this application. Stanford, SRI, Honeywell, and Unimation have under development welding systems with varying degrees of capability which can automatically track along the path to be welded.

There are three techniques under study to resolve the three-dimensional vision problem. These are stereo vision, range finding, and structured light. The latter two present fewer problems and are further along in development than the first. Range finding uses the time of flight of laser light to measure distance which a computer converts to an object profile. Structured light sensing interprets the reflection of a controlled light source. Reflected light patterns are compared with the source to determine object shapes. Range information is

generated by triangulation on the shadows produced by the object of interest.

Stereo or binocular vision has the greatest potential for information content but also presents the most challenging problems. Significant computational capability and computing times are required with state-of-the-art techniques. Heavy emphasis is placed on this type of vision research at MIT and Stanford. In addition, Stanford is developing a two-arm coordination capability in conjunction with vision.⁽¹⁾

A vision research program is also being conducted at the University of Rhode Island under the direction of John Birk.⁽²³⁾ The emphasis in this program has been the acquisition of parts from a bin or hopper, the identification of the orientation of the part, and its placement into a fixture. The Rhode Island group has also used vision to teach manipulator arm paths and gripper position points on an object manipulator control.

2.1.6 Tactile Sensing

Tactile and force sensors represent another significant area of sensory research. They are being pursued particularly in relation to assembly operations. Vector force sensors for assembly operations are being investigated at the Charles Stark Draper Laboratory. There, sensors which measure the three components of force or torque at various joints in a manipulator arm have been developed.

The Draper work on the control of manipulators by processing force feedback signals to develop an insertion capability led to a significant alternate solution called the Remote Centered Compliance device. This is a totally passive linkage mechanism which compensates for minor misalignment of a manipulator when attempting to insert a close fitting part. The mechanical solution is a very effective replacement for a complicated computer-controlled servo problem.

At the MIT Artificial Intelligence Laboratory, work is progressing on touch sensing with a more traditional connotation. As described by MIT's Dan Hillis: ⁽⁷⁾

The mechanical hand of the future will roll a screw between its fingers and sense, by touch, which end is which (with) a robot finger that is used to recognize small objects by touch. The device incorporates a novel imaging tactile sensor - an artificial skin with hundreds of pressure sensors in a space the size of a finger tip. The sensor is mounted on a tendon-actuated mechanical finger, similar in size and range of motion to a human index finger. A program controls the finger, using it to press and probe the object placed in front of it. Based on how the object feels, the program guesses its shape and orientation and then uses the finger to test and refine the hypothesis.

The capability to recognize a variety of commonly used fasteners has been demonstrated.

The technology for building general purpose tactile sensors appears to be available. The significant problem in their use, however, involves their use in machine control. The best way to incorporate the sensor output to produce a useful result is the subject of continuing investigation.

2.1.7 "Hearing" Sensing

Numerical control of machine tools produced a dramatic improvement in machine productivity. Expanding computer capability coupled with numerical machine control has led to adaptive control of machines. In this mode, process variables such as cutting forces, temperature, tool wear, and workpiece variations (i.e., hard spots) are measured and machine operation is altered to keep the process optimized. As operations are being performed, sound patterns are generated and transmitted through the workpiece. When a failure becomes imminent, such as a drill bit nearing the point of breaking in the workpiece, a characteristic sound pattern is generated. A continuously monitoring accelerometer converts the wave train to a digital format which is constantly scanned for fault patterns.

On finding a match between a detected pattern and a stored "bad" pattern, with an amplitude at or beyond the required threshold, a signal is generated to command the tool to be withdrawn from the workpiece before failure occurs. This system, developed by the National Bureau of Standards Center for Manufacturing Engineering, has a success rate of better than 98 percent with the machine tool on which the system was developed.

2.2 TELEPRESENCE

Teleoperators improve in performance in parallel with robots and robotic systems. Binary vision, force, torque, and touch sensing with feedback could give the operator a very real sense of performing an action personally. With the operator linked to the performing hardware through electrical and electronic coupling rather than mechanically, the location of each become independent of the other.⁽¹¹⁾ This capability has applications in environmentally hazardous places such as underground and under-sea mining or planet exploration. It could be used to transfer a surgeon's skill between any two points having appropriate equipment.⁽¹⁴⁾ Used as a substitute for commuting to work, telepresence has enormous implications for conservation of transportation fuels.

2.3 ROBOTICS IN THE PULP AND PAPER INDUSTRY

2.3.1 Industry Status

Between 50 and 80 percent of U.S. papermaking capacity toward the end of the last decade consisted of computer-controlled machines. These are automatic systems that are monitored from single point control rooms. From headbox to finished product, these existing systems operate within the context of robotic systems as defined herein.

The industry has a net annual energy consumption of 1.1 quads.⁽²⁴⁾ Over 50 percent of its total energy requirement is generated from process waste materials. Residual oil accounts for over one-third of purchased fuel. Table 2, adapted from "The Industrial Energy Efficiency Improvement Program,"⁽²⁴⁾ identifies the types of fuels and the percentages of

A-6948

TABLE 2
TYPES OF FUELS PURCHASED BY
PULP AND PAPER INDUSTRY - 1979

Fuel Type	Consumption (Billion Btu)	Percent of Total
Electricity	124323.3	11.2
Natural Gas	368312.1	33.3
Propane	35.0	-
LPG	1521.0	-
Bituminous Coal	200960.9	18.2
Anthracite Coal	0.0	-
Coke	0.0	-
Gasoline	14.0	-
Distillate Fuel Oil	10802.4	1.0
Residual Fuel Oil	373378.9	33.8
Petroleum Coke	0.0	-
Purchased Steam	16976.3	1.6
Other	9183.9	67.1*

*Percent increase since 1972.

total fuels purchased by the industry in 1979, the last year for which data are available. Coal and fuel/quality waste materials are being substituted for more expensive fuels, but there continues to be heavy dependence on residual fuel oil. Usage of this fuel has shown little decrease (6.4 percent) since the 1972 base year for reporting. It is relied upon to stabilize combustion in the recovery boiler as well as for startup and peaking.

Additional energy productivity improvements can be expected from fine tuning of automatic systems and components which are now available for use in papermaking. However, the major gains in papermaking energy efficiency will result from incorporation of these systems in installations not now so equipped or in new construction.

In the pulping process, however, little has been done toward the development of a similar degree of energy control. The closest approach is the Union Camp Installation at Franklin, Virginia.⁽²⁵⁾ That facility, designed by the Measurex Corporation, was developed to provide closed loop control of a multiple boiler, multiple turbine-generator energy complex. Three black liquor recovery boilers, four power boilers, and four turbine-generators are the major controlled equipment.

Measurex used their own off-the-shelf standard control system for the recovery boilers. It incorporated one of these for each of the four recovery boilers. The overall control scheme embodies steady-state recovery boiler operation with changes in power demand satisfied by the four other boilers fired with combinations of oil, coal, and bark. Fuel mix is automatically controlled to meet power demand with minimum fuel cost in the four variable boilers. The output of this energy complex feeds the power demand of the entire plant, both the pulping and papermaking processes. The energy control scheme was coupled to the production process by balancing power required with power produced. Deficit power is purchased from the utility grid.

Recovery boilers by themselves offer significant opportunity for energy productivity improvement. The sulfate pulping process, also known as the kraft process, is used for about 70 percent of U.S. pulp production. In this process, alkaline chemicals dissolve all of the non-cellulose part of the wood while the mixture is cooked in a "digester." The cellulose fibers (pulp) are separated and sent to the papermaking process. The remaining liquid, called black liquor, is recycled (Figure 2). Dissolved wood material, lignin, is concentrated in evaporators and then dried and burned in the recovery boiler as fuel to provide energy for the process. Dissolved chemicals collect on the hearth of the recovery boiler as a liquid where they undergo chemical reduction as they begin the recovery process. Because the lignin is a constantly changing mixture of molecular species it has a constantly changing fuel value. The water content of the black liquor represents a boiler efficiency penalty which must be accepted but can be minimized through proper control. The percent solids must be maintained between limits dictated by risk of explosion at one extreme and termination of combustion at the other. On-line, real-time sensing of variables in the black liquor such as solids, viscosity, and heat value would allow automatic operation of process controls to keep its constituents optimized. Additional recovery boiler efficiency improvements can be obtained through controls designed to respond to measurement of reduction efficiency, bed and combustion zone temperature profiles, dust concentration, and fuel injection droplet size. Sensors do not exist to provide input to such controls.

Energy inputs are required at several points in the pulping process. A significant amount of supplementary fuel is usually required in the boiler to maintain stable operation and generate the required output. The lime kiln, required as part of the chemical recovery process, represents another major energy input. Its energy productivity could be significantly improved with good temperature control in the conversion zone. However, reliable temperature sensors that can survive in this environment do not

Figure 2. Pulping Process Major Steps

exist. Evaporators, used to remove water from the black liquor, require a large energy input. Close control of the percentage of solids in the black liquor exiting the evaporator compliments recovery boiler performance. The digester wherein the pulping occurs also requires a large energy input. Better control based on real-time knowledge of the process would reduce its energy requirement. Sensors do not exist for these measurements.

Estimates by Dr. Ray Harrison⁽³³⁾ place the process energy requirement for a kraft pulp plant and paper mill at about 25 million Btu per ton of pulp. Major system component energy requirements are:

<u>Component</u>	<u>Million of Btu's</u>
Pulping	5
Evaporators	5
Lime Kiln	2
Recovery Boiler	1
Paper Mill	12
	<u>25</u>

Almost half of this requirement is met in the recovery boiler. A bark burner which burns the material not suitable for pulping contributes about one-fifth of the requirement. The balance, about one-third of the requirement, is input in a combination of fuels and electric power.

Pulping operations in the future may have additional problems. Should reserves of long fiber softwood be consumed, shorter fiber hardwoods would be substituted. It is likely that the hardwoods would be a variety of tree species and, hence, would produce a variety of fiber lengths requiring different digester treatment. Sensor requirements may become even more demanding than for existing conditions.

2.3.2 Prospects for Improvement

There is high confidence that paper equipment improvements, such as high consistency forming, improved mechanical drying, and waste heat recovery, will further reduce the mill energy requirement beyond the improvements of the Measurex design in Franklin, Virginia.

The pulping process appears to provide the greatest opportunity for energy productivity improvement. Because the process recirculates several of the constituents, changes which improve one step in the process may detract from another. Present control schemes require periodic sampling, often manually, to obtain a laboratory analysis. The resulting information, minutes to hours old, is used to change a variable with little more than a "seat-of-the-pants" feel for the effect of the change on the balance of the system.

Reliable sensors to measure the variables which must be controlled for system optimization do not yet exist. Were they to exist, the pulping process could be operated as a robotic system. Improvements in the operation of the energy-intensive pulping system components which could be obtained with appropriate sensors combined with paper mill advances could make the entire process energy self-sufficient.

Robots in a more traditional sense could improve handling of both raw materials and finished product. In the woodyard, robots may have potential to improve efficiency through complete mechanization of raw materials handling. The fringe benefit of enhanced personnel safety would also be realized by removing workers from this relatively hazardous area. At the finished product end, manipulating and loading rolls and packaged products may have both cost and productivity benefits. Some recently constructed or refurbished facilities have varying degrees of automation in these areas. In the context of a robotic system as defined for this analysis, one can envision a fully automated facility where human intervention is routinely not required between the raw materials stockpiles and finished product loading. In order for it to be realized, devices must be created through research and development to generate information to be used in the robotic system.

2.3.3 Requirements

Over the past five years there have been at least three forums in which pulp and paper industry representatives have expressed their views on

sensor needs for better pulping process control. In 1977-78 the industry, in an ERDA-sponsored conference, listed a need for sensors as follows:⁽³⁾

Recovery Boiler Control Sensor Development Areas

- Liquor Combustion Stabilization
- Smelt Bed Condition
- Real-Time Measurement of Liquor Calorific Value
- Viscosity
- Surface Tension

Better Real-Time Measurement of Present Solids

Digester Control

- Real-Time Management of "Pulp Quality"
- Bulk Density Measurement
- Improved Chip Moisture Measurement
- Improved Active Alkali Measurement

In July 1981, an ad hoc working group on recovery boiler instrumentation comprised of members of the Research and Development Subcommittee of the Recovery Boiler Committee and the Instrumentation Research Committee of the American Paper Institute met to consider instrumentation needs for a recovery boiler control project. The group identified instrument needs as follows:

- Droplet Size Measurement
- Droplet Size Prediction
- Viscosity
- Fine Sticking Tendency
- Temperature Profiles
 - Furnace
 - Screen Tube
 - Superheat Gas
- Bed Height and Geometry
- Bed Temperature Profile
- Reduction Efficiency
- Leak Detection

In December 1981, the Center for Chemical Engineering at the National Bureau of Standards' National Engineering Laboratory summarized information on papermaking sensor needs obtained from the consensus

of an industry working group assembled for this purpose. It indicated requirements for the following measurements or sensors: ⁽²⁶⁾

- Lignin Concentration in Pulp Mass
- Pulp Quality
- Steam Flow
- Active Alkali
- Black Liquor Combustion
- Smelt Bed Parameters
- Black Liquor Characteristics
- Lime Kiln Temperature Profile
- Solids Concentration of Black Liquor
- Consistency
- Chip Moisture
- Bulk Chip Density

Comparing these lists, it is apparent that few (if any) of these sensor requirements have been met.

As an analysis of the kraft pulping process is made more detailed, the spectrum of sensors required for its precise control widens. Considering major components individually produces the following list of sensor requirements:

Recovery Boiler	
Black Liquor Solids	Bed Density
Black Liquor Viscosity	Reduction Efficiency
Black Liquor Heat Value	Dust Concentration
Bed Temperature Profile	Droplet Size at Injector
Bed Geometry	
Evaporator Concentrator	
Soap-Liquor Interface	Active Alkali Concentration
Soap Concentration	Black Liquor Solids
Lime Kiln and Recausticizing	
Conversion Section	Lime Availability
Temperature Profile	Active Alkali Concentrate
Carbonate Concentrate	Mid Concentration
Particulate Concentrate	Solids Concentration
Lime Flow	

(Duplication in this listing reflects the fact that output from one system component is input to another.)

2.3.4 Energy Conservation Potential

Reasonable agreement exists among industry representatives that a 10-percent improvement in the quantity of energy derived from the recovery boiler is both a realistic and significant objective. If the following assumptions are made:

Annual Kraft Process Pulp Production	40×10^6 tons
Energy Recoverable from Black Liquor in Recovery Boiler	12×10^6 Btu/ton of Pulp Produced
Heat Content of Oil	6×10^6 Btu/bbl

and an objective of 10-percent improvement in energy recovery in the recovery boiler is achieved, the barrels of oil energy equivalent savings would be:

$$\frac{40 \times 10^6 \frac{\text{tons pulp}}{\text{year}} \times 12 \times 10^6 \times 0.1}{6 \times 10^6 \frac{\text{Btu}}{\text{bbl oil}}} = 8 \times 10^6 \text{ bbl oil/year,}$$

This number compares to 16×10^6 bbl of oil/year equivalent determined by Sherif Fam⁽⁴⁾ for total annual paper and paperboard production of just under 60×10^6 tons in 1976. That analysis was based on incorporation of automatic process controls in each of the elements of the process, i.e., evaporators, lime kiln, recovery boiler. (A section of that study, "Potential for Energy Savings," is included in this report as Appendix C.) That report also makes the observation that sensor development would be required, along with development of associated software, to operate a recovery boiler with an automatic control system. It is likely that improved control would also produce an increase in capacity with existing capital equipment.

The sensors needed for reliable operation of a recovery boiler as a part of a robotic system do not exist. A research and development effort is required. Industry is unlikely to do the job unless there is a marginal increase in production large enough to pay for the program.

There are generic categories of sensors which have application in many industrial processes including those in the pulp and paper industry. Because the recovery boiler provides the opportunity for the greatest energy savings, the types of sensors which would contribute to its more efficient control and monitoring should be considered. Any program with this objective should be coordinated with the sensor development effort now underway at the National Bureau of Standards funded by the Department of Energy's Office of Industrial Programs and cooperating industry groups.

However, before any significant investment is made in research dedicated to achieving energy savings in this area, a rigorous cost-to-benefit analysis should be made. As emphasized earlier by Sherif Fam: ⁽⁴⁾

Investments in control systems (to be retrofitted) must usually fit into the cycle for asset turnover or scheduled shutdowns, and the rate for replacing equipment is very low in the pulp and paper industry. If the market demands high capacity utilization, installation of a major control system for energy savings will be delayed.

3. PRECISION ENGINEERING

3.1 INTRODUCTION

Precision engineering is a generic term having numerous meanings. In the context of this discussion, precision engineering involves the generation or manufacture of components wherein geometry, dimension, and surface finish are controlled to within several hundred Angstroms in single point turning operations. The purpose of this discussion, then, is to explore the value of precision engineering and related sciences to energy conservation (fuel savings) in a variety of industries, including the paper and pulp industry.

3.2 PRECISION ENGINEERING PERSPECTIVE

In the United States, much of the Nation's existing capability in precision engineering resides within our National Laboratories such as Lawrence Livermore and Oak Ridge. Although this technology is of the highest quality, it is too narrowly focused to meet present and future U.S. industrial needs. Thus, there is a need for industry to perform research that would bring precision engineering sciences and supporting disciplines into the marketplace to assure rapid dissemination of this strategically important national resource.

The principal center for precision engineering in western Europe is at Cranfield, U.K. The Cranfield Unit for Precision Engineering (CUPE), with its associated academic program, has some 50 graduate students.

It is fair to state that America is slipping behind in precision engineering. It would be easy to cite the purchase of special lenses for micro-circuit manufacturing from Germany, or the absence of high-grade camera manufacturing, or the purchase abroad of silent rolling contact bearings for stealth in nautical systems. In discussions with many persons versed in American and world activities in the field, it was generally felt that we still lead in precision engineering at least in areas related to weaponry.

In view of this, it is surprising that such technical proficiency is not reflected, promulgated, and rationalized in our academic institutional structure. One can only suggest that the conservatism and homogeneity of our National Laboratories and engineering institutions has not allowed such a development to take place.

Precision engineering is concerned with the generation of solid objects of precise shape, the control of surface texture, the generation of extremely precise linear and rotary motions, and the measurement and evaluation of the effectiveness of such efforts. The actual surfaces, the stability of their shape, and many of the problems of removal of material lie in the field of materials science. Tribologists have been working at this edge of material science for many years, and it was not surprising to find tribologists rapidly moving into the field of precision engineering.

The control of motions lies in the field of mechanics, but in recent years it has been totally revolutionized by the addition of feedback control, exploiting the computer or microcomputer in the control loop. (10,19,20) The field of engineering technology known as metrology has also been totally changed by the presence of the computer, its ability to remember and to compare. (13,22) It has the ability to correct for motions of the holder of the workpiece and subtract these from the measurements of the surface configuration itself.

In summary, the fields of tribology, dynamic analysis of machines, materials science, metrology, and computer control are all called upon in precision engineering.

In the United States the greatest strength in such areas lies in the National Laboratories and the Bureau of Standards, although these groups have little interest in precision fabrication or manufacture, other than instruments for scientific purposes.

There has been a long tradition in Great Britain in both institutional and industrial participation in this field. Many of the persons at the forefront were known through research and publication in tribology. This study was undertaken to assess the possibility of using precision engineering in potential defense applications and industrial needs of the United States, such as paper and pulp, and to determine how these findings might relate to the institutional structure in the United States, to facilitate the availability of the best in precision engineering when it is needed.

Concern with producing dimensions at the limit of the machinist's skill has always resided with astronomers and precision instrument makers. Now the same care and precision is needed in many other manufacturing capabilities. New systems are continually being conceived, where the state of the art must be exceeded for them to be effectively produced.

The necessary skills have been found piecemeal. In America one finds excellent precision engineers in aerospace centers, and occasionally among the instrument displayers at trade fairs. Appendix C shows a list of U.S. industrial companies that are interested in precision engineering and have some limited capabilities. In Europe the art and science have been institutionalized and ideas are regularly traded and improved upon among the participants in a range of government and academic institutions. Except for the most humble beginnings, there are no such groups accessible to the public or defense agencies in America. To be specific, a role for such groups would be to:

- Actively work in precision manufacture at the laboratory level, and in the development of precision manufacturing devices.
- Continually assess instrument technology and achievements of others.
- Offer a teaching function to aid in the transfer of technology to industrial groups who need it.
- Be on standby to aid in defense areas.

When one looks for the most serious problem areas, one finds: The generation of the surface itself (the interface where tool meets workpiece) is the least understood. The process by which material is removed, added, or rearranged will remain an interdisciplinary area of study for a long time to come. The support for the surface (the structure behind it) must be stable, and in many cases, self-correcting. The study of active structures with computer-controlled feedback is in its infancy and is fundamental to the generation of precise surfaces and the maintenance of their integrity in the working application. The precise control of relative motions in the machining process (where modern measurement techniques are used to feed back information through computer processing units to accurate control systems) is also in its infancy although it has advanced to a stage where it is a great promise. The three activities at the leading edge are:

1. The production of surface finish and contour by mechanical, electronic, or other physical means.
2. The control of the integrity of structures, particularly through the use of active feedback and computational systems.
3. The control of motions through accurate metrology techniques, especially through feedback loops using computers.

These three areas are being addressed effectively at Cranfield for individual applications and Lawrence Livermore Laboratory for the weapons program.

3.3 MACHINE MATERIALS

One of the most important factors in precision engineering is the ability of the material to be machined to the tolerances required. To date, the machining of materials in the United States has been done exclusively on diamond turning machines. This is also true in the rest of the world with the possible exception of Japan.

In order to attain the tolerances of 10^{-6} to 10^{-7} , it has been found that only nonferrous materials could be machined with diamond turning lathes. When ferrous materials were used, the quality of workmanship desired was unsatisfactory. The factors that affect the diamond turning machineability of metals and metallic salts are hardness, crystal structures, inclusions of hard particles, and graphitization. In general, the softer face center cubic (FCC) crystals machine well, meaning with a specular finish of optical quality. Nickel, copper, aluminum, gold, silver, lead, and brass have been successfully machined. Efforts continue to expand the list of materials that can be machined to optical quality. FCC materials such as platinum, high purity iron, and nickel have been cut using diamond tool bits but failed to produce the desired optical properties. Beryllium and steel machining have been attempted. The inclusion of the ever present beryllium oxide in the base hot pressed beryllium metal causes a high rate of diamond tool wear. This limits the diamond machining of this metal. Steel machining exhibits high diamond tool wear attributed to graphitization.

This is diffusion of carbon into iron, under the local cutting edge stresses. Molecules of the diamond are attracted to the iron. When ordering material for diamond turning, consider whether the impurities in the material can be cut by the diamond. For example, machinists have reported aluminum oxide inclusion in 6061-T6 aluminum that has not been cut but rather pushed aside by the diamond tool. Order optical-grade clean and filtered material. If the price is prohibitive, consider plating with copper or electroless nickel. Copper in billet form produced electrolytically machines well but inclusions have been found in rather expensive billets. This suggests that the most predictable means of obtaining a near perfect surface is to plate it. Other materials that are not FCC but have diamond turned successfully are zinc selenide, zinc sulfide, germanium, silicone, and beryllium copper. Also, halide salts, sodium chloride and potassium chloride, and some plastics machine well.

Table 3 lists some of these materials and provides a generalized indication of the surface finishes attainable along with the types of configurations that have been prepared. These materials may be of potential applicability to the paper and pulp industry.

It has been determined by Lawrence Livermore Laboratory that single crystal boron nitride tool bits should give the desired finishes that are of interest, but there are no tool bits available in the United States. A new development program has been initiated to produce single crystal boron nitride for use in diamond turning machines.

This development program could lead to a major breakthrough in the surface finishing of ferrous materials.

3.4 PRECISION ENGINEERING AND ENERGY CONSERVATION

The ability to generate extremely precise machined surfaces (e.g., accurate to 10^{-7} inches or better), can yield important energy conservation advantages in a wide variety of machines used throughout society. The advantages accrue either as a result of reduced mechanical friction in moving parts or through the reduction of losses by means of more accurate control of certain processes, for example, the metering of fuel in diesel injection systems and improved seal interfaces. In the heat pipe technology field if more accurately machine surfaces were made available, it is estimated by Lawrence Livermore, improvement in efficiency would be forthcoming. Coupling heat pipes with mechanical devices could further improve efficiencies where this technology was applicable. One must therefore examine the entire scope of efficiency improvements that would be created by precision engineering.

In addition to the improved performance of heat pipes, of particular significance is the "leverage" exerted by saving mechanical work in such devices as electric motors, reciprocating engines, power transmissions, pumps, compressors, etc. Mechanical work, according to the second law

TABLE 3
MACHINEABLE MATERIALS

Material Classification	Material Specification	Machined Forms	Surface Finish Quality
Aluminum	1000, 2014, 6061-T6, optical-grade 5257	All configurations	0.6 to 1 μ in.
Brass	Several types	Several configurations used for fixtures	
Bronze	Unknown	Flat	SDNA
Nickel	Process specified herein	All configurations	1.0 to 2.0 μ in. p to v
Lead	Calcited 0.7%	Several configurations	1.0 to 2.0 μ in.
Gold	Unknown	Flat	SDNA
Silver	Unknown	All configurations	SDNA
Germanium	Unknown	Flat	1.1 to 5.4 μ in. p to v
Beryllium	Berylco 10 AT	Flat	0.8 μ in.
Copper	Berylco 25 A		p to v
	Berylco 33-25 A		1.3 μ in.
Copper	OFHC	All configurations	0.2 to 2 μ in. p to v
Electroplated Overcoat of:			
Silver	Pure electrodeposited	Flat	SDNA
Gold	Pure electrodeposited	Irregular	SDNA
Copper	Pure electrodeposited - Process specified herein	All configurations	1.4 to 3.2 μ in. p to v

of thermodynamics, is the highest grade form of energy and is the yardstick against which the quality of other energy forms must be measured. The "available work" in a system is a parameter that takes into account both the quality and the quantity of energy.

A given quantity of energy is said to have 100-percent "availability" if it exists as mechanical work. An equal amount of energy in the form, for example, of saturated steam at 100 pounds per square inch pressure has less than 30-percent availability. The practical implications of the second law can be seen in energy conversion process where fuel is first consumed to produce shaft power (e.g., the steam turbine of a large powerplant), then converted to electricity in a generator, distributed through transmission lines to end-users, and finally applied to a specific task such as operating an electric motor which, in turn, drives a pump.

Losses attend each stage of the energy transformation from fuel to the final task of pumping a fluid. Thus, any improvement in efficiency at the pump itself will be reflected in successively larger savings in energy at each upstream stage of energy conversion. Assume, for example, that the pump absorbs 100 hp, of which 20 percent is accounted for by seal and bearing friction. If, through precision machining processes, we can reduce mechanical losses by one-quarter, the saving 5 hp will be leveraged all the way through the energy supply system. Losses in the bearings may also be reduced by improved manufacturing, saving an additional 2 hp.

Reflecting the 7-hp total mechanical savings through the motor efficiency, we obtain the electrical savings of about 10 hp. Working further "upstream," these savings represent a thermal input at least three times as large (i.e., 30 hp or about 78,000 Btu per hour). For an industrial motor operating 6000 hours per year, this represents the energy equivalent of more than 3200 gallons of petroleum per year.

The pumping of fluids in the paper and pulp industry could benefit immensely from any improvements in pumping efficiency. The pumping power requirements of an average integrated mill making newsprint is 15,000 hp.⁽⁴⁹⁾ If a 5-percent savings due to precision engineering is assumed, then a potential savings of 750 hp or 1,950,000 Btu/hr could be realized. This is the equivalent of saving 100,000 gallons of oil per year per plant. With a total wood pulp production of about 57,130,000 tons per year⁽⁴⁾ and the estimated savings of 100,000 gallons of oil equivalent per year for a 500-ton capacity plant, an annual savings of 461×10^5 gallons of oil equivalent or 900,000 barrels is estimated.

Similar leverage exists in vehicle applications. For example, an improved automobile wheel bearing that reduces rolling resistance by only 1 hp saves about 10 hp in equivalent fuel input due to the compounded inefficiencies of engine, transmission, and power train. Further savings are, of course, possible in the transmission bearings and gears, in the engine bearings and other sliding surfaces (e.g., camshaft, valve guides, and cylinder bores). Finally, there are additional gains resulting from the reduced size and weight of engines and drive trains that occur when friction losses are cut (i.e., smaller total horsepower required for equivalent vehicle performance).

About 60 percent of all U.S. petroleum is consumed by the transportation sector in the form of high-grade distillate and gasoline fuels. Hence, any efficiency improvements relating to spark-ignition, diesel or gas turbine engines, or to the vehicles in which they are installed will directly affect the most critical demand element, i.e., refined petroleum product. Equally important is the national impact of reduced electricity demand resulting from reduced losses in electric motors. Electric power generation accounts for over 30 percent of all U.S. fuel consumption and almost two-thirds of all capital investment for energy supply. Since half of the Nation's electricity output is ultimately consumed in electric motors,

the potential savings in both energy and capital are extremely large. In fact, calculations indicate that each horsepower of reduced demand in electric motors represent a savings of at least \$15,000 in avoided cost of new investment for powerplants, fuel supply, and electrical transmission capacity.

Overall, it has been estimated⁽²⁷⁾ that the reduction of friction in mechanical systems could account for as much as four million barrels per day equivalent energy savings - about 10 percent of the total U.S. energy consumption.

The possible energy (fuel) savings in reworking aircraft compressor and fan blades has been documented by Dr. Ralph Burton, of North Carolina State University and others in NASA SP-381, 1975, p. 166.

One of the conclusions reached during this study is shown by the bar on the right side of Figure 3. The total length of the bar represents 100 percent of the repaired engine performance deterioration. As is noted on the bar, 15 percent of the total deterioration is associated with the turbine. Such things as turbine nozzle area changes, tip seal wear, and vane platform leakage were judged to be responsible. These losses are over and above the losses that are typically corrected during overhaul.

Another 20 percent of the losses are attributed to seal leakages. The combination of a large number of seals and their relative inaccessability precludes seal repair or replacement except in the more obvious cases. Finally, about 65 percent of the performance deterioration is charged to the fan-compressor gas-path parts. As indicated in the figure, these parts suffered because of erosion, foreign object damage, or increased surface roughness. Of these categories, foreign object damage is the only one consistently dealt with, primarily because it is the only one affecting structural integrity. The cure generally consists of smoothing out the rough edges, or in the more severe cases, welding on additional metal. Neither of these contributes greatly to restoring performance.

Figure 3: Performance Deterioration Causes

Restating the last comment, the surfaces of the compressor and fan blades have been modified by foreign bodies, these ranging from dust to large particles.

The increase of specific fuel consumption ranges between 5 and 10 percent, depending on overhaul procedures and operating conditions (see Figure 4). Taking an average of 5 percent if applied to the entire military and civilian fleet, which our figures show⁽⁴⁾ consume 4×10^8 bbl/yr, to halve this loss would save 10^7 bbl/yr.

The problem is that restoration of surfaces of the blades is not simply a matter of restoring finish. The very subtle contour, which strongly affects optimal drag, must be restored, and can be restored through the use of precision machinery.

3.5 PRECISION ENGINEERING AND THE PULP AND PAPER INDUSTRY

Through communication with pulp and paper industry representatives it appears that the direct energy conservation benefit which would accrue to the incorporation of precision engineering in the industry is slight. Some gains in productivity through quality control and increased pump and motor efficiency would be realized in making paper. However, significant improvement would be expected in the meantime between failures in papermaking equipment. This result would have the effect of spreading the "overhead" fraction of total energy consumed over greater tonnage of output, thereby improving energy productivity.⁽²⁷⁾

The following recommendations are offered for consideration:

1. Computer control and robotics should be exploited. A proper starting place would be through exchanges of persons with Cranfield University Precision Engineering (CUPE). CUPE welcomes such exchanges.

A-6945

Figure 4. Engine Performance Deterioration

2. Should one or more U.S. centers be developed, they must from the outset establish relationships with appropriate industrial groups. They should work as partners on specific projects.
3. A precision engineering center should be prepared to offer a teaching function in metrology and precision manufacturing techniques. This should include (a) degree work and (b) special courses.
4. A precision engineering center should have a strong interrelationship with defense agencies, should cooperate with laboratories such as the Naval Research Laboratory and the David Taylor Naval Ships Research and Development Center, and should have members on task groups pursuing precision engineering problems.
5. A more thorough study of potential industrial and military research opportunities relative to energy conservation should be undertaken.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 ROBOTICS

There is a massive effort underway in the United States to improve robots and related systems. Research and development in all aspects of manipulator arms is producing a steady stream of improvement. Through the use of two-dimensional vision, force, torque, and feel sensing, a new generation of robotic machine is emerging. The resources applied to these areas appear to be adequate.

Three-dimensional vision sensing has a potential for significant (although difficult to quantify) gains in productivity. The machine capability to reach into a bin and select and inspect the correct part translates into increased throughput with stable quality and reduced tooling costs. Support for research in this area should be considered.

There are generic categories of sensors which have application in many industrial processes including those in the pulp and paper industry. Because the recovery boiler provides the opportunity for the greatest energy savings, the types of sensors which would contribute to its control should be considered. The fuel value of the black liquor sent to the recovery boiler is constantly changing and, therefore, makes boiler control difficult and, on occasion, dangerous. Real-time knowledge of water properties such as water content, percent solids, viscosity, and heating value would allow the boiler to be operated as a robotic system. The particular physical measurements that will translate into quantitative descriptions of these properties are not known. Research is required to learn which physical properties can be sensed to reliably produce an accurate determination of the contents of the stream being measured. The same situation exists with regard to the other components of the pulping process.

There is sufficient energy conservation potential in the pulp and paper industry that could be exploited by industrial research. Some of the priorities to be investigated include:

- Determining the properties to be sensed
- Developing the interfaces between sensors and controls
- Estimating the cost per installed system
- Estimating the marginal increase in capacity which results
- Determining if the return on the investment warrants continued effort

The pulping process should be considered as the first candidate for this industrial analysis.

4.2 PRECISION ENGINEERING

Much of the Nation's existing capability in precision engineering resides within our National laboratories such as Lawrence Livermore and Oak Ridge. Although this technology is of the highest quality, it is far too narrowly focused to meet present and future U.S. industrial needs. Thus, there is a need for industry to carry out research that could bring precision engineering sciences and supporting disciplines into the marketplace in order to assure rapid dissemination of this strategically important national resource. Further, competitive growth of American industry calls for more persons who understand engineering operations carried out to the limits of measurement.

It is recommended that the Department of Energy capitalize on the development of precision engineering and related sciences appropriate to energy conservation.

The Department of Energy should consider a more in-depth study of potential research opportunities relative to industrial and military programs. This study should examine energy-conserving opportunities and should be done using a methodology that will maximize the exploitation of such opportunities.

APPENDICES

APPENDIX A

REFERENCES

1. Binford, T.O., "Computer Integrated Assembly System," AI Lab, Stanford University, 1981.
2. Chang, J.C.H. and Soong, T.T., "Structural Control Using Active Tuned Mass Dampers," Journal of the Engineering Mechanics Division, Proceedings of the ASCE, Vol. 106, n. EM6, Dec. 1980. p. 1091.
3. "Energy Conservation in the Pulp and Paper Industry," Advanced Energy and Technology Associates, ERDA Report CONF-770234, 1977.
4. Fam, S., "Impact on Energy Conservation of Automatic Control Systems Utilization in the U.S. Pulp and Paper Industry," Report DOE/CS/40150-1, 1978.
5. "Future Robotics Markets," Technology Growth Markets and Opportunities, Vol. 1, No. 4, March 1981.
6. Craig, J., Cunningham, R., and Ruoff, C., "Hand-Eye Control in a Robotic Assembly Task," Jet Propulsion Laboratory, California Institute of Technology, NASA Contract NAS 7-100.
7. Hillis, W.D., "Active Touch Sensing," Massachusetts Institute of Technology, Artificial Intelligence Laboratory, A.I. Memo 629, April 1981.
8. Kinnucan, P., "How Smart Robots are Becoming Smarter," High Technology, Sept./Oct. 1981.
9. Larson, G., "Source Document on Robotics," U.S. Department of Transportation, November 1981.
10. Machizaki, M. et al., "Design of Servodamper Control System," Bulletin of the MSME, Vol. 20, No. 148, October 1977, pp. 1269-1276.
11. Minski, M., "Telepresence," Omni, June 1980.
12. Movich, R.C., "Robotic Drilling and Riveting Using Computer Vision," Robotics Today, Winter 1980-81.
13. Okada, Y. and Nakada, T., "Analysis and Experiments on an Electro-Hydraulic Torsional Servo Vibration Damper," Bulletin of the JSME, Vol. 19, No. 131, May 1976, pp. 477-484.
14. "Robotics Age," July/Aug. 1981, Sept./Oct. 1981, Nov./Dec. 1981.
15. "Robotics Age," Sept./Oct. 1981.
16. "Robotics Age," Nov./Dec. 1981.
17. "Robotics Industry Directory 1981," Robotics Publishing Corp.

18. Rosen, C.A. and Nitzan, D., "Use of Sensors in Programmable Automation," IEEE Computer Society Magazine, December 1977.
19. Tanaka, N. et al., "Design of Servodamper Control Systems," Bulletin of the JSME, Vol. 20, No. 148, October 1977, pp. 1269-1276.
20. Tanaka, N. et al., "On the Suppression of Self-Excited Vibrations by Servodamper," Bulletin of the JSME, Vol. 23, No. 176, February 1980, pp. 265-272.
21. "Technology Assessment: The Impact of Robots," Eikonix Corp., September 30, 1979.
22. Yamkama, I. et al., "Behavior of a New Type Dynamic Vibration Absorber Consisting of Three Permanent Magnets," Bulletin of the JSME, Vol. 20, No. 148, October 1977, pp. 1261-1268.
23. Tesar, D. and Soldner, K., "Assessment for the Physical Structure and Hardware of General Robotic Manipulator Systems," University of Florida, NSF Grant No. ENG78-20112, DOE Contract No. ER-78-S-05-6102.
24. "The Industrial Energy Efficiency Improvement Program," Annual Report to Congress and the President, Department of Energy, 1980.
25. "Energy Management," September 1978.
26. Whetstone, J.R. and Johnson, E.G., "Sensors for Efficient Energy Utilization in the Paper Industry," National Bureau of Standards, December 1981.
27. "Precision Engineering Commercialization," Lawrence Livermore Laboratory, Oct. 1981.

Interviews*

28. Mr. Robert Bareiss, St. Regis Paper Co.
29. Dr. Tom Binford, Stanford
30. Dr. Don Blomquest, NBS
31. Dr. Bob Cunningham, JPL
32. Mr. Ken Fugate, Panel Displays, Inc.
33. Mr. Gerald Gleason, Machine Intelligence Corporation
34. Dr. Ray Harrison, Weyerhaeuser
35. Dr. Dick Hessler, Boeing Aircraft

*Some of these contacts were developed through communication with the offices of The American Paper Institute.

36. Mr. Jim Held, Machine Intelligence Corporation
37. Dr. Dan Hillis, MIT
38. Mr. Rich Movich, Lockheed California at Burbank
39. Mr. W. Richard Olson, Honeywell Corp.
40. Mr. Bill Park, SRI
41. Mr. Ned Rasor, Rasor Associates
42. Mr. John Rossmeissl, DOE
43. Mr. Gene Rowland, National Bureau of Standards
44. Mr. Steven E. Scarborough, Honeywell Corp.
45. Mr. Jim Smith, United States Robots
46. Mr. Stan Sobeyzyski, DOE
47. Mr. H.H. Walbaum, International Paper Co.
48. Dr. John Watkins, Weyerhaeuser
49. Mr. Robert Crawford, Black-Crawford Co.

APPENDIX B
REPRINTED SECTIONS OF REFERENCE 4

6. POTENTIAL FOR ENERGY SAVINGS

6.1 INTRODUCTION

To learn about industry's attitudes toward automatic process controls, we conducted in-depth interviews with management personnel at selected pulp and paper firms and with manufacturers of process controls. (Appendix A describes our interviewing method.) By agreement with OIP, we focused our interviews on 600-ton/day integrated pulp and paper mills located in the southern region of the United States, for the following reasons:

- The average-size integrated mill produces about 600 tons of product a day.
- About 75 percent of pulp and paper is produced by integrated mills.
- About two-thirds of pulping capacity and one-half of papermaking capacity are located in the South.

We regard our conclusions as preliminary for several reasons. First, we were limited in the number of pulp and paper companies we could interview, and in the amount of time we could spend interviewing them and visiting their facilities. Second, ACS is a fledgling technology which has not yet permeated the thinking of the pulp and paper industry, an industry which generally views new technologies from a highly conservative perspective. Moreover, a good deal of controversy surrounds process control technologies, particularly in the pulping and recovery areas. Finally, because vendors and users perceive ACS needs and performance so differently, it is difficult to define the benefits and limits of existing and advanced technologies.

Nevertheless, we believe that this preliminary effort reveals a significant opportunity for energy conservation through use of ACS in the pulp and paper industry, enough so to warrant a programmatic effort by

OIP to overcome the barriers identified as currently limiting achievement of ACS potential.

6.2 ENERGY SAVINGS USING AUTOMATIC CONTROL SYSTEMS

Over 80 percent of the energy used in pulp and papermaking is used in the digesting, refining, bleaching, and papermaking processes, and by the evaporators and lime kilns. Because of this, these areas offer the best opportunities for energy conservation. In addition, improved control of the recovery boiler will reduce the amount of fuel required by the mill powerplant. Typical distribution of energy consumption within a mill is shown in Figure 6.1.

To assess the energy savings that ACS could provide at level 1, we asked the companies we interviewed to comment on the probable market penetration and relative energy savings associated with both existing and advanced automatic control systems. Potential energy savings using existing controls for three of the most energy-intensive processes (digesting, bleaching, and papermaking) are detailed in Figure 6.2. This figure does not cover potential energy savings in the recovery area (evaporator, recovery boiler, lime kiln), for which few controls have been developed. As shown in Figure 6.2, ACS market penetration is relatively high for papermaking, however, ACS is generally used not for energy conservation but to control quality and production. Bleaching and digesting, for which potential savings are also high, show low ACS market penetration suggesting that there are barriers to its acceptance (see Chapter 7).

Advanced level 1 control systems and the energy benefits they are likely to produce are described in Figure 6.3. We summarized the control technology needs for the most energy-intensive processes, including those in the recovery area. There was general agreement among people we interviewed that the evaporators, recovery boiler, and lime kiln offered the best energy-saving opportunities for ACS, even using conservative estimates of benefits.

Figure 6.1 Energy Flow in a Pulp and Paper Mill

Unit Process	Average Energy Use		Benefits with Controls			Cost of Controls		Market Penetration
	Million Btu/Ton *	Percent of Total Energy **	Energy Savings		Other	Capital	O&M	
			Percent	Million Btu/Ton *		(\$1000)	(\$1000/Month)	
Batch digesting [†]	4.4	14.0	15-25	0.66 - 1.10	Increased yield: 1-2% Reduced wood use: 3-4% Chemical savings: 7-10% Steam leveling Reduced steam blowdown	350-400	2-4	Low (10-25%) ^{††}
Continuous digesting [†]	1.8	3.5	Negligible	Negligible	Increased yield: 1.5-2% Reduced wood use: 3-4% Chemical savings: 7-10%	350-400	2-4	Low (15-25%)
Bleaching	4.4	14.0	5-12	0.22 - 0.53	Increased production: 2-5% Chemical savings: 8-10%	350-400	2-4	Low (5-10%)
Papermaking	11.3	36.0	3-6 (Using moisture control)	0.34 - 0.66	Increased production: 3-6% Reduced downtime Fewer rejects [§]	300-500 depending on degree of control	8-10	High (75-85%)
			1-2 (Using basic weight control)	0.11 - 0.23	Increased production: 1-2% Reduced fiber consumption: 1-2% Fewer rejects Reduced drying time	300-500 depending on degree of control	8-10	High (75-85%)

SOJRC: Resource Planning Associates, Inc., based on data provided by
Thermo Electron Corp. and companies interviewed.

* Air-dried ton of finished product.

** Average percent of total energy required for paper production
(31.4 million Btu/ton for first half of 1978.)

† Batch digesting represents 60% of installed pulping capacity;
continuous digesting, 20%

†† Percent figures derived from company interviews; based on total capacity.

§ Another benefit of computer controls is reduced grade change time
(from an average of 15-30 minutes without controls to an average of 2-5
minutes with controls), which results in increased production and energy savings, and fewer rejects.

Figure 6.2 Potential Energy Savings with Existing Automatic Control Systems

Unit Process	Technology Needs	Average Energy Use		Probable Control Benefits		
		Million Btu/ton*	Percent of Total Energy**	Energy Savings Million Btu/ton ⁺	Other	Comments
Batch Digesting	Reliable measurement of chip moisture under all conditions, including freezing	4.4	14	0.06 (reduced steam requirement for adequate cook)	More uniform kappa number, resulting in higher production	Paper companies agreed that these needs should be addressed. One vendor said the energy benefits would come primarily from steam leveling, not reduced steam use.
	Reliable measurement of active alkali			0.06 (reduced steam requirement for adequate cook)		
	Reliable on-line measurement of kappa number during cook			0.12 (reduced steam requirement for adequate cook). This capability would alleviate need to measure other cooking variables (chip moisture, active alkali, etc.)		Two companies agreed it would be useful, but did not believe it could be measured; one vendor said substitute measurements will produce the same results.
Brown Stock Washing	Reliable measurement of sodium content of pulp from the washers	0.94	3	0.14 (reduced steam to evaporators)	Reduction in bleach plant chemicals; reduction in make-up salt cake requirements	A reliable sensor is already available; companies interviewed disagreed on whether significant energy savings were possible.
Refining (Stock Preparation)	Reliable on-line measurement of freeness	3.1	10	0.11 (reduced refiner horsepower and moisture content of sheet to dryers)	More uniform sheet formation and increased production	Important area for control although one paper company said freeness doesn't indicate anything; more important is a measure for refining.
Papermaking	Reliable on-line measurement of sheet properties, i.e., machine and cross-machine direction strength, stiffness, and tear	11.3	36	0.12 (reduced steam requirement to dry off-grade paper)	Fewer off-grade products	The sheet properties mentioned are all destructive in nature and difficult to measure on-line.

Figure 6.3 Potential Energy Savings with Advanced Level 1 Automatic Control Systems

Unit Process	Technology Needs	Average Energy Use		Probable Control Benefits		Comments
		Million Btu/ton*	Percent of Total Energy**	Energy Savings Million Btu/ton†	Other	
Evaporators	Need computer model for most efficient time for boil-out of evaporators	2.83	9	0.19 (reduced steam requirement)		Important area for control. Estimate of savings conservative.
Recovery Boiler	Reliable measurement of black liquor as to: viscosity, surface tension, and heat value	—	—	1.42 (eliminates starting burner oil) 0.08 (reduced steam required to heat excess air)	Allows more stable operation of boiler due to uniform particle size and distribution at spray nozzles	Opinions varied as to the usefulness of measuring viscosity and surface tension; two companies would focus on measuring liquor composition (organic/inorganic ratio) and bed height.
	Reliable measurement of steam to determine adequacy of blow-down	—	—	0.12 (reduced steam use in continuous blowdown)	Reduced need for pollution treatment	One company would not want to restrict the amount to blow-down, to ensure safe operations.
	Soot blowing					Two companies emphasize the need for controls that measure when to blow soot from the boiler tubes.
Lime Kiln	Reliable measurement of temperature gradient in kiln, and of sodium in lime mud.	2.2	7	0.09 (reduced fuel use)	Better slaking control resulting in more uniform liquor composition to digester	General agreement that this is a conservative estimate of savings. One company said burning coal in the lime kiln would be a lot cheaper, but mills are reluctant to do so, because they don't know the effect carbon ash has on the calcining of lime.
	Reliable measurement of flame qualities	2.2	7	0.09 (reduced fuel use)		

SOURCE: Resource Planning Associates, Inc., based on estimates provided by J.E. Serrine Company, and reactions from companies interviewed by RPA.

* Air-dried ton of finished product.

** Average percent of total energy required for paper production: 31.4 million Btu/ton for the first half of 1978).

† Unit: energy savings were based on a 600-ton-a-day integrated pulp and paper mill.

Figure 6.3 (Cont'd) Potential Energy Savings with Advanced Level 1 Automatic Control Systems

APPENDIX C
MANUFACTURERS LIST

PRECISION DIAMOND TURNING MACHINES

Turnkey Machines

Pneumo Precision, Inc.
Precision Park
59 Optical Avenue
Keene, NH 03431
Tel. (603) 352-5242

Moore Special Tool Company
800 Union Avenue
Bridgeport, CT 06607
Tel. (203) 366-3224

Special Machine Assemblies

Professional Instruments Company
4601 Highway 7
St. Louis Park
Minneapolis, MN 55416
Tel. (612) 927-9445

Pantek Systems, Inc.
P.O. Box 137
Fairfield, CT 06430
Tel. (203) 255-4980

Diamond Tool Bits

J. Robert Moore Company
Box 347
Petersham, MA 01366
Tel. (617) 722-3206

3M Company
3M Center
St. Paul, MN 55101
Tel. (612) 733-4280

Indimant GMBH
AM Redder-1
D-2072 Bargtheide
West Germany
Tel. (04532) 6555

American Representative
P.O. Box 6507
St. Paul, MN 55016
Tel. (612) 733-1110

BASIC METROLOGICAL REFERENCES

Electronic Indicator - Contact LVDT Type (Cartridge-type)

The Bendix Corporation
Automation & Measurement Division
Box 1127
Dayton, OH 45401
Tel. (513) 254-5377

Blanchette Tool & Gage Mfg. Corp.
P.O. Box 1270
845 Bloomfield Avenue
Clifton, NJ 07012
Tel. (201) 471-2100

Electronic Indicator - Contact LVDT Type (Air Bearing)

Pneumo Precision, Inc.
Precision Park
59 Optical Avenue
Keene, NH 03431
Tel. (603) 352-5242

Electronic Indicator - Noncontact

ADE Corporation
127 Coolidge Hill Road
Watertown, MA 02172
Tel. (617) 923-2180

Electronic Level

Federal Products Corp.
1118 Eddy Street
Providence, RI 02901
Tel. (401) 781-9300

Electronic Stethoscope

Horstmann

Brass Mill Works
Bath BAI-3JH England
Tel. Bath-26206

Minear

One First Street
Los Altos, CA 94022
Tel. (415) 941-8780

Master Ball

The Bendix Corporation
Automation & Measurement Division
721 Springfield Street
Dayton, OH 45401
Tel. (513) 254-5377

Master Step Gage

Moore Special Tool Company, Inc.
800 Union Avenue
Bridgeport, CT 06607
Tel. (203) 366-3234

Optical Flats

Rahn Granite Surface Plate Corporation
641 N. Western Avenue
Dayton, OH 45407
Tel. (513) 263-1951

Precision Indexing Table

Pneumo Precision, Inc.
Precision Park
59 Optical Avenue
Keene, NH 03431
Tel. (603) 352-5243

AA Gage Company
P.O. Box 774-A
Detroit, MI 48232
Tel. (313) 548-3810

Moore Special Tool Company, Inc.
800 Union Avenue
Bridgeport, CT 06607
Tel. (203) 366-3234

Gage Calibrator

Arizona Tool & Die
31 East Rillito
Tucson, AZ 85705
Tel. (602) 623-8842

High Magnification Microscope

Leitz GMBH
D-6330 Wetzlar
Rockleight, NJ 07647
Tel. (201) 767-1100

Reichert-Wien
William J. Hacker & Co., Inc.
P.O. Box 646
West Caldwell, NJ 07006

Bausch & Lomb
One Lincoln First Square
Rochester, NY 14601
Tel. (716) 338-6000

Interference Microscopes

Gaetner Scientific Company
1267 Wrightwood Avenue
Chicago, IL 60614
Tel. (312) 281-5335

Nikon, Inc.
Sub. of Ehrenreich Photo-Optical Industry
623 Stewart Avenue
Garden City, NY 11530
Tel. (516) 222-0200

Unitron
Sub. of Ehrenreich Photo-Optical Industry
101 Crossways Park West
Woodbury, NY 11797
Tel. (516) 364-8046

Carl Ziess Inc.
444 Fifth Avenue
New York, NY 10018
Tel. (212) 730-4400

Wild Heerbrugg Instruments
465 Smith Street
Farmingdale, NY 11735
Tel. (516) 293-7400

Interferometers

Davidson Optronics
2223 Ramona Boulevard
West Covina, CA 91790
Tel. (213) 962-5181

The Ealing Corporation
22 Pleasant Street
South Natick, MA 01760
Tel. (617) 655-7000

Tinsley Laboratories
2448 Sixth Street
Berkeley, CA 94710
Tel. (415) 843-6836

Zygo Corporation
Laurel Brook Road
Middlefield, CT 06455
Tel. (203) 347-8507

Laser Unequal Path Interferometer

Tinsley Laboratories
2448 Sixth Street
Berkeley, CA 94710
Tel. (415) 843-6836

Laser Measuring System

Hewlett Packard
5301 Stevens Creek Blvd.
Santa Clara, CA 95050
Tel. (408) 249-7020

Reference Discs

Professional Instrument Company
4601 Highway 7
St. Louis Park
Minneapolis, MN 55416
Tel. (612) 927-4495

Pratt & Whitney
Charter Oak Boulevard
West Hartford, CT 06091
Tel. (203) 233-7561

Brown & Sharp
Industrial Products Division
Precision Park
North Kingstown, RI 02852
Tel. (401) 886-2000

Taft Pierce
32 Mechanic Avenue
Woonsocket, RI 02895
Tel. (401) 762-1000

Roundness Instruments

The Bendix Corporation
Automation & Measurements Division
P.O. Box 1127
Dayton, OH 45401
Tel. (513) 254-5377

Rank Taylor Hobson 7
P.O. Box 64
Stoughton Street
Leicester, England

See American Representatives listed on next page

Surface Analyzer - Profilometer

Clevite-Brush
37th and Perkins
Cleveland, OH 44114
Tel. (216) 361-3315

The Bendix Corporation
Automation & Measurements Division
P.O. Box 1127
Dayton, OH 45401
Tel. (513) 254-5377

Rank Taylor Hobson 7
P.O. Box 64
Stoughton Street
Leicester, England

Rank Precision Industries
411 Jarvis Street
Des Plaines, IL 60018
Tel. (312) 297-7720

Rank Precision Industries
260 North Route 303
West Nyack, NY 10994
Tel. (914) 358-4450

Potting Compounds - DPR 336

Hardman, Incorporated
Belleville, NJ 07109
Tel. (201) 751-3000

Potting Compounds - Rubberjel (Syringe)

L.D. Caulk Company
Division of Dentsply Int., Inc.
Milford, DE 19963
Tel. (302) 422-4511