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A CRITICAL REVIEW OF OPTIONS FOR TOOL AND WORKPIECE SENSING

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Final technical report for MMT projects 6848416 and 6858416, Flexible Manufacturing System with Special Tooling. First of four technical reports for RIA contract number DAAA08-87-C-0136.

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The first interim report, "A Critical Review of Options for Tool and Workpiece Sensing," of a two-phase project identifies and analyzes existing and emerging state-of-the-art sensors for assessing and forecasting the condition of cutting tools and for measuring the dimensions and surface finish of workpieces. The goal of the project is to provide a versatile means to use the sensor data for reducing manufacturing costs and improving the quality of parts in production at the Rock Island Arsenal and other similar facilities. The study concludes that to minimize the number of sensors and the frequency of their use, an integrated system is needed in which the sensor outputs are fused by an algorithm and used in a mathematical model that automatically adapts to the changing process, tool, and workpiece conditions. The report defines integrated sensor systems for rotary and stationary cutters and recommends six sensor types for performance suitability verification by bench-top experimental tests. The next scheduled interim report will present the results of these tests, and the Phase I final report will provide conceptual designs and recommend a system

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configuration for evaluation in Phase II. Under Phase II, the selected sensor system will be demonstrated as an integral part of an automated machining system.

SUMMARY

To remain competitive globally, American manufacturers must rely on automated facilities to produce an increasing percentage of their products. Driven by cost savings and quality goals, the products being shifted to automated facilities show a trend toward increasing complexity due to assemblies with fewer, more complicated components that have more critical features and tighter tolerances. While the technical aspects of manufacturing these products are increasing in complexity, the economics of competition make it unlikely that operators will be assigned to run individual machines. With more product complexity and less human attention at the machine level, automatic monitoring and control of the machining process and the workpiece are essential if greater productivity and higher product quality are to be obtained.

There exists a great need for universally accepted, factory-hardened tool and workpiece sensor systems for on-machine use. Such sensor systems must be cost effective, accurate, and applicable to the current generation of machine tool controls in order to help revitalize the domestic machine tool market. They must function with both stationary and rotary tools, as well as be applicable to a broad range of workpiece materials such as alloys of steel or aluminum.

To meet these needs, machining systems equipped with sensors that provide repeatable control of dimensions and surface finish are required, since this generally leads to reliable functional performance of the product. The requirements for such systems dictate that they perform several critical tasks. They must ensure that the workpiece is set up correctly, compensate for out-of-tolerance trends, and stop the process if operator intervention is required. To avoid adding value to nonconforming parts, the control system must avoid processing new parts until any causes for nonconformance in previous parts are corrected. To make efficient use of costly cutting tools, the control system must consider the current state of the cutting tools and accurately forecast their remaining useful life. Equally important, the control system must know, as quickly as possible, if the first part of a batch of parts is a good part and, if not, what must be changed to make good parts.

Research has shown that it is very unlikely that the needs for tool and workpiece sensing can be met by a single sensor or even the combination of a single sensor and a process model. There are simply too many independent variables that influence the outcome. It appears inevitable that a satisfactory solution will combine data from multiple sensors with an adaptive mathematical model. Such a model would reduce the need for measuring every important variable. It would assist in interpreting multiple sensor data and forecast critical events based on a combination of current measurements and past experience. The model could then be used as a substitute for continuous monitoring.

The state-of-the-art means for first-part evaluation is an off-line computer-controlled coordinate measuring machine using a tactile sensor. This method has a major fault when used with fast, automated facilities. Since the turn-around time for such an off-line system is slow, inspection costs are high because the automated facility must wait until the off-line inspection confirms that the first part conforms to specifications. Although some machine tool builders have reduced this cost by providing spindle-mounted tactile sensors, these sensors have fundamental speed and accuracy

limitations. Consequently, the state of the art does not offer a satisfactory solution.

However, great strides towards developing factory-hardened sensors have been made in recent years. When combined with the recent increases in computational power and development of sophisticated, inexpensive signal processing algorithms and hardware, these new sensor types have led to successful prototypes and factory implementations of in-process control systems. Rock Island Arsenal (RIA) has recently sponsored the development of two in-process control systems: an in-process control of milling system and an in-process control of turning system [1,2].* Used for machining orifices, the milling system is installed in the RIA production facility and has resulted in a production increase by a factor of four and a scrap part reduction to almost zero. Used for processing large alloy steel parts, preliminary testing of the turning system has been completed, and test results indicate that substantial improvements will be achieved in reducing floor-to-floor time and in tightening dimensional control of critical features. Both of these systems use commercial sensors to gage workpiece dimensions as the cutting process proceeds.

Due to the success achieved with these sensor-based machine control systems, RIA is now involved in a program to increase both manufacturing productivity and part quality by focusing on product improvements that can be obtained from tool and workpiece sensing. This program has been initiated to seek solutions to the manufacturing problems and technology needs outlined above. With these elements in mind, the specific goals of the tool and workpiece sensing program are to:

- Identify, develop, and demonstrate tool and workpiece sensing systems that will both advance the state of the art and be suitable for integration with the current generation of American machine tools

- Select sensors that can be applied to stationary or rotary tools for a variety of workpiece materials

- Develop sensor systems that can:
  - Detect broken or worn tools
  - Estimate the end of the cutting edge's useful life
  - Optimize tool life
  - Prevent out-of-tolerance and surface-damaged parts
  - Measure workpiece dimensions and surface finish for on-machine part acceptance

- Factory harden the sensor systems so they will be acceptable to the manufacturing community

- Use the sensor information to help control the process so that only good parts are manufactured.

The program is structured in two phases. Phase I activity will determine sensor system options and will assess the performance and feasibility of application of the selected sensing options for machining processes. Phase II

*Numbers in brackets designate references presented after Section 6.0.

activity will design, build, and evaluate a factory-hardened sensor system as an integrated part of an automated machining system.

In addition to the above goals, this program is focused on obtaining a meaningful measurement of tool wear. Because of the demonstrated successes with workpiece dimensional measurements and recent accomplishments with surface finish measurement by the National Institute of Standards and Technology (NIST) and others, measurement of tool wear is considered the greatest remaining challenge. Tool wear is a highly complex process with many variables interacting in a hostile environment. Although there are solutions to a limited class of tool wear cases, a comprehensive, satisfactory solution does not exist. While tool wear measurement represents a significant challenge, it also presents a significant opportunity. Development of a widely applicable and cost-effective method to sense tool wear could result in a 40% reduction in tool costs [3].

Since the hardware and software elements for developing a successful system are in hand, the time is right for a research program to address the problems inherent in controlling machining processes. When tool wear sensing is combined with other sensor outputs such as workpiece measurements, cutting forces, and machine vibration and these results are used in conjunction with an adaptive process model, a very powerful tool will be available to control machining processes. Process control achieved with these types of advanced technology can lead to a consistently higher level of product quality at lower cost than can be obtained with today's technology. This concept sets the ultimate program goal -- to produce the first factory-hardened version of a tool and workpiece monitoring and control system based on advanced sensing technologies.

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PREFACE

The work described in this report was performed under the direction of Mr. J.T. McCabe for the Engineering Directorate of the Rock Island Arsenal (RIA) by the Machining Programs Office, Shaker Research Division of Mechanical Technology Incorporated (MTI). This project is part of the U.S. Army's Manufacturing Methods and Technology (MM&T) Program.

The Project Manager for MTI is Mr. R.W. Gamache and the Project Engineer for RIA is Dr. J. Moriarty.

The authors wish to thank Dr. J. Moriarty and Mr. R. Kaikan of the Rock Island Arsenal for their guidance, insight into the practical aspects of factory floor implementation of advanced sensing systems, and for their thorough review and many constructive comments on this work.

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1.0 INTRODUCTION

This document presents the first Phase I interim report (CDRL A001) prepared by Mechanical Technology Incorporated (MTI) for Rock Island Arsenal (RIA) under contract DAAA08-87-C-0136.

The program is structured in two phases. Phase I activity will determine sensor system options for tools and workpieces and will develop and prove the principles of application of the selected options for machining processes. Phase II activity will design, build, and evaluate a factory-hardened sensor system as an integrated part of an automated machining system.

The Phase I activity reported herein addresses:

- A discussion of the measurement and process model approaches necessary to establish a system architecture
- Literature survey of the state of the art of sensor types for tool and workpiece sensing. This includes a summary of the operational characteristics of the candidate sensors
- A detailed evaluation of the candidate sensor types to identify those sensors recommended for application testing. Several sensors that require further development are recommended
- Test plans for those sensors that require further development
- A summary of vendor data for commercially available sensor systems.

The second Phase I interim report will cover the results of the test plans outlined in Section 5.0. The Phase I final report will include conceptual designs for selected sensing systems as well as describe all Phase I activity.

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2.0 APPROACHES TO SYSTEM ARCHITECTURE

To achieve the goals of untended machining and on-machine inspection, basic choices as to measurement and process model approaches must be made to determine the system architecture for a tool and workpiece sensing system. This section presents an overview of these approaches and then outlines the proposed system architecture based on this discussion. The concepts discussed herein reflect the results of the literature survey and contributions by both in-house experts and outside consultants.

2.1 Approaches to Measurement

To determine the system architecture, choices must be made as to the measurement approach or combination of approaches that will best meet RIA application needs. Two general approaches are possible in the measurement by a sensor of any physical quantity such as tool wear: direct measurement and indirect measurement. Each of these can be generally characterized by contact or noncontact, where contact requires the sensing device and the object being measured to exert a finite force on each other. The desired rates for data acquisition and the large quantity of data desired make wear of the sensing device a limiting factor for the application of contact sensing. Therefore, where ever possible, noncontacting sensing is preferred in the current application.

Direct measurement is a process in which data are taken by actual observation of the desired quantity, for example, measurement of tool wear using a measuring microscope. The accuracy of a direct measurement is limited only by the accuracy of the instrument/operator. With indirect measurement, the desired parameter is estimated by observation of some other parameter(s) which is presumed to bear a known relationship to the desired parameter. For example, one of the first indirect measurements of tool wear was obtained from the temperature data provided by the natural thermocouple formed at the tool-workpiece interface when the tool and workpiece are different materials [30,1]. One of the problems with this method is that the actual temperature observed is a factor of a number of quantities such as materials, geometry, presence of coolant, and speeds and feeds. In order to precisely predict temperature as a function of wear, a comprehensive model of the complex cutting process would be required.

By its very nature, a direct measurement approach is preferred since a direct sensor actually "sees" the desired parameter. Although from a purely technical standpoint one would choose a direct approach, several practical disadvantages have been associated with it:

- Inability to make in-process measurements due to obscuration or motion
- Noncutting machine time consumed by the measurements
- Additional fixturing and precision motions are often required
- Cost and complexity of the sensors and their associated electronics.

However, in the workpiece sensing area, several direct sensor types have been applied on-machine to in-process applications. Related programs for RIA have successfully used direct noncontact workpiece dimension sensing techniques for in-process control of milling and turning [1,2].

For certain aspects of tool and workpiece sensing systems, direct measurement sensors would provide distinct advantages over indirect sensors. However, the indirect measurement approach also has certain features that recommend its use. Since many indirect approaches are applicable while cutting, the cutting process could be monitored to detect other events such as tool breakage, tool chipping, excessive machine vibration or improper chip formation. For this reason and due to the complex nature of tool geometries, most of the research in the past 20 years has centered on indirect approaches for tool and workpiece sensing, especially in the area of tool wear measurement. Variables such as acoustic emission, cutting forces, spindle power draw, sound, temperature, and vibration have been measured in an attempt to estimate tool wear. Much of the documented research has attempted to empirically relate change in one of these variables to the progression of wear, as measured directly. Because of the large number of parameters that affect these variables such as machine stiffness, built-up cutter edges, workpiece hardness, process variables, tool material, and fixturing, success has been mixed. Direct, repeatable correlations have been found to exist only in certain well-behaved applications. Usually the sensing system must be taught specific characteristic signatures of the normal process and then to compare the current situation to the learned behavior. Several commercial systems based on force-related variables or acoustic emission are available to measure breakage and/or wear and may achieve some degree of success in constrained situations (see Section 6.0 for a discussion of these commercial systems).

2.2 Approaches to Process Models

Selection of a process model is another basic consideration in determining the system architecture. Two types of process model approaches are considered: analytical and empirical.

An analytical approach attempts to fully describe a process in terms of equations developed from physical theories. In an attempt to generate more accurate estimates of tool wear than the purely empirical single-variable approaches, analytic models of the cutting process have been developed [6]. Because of the complexity of the cutting process, these models are generally simplifications of the process (no coolant, infinite stiffness, etc.) and require the measurement of several indirect variables such as temperature, forces, and strains to provide an accurate estimation of wear. Many of these variables, for example, the tool-workpiece interface temperature, are difficult or impossible to ascertain with any precision. However, even if a suitable analytical model were developed and the required variables could be measured, the computing power and complex ancilliary hardware required to solve such a comprehensive system of equations would probably be greater than could be practically applied to the problem.

In the empirical approach, one attempts to experimentally establish the relationship between the measured variable(s) and the desired quantity. While much of the published work has centered on this method, usually looking at only one variable, most experts in the tool wear field today believe that the cutting process is too complex to be characterized by one or two variables except for restricted cases.

Either of the two approaches discussed above may be invariant or adaptive models. In an invariant model, the relationship between outputs and inputs does not change over time. Most models being researched or in use today are of the invariant type. In an adaptive model, the outputs are functions not only of the inputs but of recent historical data and possibly time. For the RIA applications, the attraction of an adaptive model lies in its similarity to the actual function of a skilled machine tool operator. It is generally acknowledged that experienced machine tool operators can recognize worn tools from a variety of sensory output emanating from the machining process. Further, their ability to estimate wear becomes better through increasing experience with a particular process, in effect, the operator is using an adaptive model. If an operator experienced with a particular process and machine is then faced with a new machine and a different machining process, his ability to estimate wear will be limited until he has gathered enough data to adapt his model.

As discussed above, there are process parameters in the machining environment that change over time and affect the output of an individual sensor. For example, tool geometry or a different coating can change the force profile seen by an indirect force sensor. Statistical trending of the data, with resulting modifications to the adaptive model when the confidence is high that a change is warranted, has the potential to overcome this problem and ensure more accurate results. Models of this type have been proposed by Wu and others [1,7,8,9].

2.3 Concept of Multiple Sensors and Sensor Fusion

A tool and workpiece sensing system that enables untended machining must measure the progression of tool wear, predict tool end of life, and detect incipient or actual tool breakage. A comprehensive system would also detect excessive vibration, workpiece hardness variations, chipped cutting edges, or other similar conditions that require process abort or an unscheduled tool change. In addition, the system must enable on-machine inspection, which requires measurement of selected workpiece dimensions and workpiece surface finish.

In view of these requirements, an integrated system should probably be equipped with sensors that perform:

- Between-cut direct measurement of tool wear
- In-cut measurement of the cutting forces, torques, or vibrations to supplement the tool wear measurement and detect tool breakage and related conditions
- On-machine measurement of workpiece dimensions independent of the accuracy and repeatability limitations imposed by the machine positioning system
- On-machine measurement of workpiece surface finish.

Since tool wear, workpiece dimension, and workpiece surface finish are related and since many of the measurements, especially indirect measurement of tool wear and surface finish, are affected by process conditions as well as the desired quantity, it has been suggested by Wu and others [8,9] that a technique called sensor fusion be used to meet the above measurement requirements.

Sensor fusion involves integrating data from multiple sensors into a pattern vector rather than looking at data from each sensor separately. Correlations are made between the pattern vector and the desired parameters, as determined by other means. Statistical mathematical methods are used to discover the relationship between the pattern vectors and the desired output, in this case, tool wear. An example of sensor fusion as applied to drilling follows and was taken from work conducted under Wu [8].

In this example, vertical acceleration and thrust data from two sensors are combined mathematically in a process called sensor fusion. The use of sensor fusion allowed tool end of life to be determined more accurately than if data from either sensor were used alone. Neural networks have also shown potential to perform sensor fusion in a tool wear estimation context.

2.4 System Architecture

Based on the above discussion, the proposed system architecture is shown in Fig. 1. The following measurement and process model approaches are recommended:

- A direct sensor to measure key workpiece dimensions. The optical shadowing sensor used to enable in-process control in RIA contract DAAA08-83-C-0052 would be considered a candidate for a turning application [2].

- A sensor to measure workpiece surface finish. An ultrasonic method based on high frequency ultrasonic scattering would be considered a candidate. Research conducted on this technique by NIST indicates that it is suitable for on-line measurement over the range of interest to RIA (20 to 150 μin. R_a) [10,11].

- Multiple sensors to measure the progression of tool wear to predict tool end of life and sense tool breakage. It is anticipated that direct between-cut tool wear measurement sensor data will be combined with multiple indirect on-line measurement sensor data (components of cutting forces, feed forces, thrusts, vibration, horsepower, or cutting time) and the output of the workpiece sensors using sensor fusion techniques in conjunction with an adaptive process model.

- Statistical or other suitable processing to find and incorporate correlations in trended data into the adaptive process model. An example might be the extraction of machine volumetric error data from workpiece dimension and tool wear data. These correlations could be used to compensate cutter path for machine errors as well as tool wear.

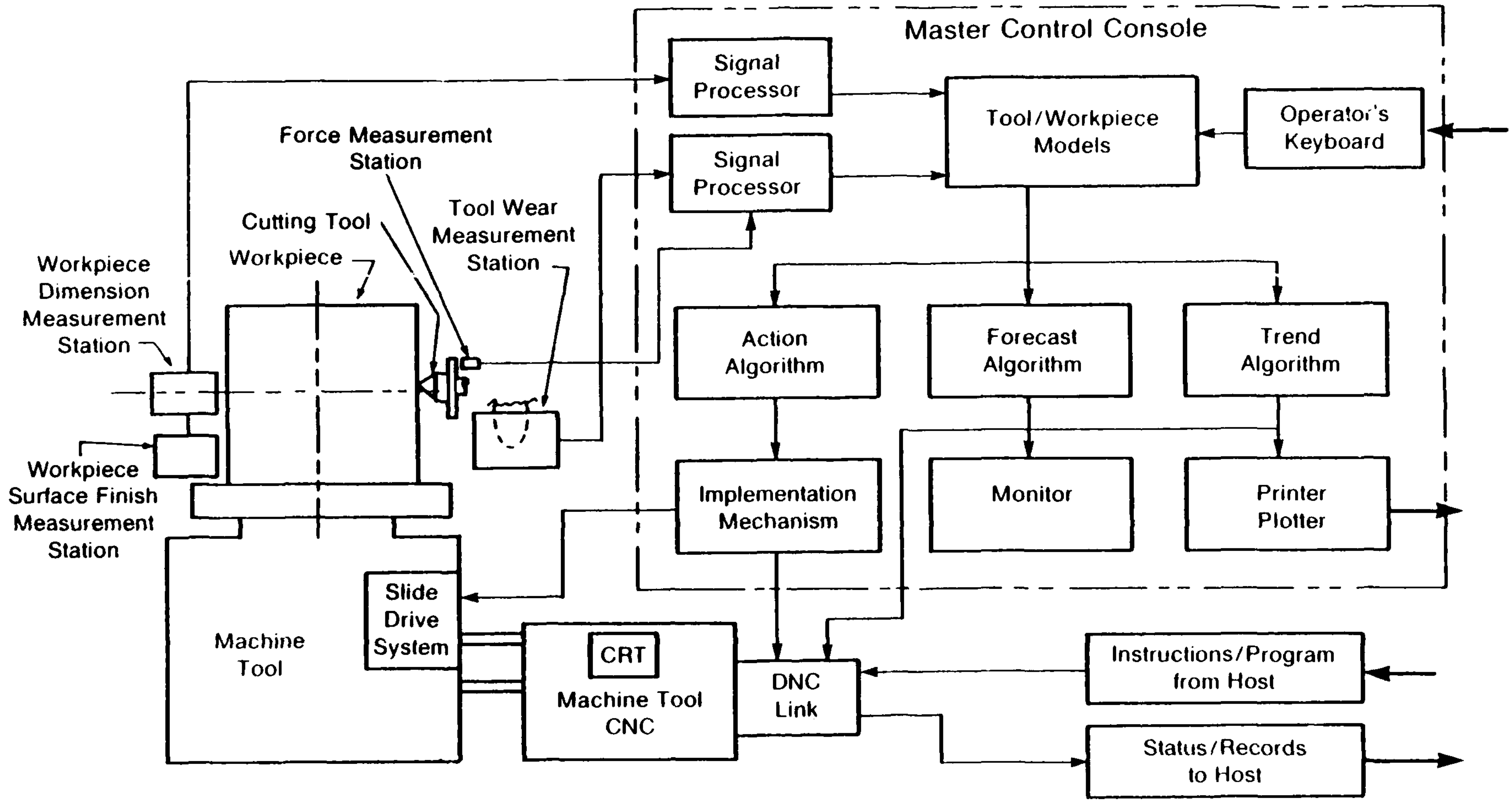

Figure 1. Proposed integrated tool and workpiece sensing system.

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3.0 DISCUSSION OF SENSOR TYPES

This section presents the results of a survey conducted to evaluate sensor types that show the greatest potential to address RIA applications at a reasonable cost and risk. Sensors were evaluated for their applicability to tool wear, workpiece dimension, and workpiece surface finish measurement.

3.1 Survey Methodology

Information for the survey was gathered from several sources, including published literature, in-house experts, external consultants, and conferences. The literature survey began with the 1975 survey of state-of-the-art sensor technology conducted by Cook, Subramanian, and Basile [5]. A search of the worldwide literature published after 1975 in the areas of tool wear, wear models, adaptive control, sensors, surface finish measurement, and dimensional measurements was used to bring the published background established by Reference 5 up to date. A panel of MTI experts in the areas of sensors, sensor applications, data acquisition systems, and manufacturing technology reviewed and participated in distillation of the published work. The panel also helped rank order the sensor types according to their potential for RIA applications. Two consultants, Dr. S.M. Wu and Dr. B.F. Von Turkovich, renowned researchers in the areas of tool wear, statistical modeling, and adaptive control, provided their insights on the proposed integrated sensing system. They also commented on appropriate statistical model-based approaches to relate the sensed data with other measured or specified process variables to produce desired outputs (e.g., tool wear or tool life index). In addition, several conferences and workshops dealing with sensors for manufacturing applications were attended [12,13,14], and follow-up contacts were made with vendors.

3.2 Sensor Types Considered for Evaluation

The complete list of the sensing methods considered for evaluation is shown in TABLE 1 and includes commercially available as well as developmental sensor types. A first cut to this list was made based on the literature survey and review by in-house experts. RIA's preference for direct, noncontact, in-process sensors was a major factor in the selection process. In the context of this project, in-process sensing means the sensing is performed simultaneously with metal cutting, without interfering with the cutting. Intraprocess sensing means sensing that is performed on the tool after it has been retracted from the workpiece between cuts. Characteristics that eliminated a sensor type from further evaluation included such factors as:

- Inadequate performance
- Unrealistic limitations to process such as no coolant, continuous chips, and no built-up edge
- Unsuitability for factory use, for example, requirement for vibration-free environment
- Limited applicability, for example, only useful for heavy drilling.

Specific reasons for why a sensor type was disqualified are given in TABLE 1.

Based on RIA program objectives, the initial cut produced a list of candidate sensor types for detailed evaluation (see TABLE 2), and these are the subject of the remainder of this section. Although a particular sensor may not be

TABLE 1. Sensor Types Considered.

Sensor Type	Computed Parameter[1] Tool Wear	Workpiece Dimension	Workpiece Surface Finish	Measurement Type[2] Direct	Non-Contact	In Process	Summary[3]
Acoustic Emission	S,M,D					x	C
Air Gage LVDT	S	S,M			x		R[4, 5, 6]
Bearing Deflectometer	S,M,D					x	C
Capacitance	S	S,M		X	X		C
Conductive Elastomer	S			X			R[4]
Contact LVDT Family	S	S,M		X			C
Conventional Machine Vision	S,M,D	S,M,D	M	X	X		C
Eddy Current		S,M					R[4, 7]
Fiber Optic Edge Detector	S			X	X		C
Fiber Optic Proximity Array	S,M		S,M	X	X		C
Fiber Optic Surface Follower	S	S		X	X	x	R[4, 8]
Holography	S,M,D	S,M,D			X	x	R[9, 10]
Infrared Imaging	S,M,D					x	R[8]
Infrared Point	S,M,D				X		R[8]
Laser Interferometry		S,M		X			R[5, 9, 10, 11]
Laser Radar	S	S,M			X		R[4, 7, 9]
Laser Velocimeter	S,M,D			X	X	x	R[9]
Load Cell Force Measurement	S,M,D					x	C
Microwave Reflection			M				R[5, 6, 7, 9, 10, 11, 12]

1 S = stationary tool application, M and D = milling and drilling, respectively, of rotary tool application.
2 Sensors that are not direct, noncontact, or in-process are assumed to be indirect, contact, or between-cut/off-machine types.
3 C = candidate for further evaluation, R = unacceptable for reason(s) noted in footnotes 4 through 12.
4 Inadequate peformance.
5 Unique fixture/setup for each tool/workpiece.
6 Little growth potential.
7 Limited applicability.

TABLE 1. (Continued).

Sensor Type	Computed Parameter: Tool Wear	Computed Parameter: Workpiece Dimension	Computed Parameter: Workpiece Surface Finish	Measurement Type: Direct	Measurement Type: Non Contact	Measurement Type: In Process	[illegible]
One-Dimensional (1D) Projection Machine Vision	S,M,D			X	X		C
Optical Profilometer		S,M,D	S,M		X		R^{4}
Optical Shadowing		S		X	X	X	C
Optical Scattering			S,M		X	X	C
Photogrammetry	S,M,D	S,M,D		X	X		$R^{6,11,12}$
Point Range Triangulation	S	S,M,D		X	X	X	C
Power	S,M,D				X	X	$R^{4,7}$
Projection Interferometry	S,M,D	S,M,D		X	X		C
Radioactive Tagging	S,M,D			X			$R^{4,6,13,14}$
Resistance	S					X	R^{4}
Sound Measurement	S,M,D						$R^{4,7}$
Speckle Interferometry							$R^{5,8,9,10,11}$
Structured Light Machine Vision	S,M,D	S,M,D		X	X	X	C
Stylus Profilometer		S,M	S,M	X			$R^{7,9,11,12}$
Thermocouples	S					X	R^{4}
Toolmaker's Microscope	S,M,D			X			$R^{4,6,11,12}$
Torque	S,M,D				X	X	$R^{4,7}$
Touch Trigger Probe	S	M,D		X			C
Ultrasonic Scattering		S,M	S,M			X	C^{15}
Vibration	S,M,D						$R^{4,7}$

[8] Impractical.
[9] Not cost effective.
[10] Unsuitable for factory use.
[11] Significantly increases process cycle time.
[12] Removal of tool/workpiece to perform measurements.
[13] Modification to tool/workpiece.
[14] Serious actual/perceived safety hazard.
[15] For workpiece surface finish only.

TABLE 2. Sensor Types Selected for Evaluation.

Sensor Type	Computed Parameter[1] Tool Wear	Workpiece Dimension	Workpiece Surface Finish	Measurement Type[2] Direct	Non Contact	In-Process
Acoustic Emission	S,M,D					x
Bearing Deflectometer	S,M,D					x
Capacitance	S	S,M		x	x	
Contact LVDT Family	S	S,M		x		
Conventional Machine Vision	S,M,D	S,M,D	M	x	x	
Fiber Optic Edge Detector	S			x	x	
Fiber Optic Proximity Array	S,M		S,M	x	x	
Load Cell Force Measurement	S,M,D					x
One-Dimensional (1D) Projection Machine Vision	S,M,D			x	x	
Optical Shadowing		S		x	x	x
Optical Scattering			S,M		x	x
Point Range Triangulation	S	S,M,D		x	x	x
Projection Interferometry	S,M,D	S,M,D		x	x	
Structured Light Machine Vision	S,M,D	S,M,D		x	x	x
Touch Trigger Probe	S	M,D		x		
Ultrasonic Scattering		S,M	S,M			x

[1]S = stationary tool application, M and D = milling and drilling, respectively, of rotary tool application.
[2]Sensors that are not direct, noncontact, or in-process are assumed to be indirect, contact, or between-cut/off-machine types.

included on TABLE 2, this may not necessarily mean that it is unsuitable for the application but that it does not conform to the specific RIA program objectives. Note that several sensor types that are not listed in TABLE 2 as candidates have been included in the discussion. These were retained to illustrate the scope of the literature survey and also to establish readily identified reference or baseline for the candidate sensors. The sensor types are organized according to their applicability to direct or indirect tool wear, workpiece dimension, and workpiece surface finish measurement. A description of each sensor concept and general performance information (if available) is provided.

3.3 Discussion of Tool Wear

Before describing the individual sensor types evaluated for direct and indirect tool wear measurement, the forms of tool wear are reviewed briefly along with the sensor performance objectives used in the evaluation.

The gradual wear of cutting tools operated under cutting conditions appropriate for the tool occurs in three interrelated forms: crater wear, nose wear, and flank wear (see Fig. 2) [15]. The presence and degree of each form is dependent on feed, speed, tool material, work material, and depth of cut. In many cases, the measured wear information can be combined with tool geometry to indicate the degree of recession of the cutting edge from its initial state.

Of the forms of wear, the flank wear land width is considered most important to RIA. It is generally accepted that a tool is worn when the average (or maximum, if the wear is irregular) flank wear land width is in the range of 0.015 to 0.020 in. As for the other forms of wear, many researchers feel that crater wear can be minimized by proper selection of tool material and cutting conditions [16] and recession of the cutting edge can be compensated for by offsets applied to the part program.

Researchers have found that all tools possess a similar wear profile during their life as shown in Regions 1 to 3 in Fig. 3a [5]. Tool end of life is considered to be the transition between Regions 2 and 3, and tool life is found to vary generally with tool vendor/material, feed, and speed as indicated in Figs. 3b, 3c, and 3d, respectively [15].

Given this background, the objectives for tool wear measurement are to:

- Measure the progression of tool flank wear as determined from the slope of the curve in Fig. 3a
- Determine tool end of life as defined by the transition from Regions 2 to 3 in Fig. 3a.

In order to satisfy these objectives, the flank wear land width must be determined to an accuracy of 0.0005 in. over a range of 0.003 to 0.020 in.

3.4 Direct Tool Wear Measurement Sensor Types

Some direct tool wear measurement methods are unsuitable for tool and workpiece sensing systems because they require laboratory-type controls or

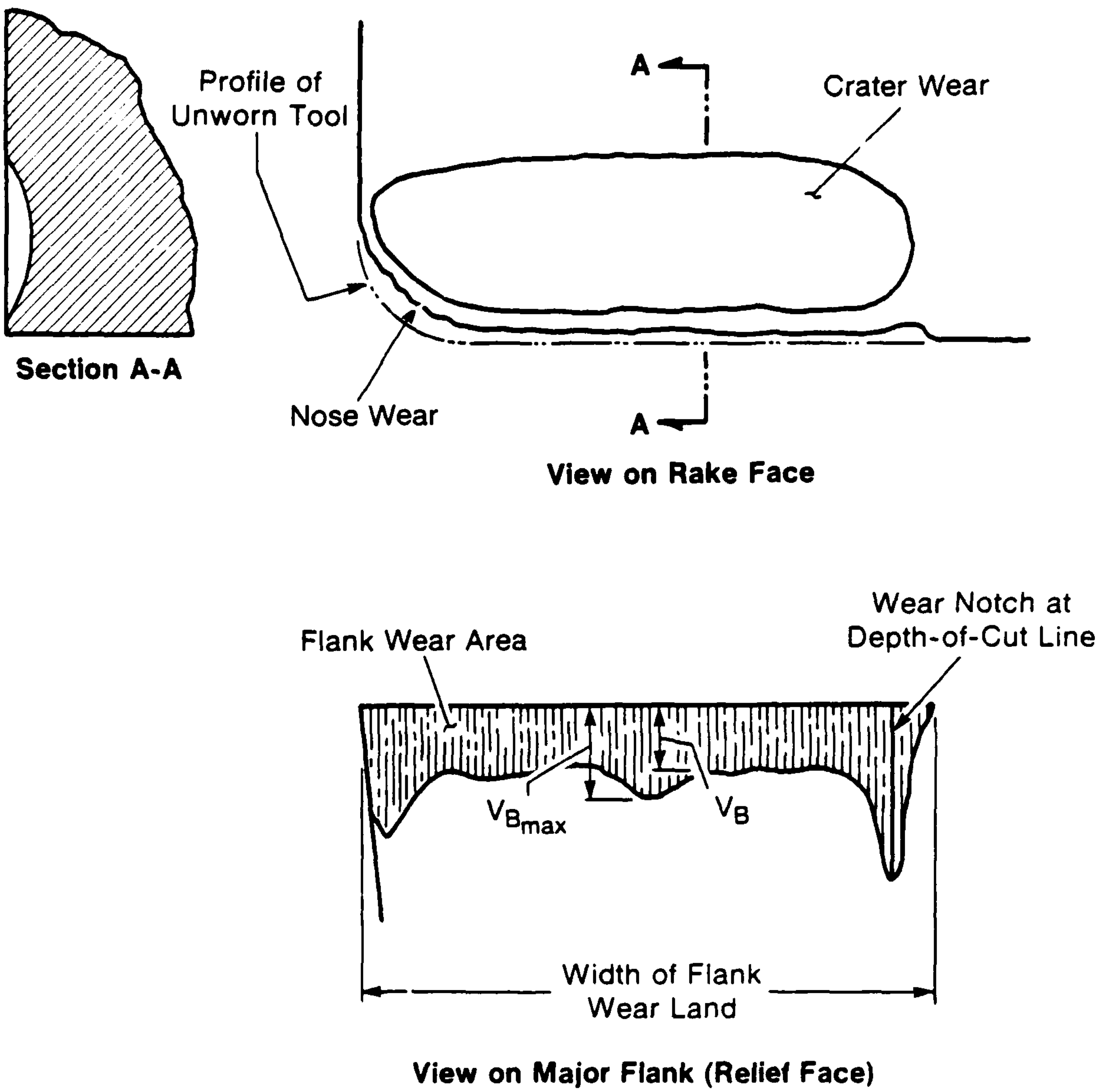

Figure 2. Forms of tool wear.

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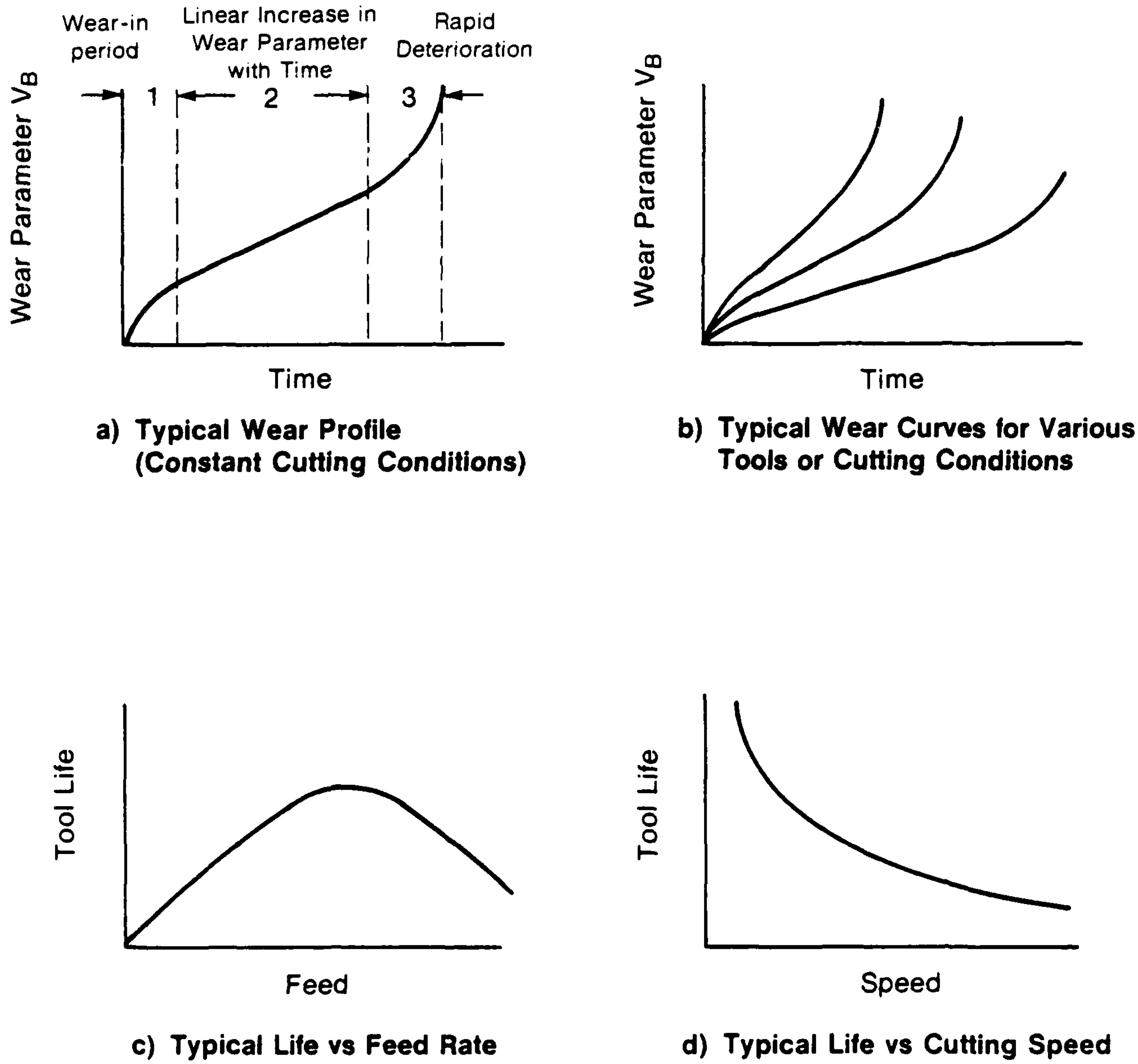

Figure 3. Characteristics of tool wear.

analysis or compensation for extraneous variables. Most of the following methods defined and discussed in Reference 5 are unsuitable:

- Direct measurement of the flank wear land
- Distance between tool support and workpiece
- Radioactive tagging
- Resistance
- Tool particles in chips
- Workpiece dimension changes.

It is interesting to note that there have been few additions to these basic methods in the 12 years since Reference 5 was published. Several of the direct methods listed above and discussed in Reference 5 show little promise because of technical or practical difficulties. Due to their stagnant state of development and poor prognosis for growth, they are discussed briefly below only to provide a complete overview of direct tool wear measurement methods.

- **Distance Between Tool Support and Workpiece** - This method uses the fact that the distance between the tool support and workpiece changes as the tool wears [5,18,19]. However, it is also sensitive to thermal expansion and relative flexing of tool and workpiece, machine way inaccuracies, and built-up material on the cutting edges. Compensation methods have been proposed by Takeyama [19] which require additional sensors to measure tool temperature and forces, but these additional variables are influenced by factors other than the parameters needed to apply the compensation (deflection and thermal expansion). This method offers the same level of potential and risk as indirect methods and is not recommended for RIA applications.
- **Radioactive Tagging** - Radioactive tagging with radioactive wear indicators provides only an end-of-life assessment and gives no information on the progression of wear. Although the amount used is minute, the use of radioactive materials on the production floor presents such practical problems with regard to safety and logistics that this method remains feasible for use only as a laboratory tool.
- **Resistance** - Systems have been implemented to measure the electrical resistance change between the tool and workpiece as wear progresses, and systems that modify the tool makeup to provide a resistance which changes in proportion to tool wear have also been investigated. These methods are considered impractical due to temperature effects on resistance, the modifications required to the tool, and extremely noisy signals. At present, resistance systems remain laboratory tools with low potential for development.
- **Tool Particles in Chips** - This method involves chemical analysis of chips to determine the amount of tool material present. Based on chip volume and knowledge of cutting conditions, the amount of tool wear can be estimated. This method requires complex off-machine analysis and is impractical for factory application.
- **Workpiece Dimension Changes** - This method has been applied to turning and grinding applications using rotating workpieces with good success. However, thermal growth and machine volumetric errors can result in inaccuracy, and surface finish may also affect results. Techniques such as optical shadowing that have been applied here are insensitive to many of the error sources indicated and have been used successfully in a production environment [2]. In many cases, in-process application of this method to prismatic parts is not straightforward and has not been researched in

detail, although some successes have been achieved in certain applications. This method also experiences problems taking measurements in the presence of coolant and chips.

The direct tool wear measurement sensor types that will be discussed in detail in the following subsections include:

- Capacitance
- Contact Linear Variable Differential Transformer (LVDT) Family
- Fiber Optic Sensors
  - Fiber Optic Edge Detector
  - Fiber Optic Proximity Array
  - Fiber Optic Surface Follower
- Laser Interferometry
- Laser Velocimeter
- Machine Vision
  - Conventional Machine Vision
  - One-Dimensional (1D) Projection Machine Vision
  - Structured Light Machine Vision
- Point Range Triangulation
- Projection Interferometry
- Touch Trigger Probe.

3.4.1 Capacitance

The electrical capacitance formed between a sensor and a target surface can be used to measure sensor-to-target displacement. Noncontact capacitance sensors use the target as one plate of a capacitor and operate on the principle that the capacitance of a pair of parallel plates is proportional to the plate area and inversely proportional to the distance between them (see Fig. 4). The capacitance is also proportional to the dielectric constant of the material separating them. Standard instruments are available which can measure the distance between a fixed area sensor and target surface with resolution and accuracy to 0.1% of the maximum gap. The maximum gap refers to the maximum distance between the sensor and target over which the response of the instrument is linear. The maximum gap depends on the face area of the active element and is typically between 0.001 and 0.010 in.

Fig. 5 depicts the possible application of a capacitance sensor to measurement of the flank wear land width for a stationary tool. The sensor consists of a rectangular surface aligned parallel to the unworn portion of the flank face. The width of the plate is slightly larger than the greatest depth of cut expected for the tool. If the wear measurement is made such that the distance between the sensor face and the tool is constant (the "sensing gap" shown in Fig. 4), the capacitance will change in proportion to the ratio of the tool volume worn away to the volume occupied by the sensor-to-target gap for the unworn tool.

Fig. 5 shows a sensor with a 0.01-in.^{2} active element area that might be used to measure the flank wear shown in this figure. Under the conditions shown in Fig. 5, the sensor would have an expected accuracy of 0.000005 in. (0.1% of gap), which easily exceeds the required accuracy of 0.0005 in. However, to attain the required accuracy, the sensor positioning mechanism error must be small compared to the required measurement accuracy, that is, it should be of

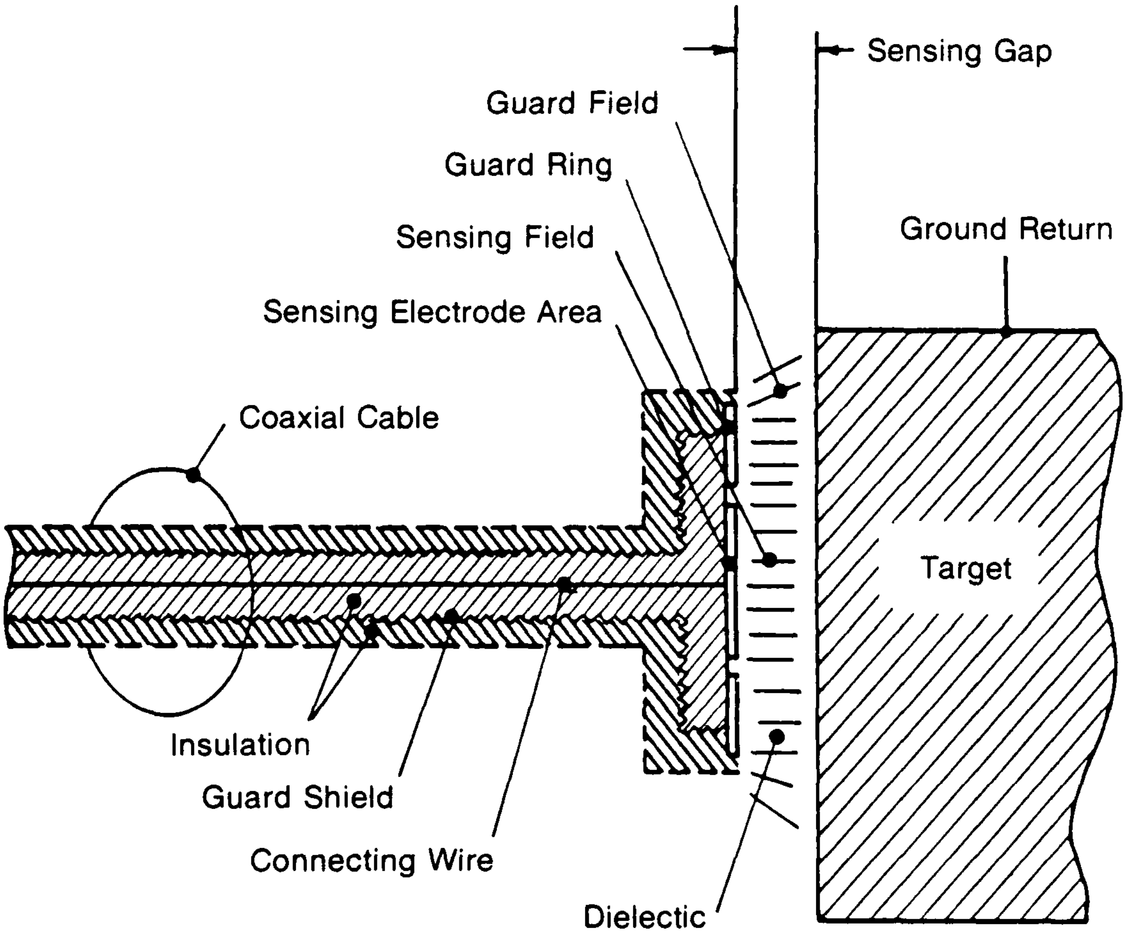

Figure 4. Capacitance concept.

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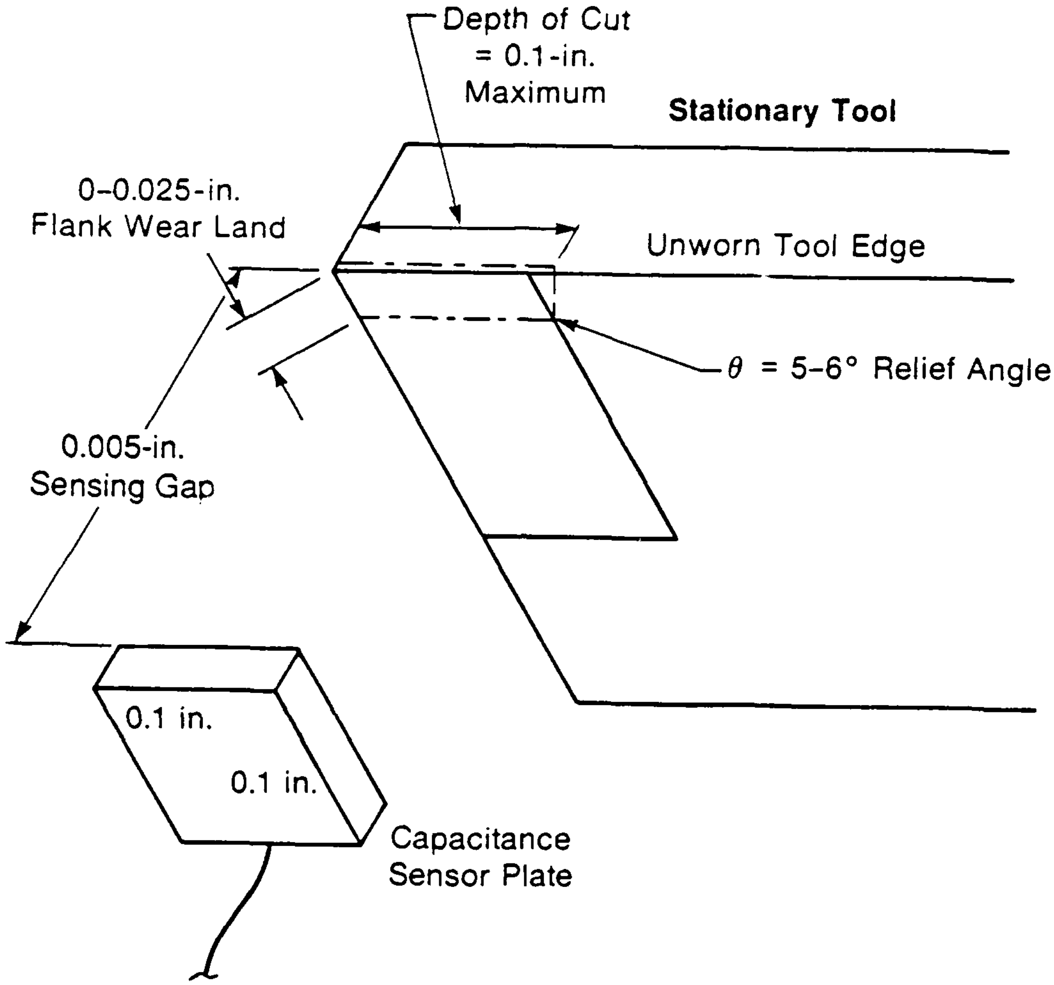

Figure 5. Tool wear measurement with capacitance sensor.

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the order of 0.00005 in. This requirement is beyond the accuracy of machine tool slides. A separate, high-precision mechanism is needed to position the sensor. Such complexity eliminates this sensor type from further consideration.

3.4.2 Contact LVDT Family

The contact LVDT sensor is perhaps better known as an electronic gage because it has often been used as a substitute for a dial position indicator. Its ruggedness and low cost have made it an attractive solution for applications where a continuous reading contact gage is appropriate, e.g., when the gage can be fixtured essentially parallel to the direction of minimum displacement and where excessive wear will not occur.

As shown in Fig. 6, the heart of the contact LVDT sensor consists of three cylindrical coils: one primary and two secondary coils. When the primary coil is energized, the iron core couples the magnetic energy into the two secondary coils, inducing a voltage in each. If these voltages are combined in an opposing sense, the net output is zero when the iron core is centered. The sensor core is connected to a stylus via a connecting rod, and the stylus contacts the workpiece. As the sensor core moves off center, the magnetic coupling between the primary coil and the secondary coil that the core is moving towards rises and thus increases the induced voltage. Conversely, the magnetic coupling between the primary coil and the secondary coil that the core is moving away from decreases and thus decreases the induced voltage. The resulting differential voltage varies linearly with position.

High-precision LVDTs use honed and selectively fit components with non-rotational cores. These sensors are rather small since they are typically 2-in. long and less than 0.5 in. in diameter. The contacting stylus is a ball tip of typically 0.156 in. in diameter. Repeatability better than 5 μin. can be achieved in sensors with a range of 0.100 in. and a typical linearity of ±0.2%.

Using different displacement sensing techniques, many variations of the LVDT are available such as capacitance, eddy current, fiber optic, laser interferometry, and others. The basic speed and performance limitations of this device are somewhat independent of the sensing technique in that they are determined by the finite size and mass of the stylus assembly. To measure flank wear land width in a lathe application, a linear positioning system is required to establish the profile of the wear area.

3.4.3 Fiber Optic Sensors

Fiber optic sensors such as MTI's Fotonic™ sensor have been applied to proximity, edge detection, and surface following tasks. The basic principles of operation of a fiber optic sensor are shown in Fig. 7 [20]. In its simplest form, a fiber optic sensor consists of a pair of fibers in close proximity. Light is conducted from a source through one fiber, called the transmitter, onto the target surface. A second fiber, called the receiver, intercepts some of the light reflected from the target as shown in Fig. 7a, and this light is converted into a proportional electrical signal. Fig. 7b shows the variation in electrical output as a function of sensor standoff from the target. In the region labeled "front slope," the output is proportional to standoff. Addi-

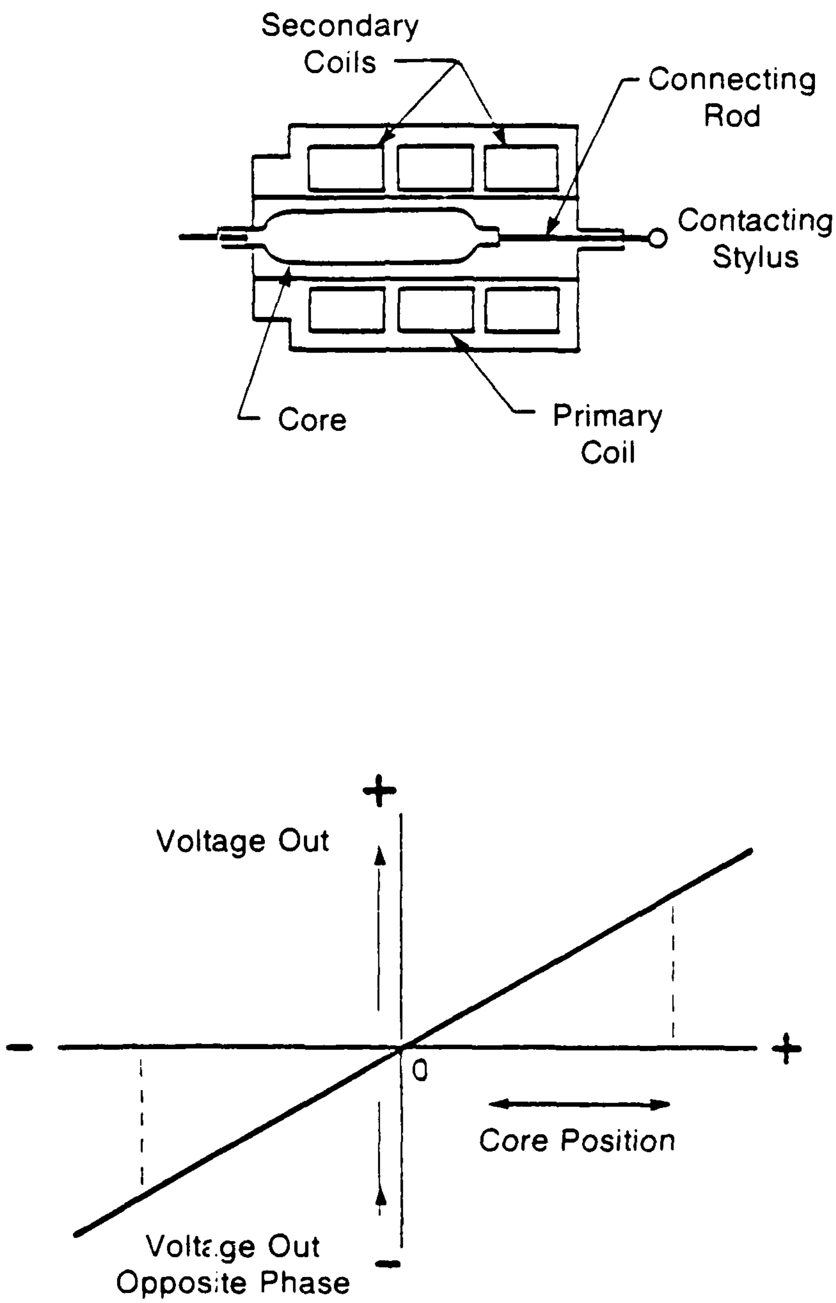

Figure 6. Contact LVDT family concept.

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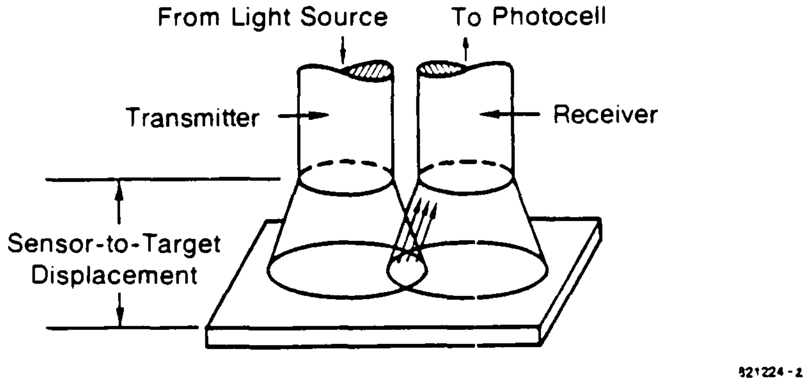
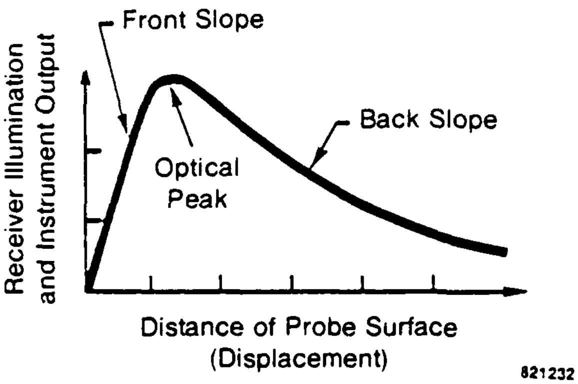
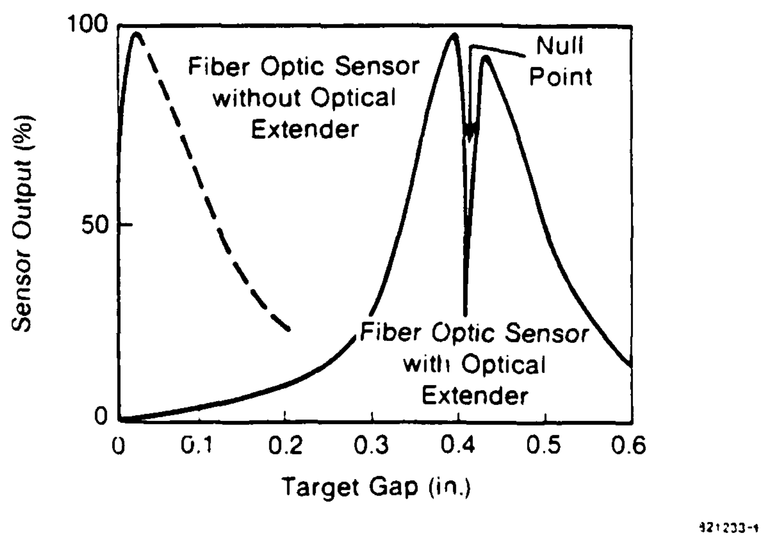


a) Basic Light Coupling Arrangement



b) Variation in Electrical Output



c) Output Affected by Optical Extender

Figure 7. Fiber optic sensor principles of operation. 881785

tion of a suitable projection lens assembly called an optical extender between the fiber optic sensor and the target produces the response shown in Fig. 7c.

3.4.3.1 Fiber Optic Edge Detector. A fiber optic edge detector has been applied to the measurement of flank wear on stationary tools [21]. An extension of this concept by MTI (patent pending) involves addition of an optical extender to achieve greater standoff and resolution. The measurement of flank wear involves finding two edges: the unworn edge of the tool and the transition on the relief face between the flank wear land and the unworn face. A fiber optic edge detector consists of a linear array of transmitting and receiving fibers that is imaged onto the flank face of the tool with a projection lens (see Fig. 8). The coupling between the transmitting and receiving fibers changes rapidly as the fiber image traverses breaks in the surface due to either distance changes or reflectivity differences.

In order to increase the sensitivity of the sensor to edges, the fibers are mounted on a bender bimorph. A direct current applied to the bender bimorph provides sufficient lateral deflection to allow traversal of the flank wear land area; an alternating current applied to the bender bimorph causes dynamic oscillation and produces a sharp peak in response to crossing an edge. Fig. 9 indicates the sensitivity of this method. Fig. 9a shows the sweep of the fiber optic sensor bundle over the edge of the worn tool. Fig. 9b shows the raw output of the sensor and Curve c indicates the processed output of the sensor which is proportional to the sensor output. Data taken by MTI reveal that this sensor type can achieve the accuracy and repeatability necessary for flank wear land width measurement on stationary tools.

3.4.3.2 Fiber Optic Proximity Array. The fiber optic proximity array offers a variation on the fiber optic edge detector for application to the measurement of flank land wear width measurement on both stationary and rotating cutters. With a fiber optic proximity array, a light source is imaged through a beam splitter onto the surface of the tool via a single fiber through a lens system using a patented approach (see Fig. 10a). Some of the reflected light is imaged onto detector I_1 via a lens system and a circle of fibers surrounding the transmitting fiber. A fraction of the light is returned from the target through the transmitting fiber, passed through the beam splitter, and imaged on detector I_2. The response of detectors I_1 and I_2 is shown on Fig. 10b. If the sensor output is taken as the scaled ratio of the detector outputs, the method provides reflectivity-compensated measurement of the distance to the target (E_0) according to the equation:

$$E_0 = \frac{I_2 - \alpha I_1}{I_2 + \alpha I_1}$$

If the target is a milling cutter rotated in front of the detector, a profile of the flank wear land will be produced in a time-varying displacement signal. If the point of fibers is now extended into a linear array of sufficient extent to image part of the unworn cutting edge, the flank wear land width can be measured, even in the presence of a built-up edge. A line of these sensors would also provide insensitivity (by averaging) to local variations in the flank wear land.

The basic concept of reflectivity-compensated displacement measurement has been proven and is covered by issued and pending MTI patents. Testing must be

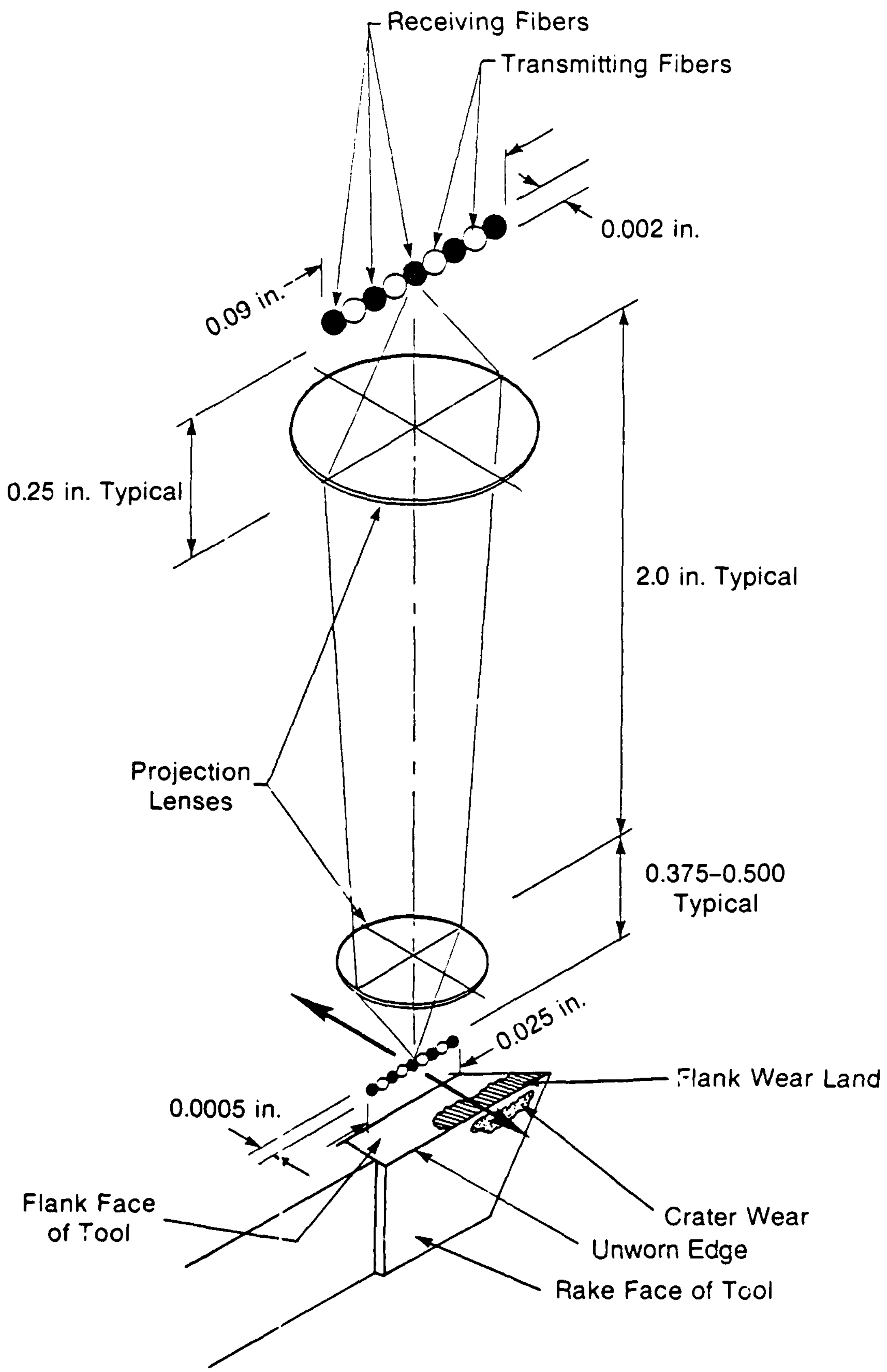


Figure 8. Fiber optic edge detector concept.

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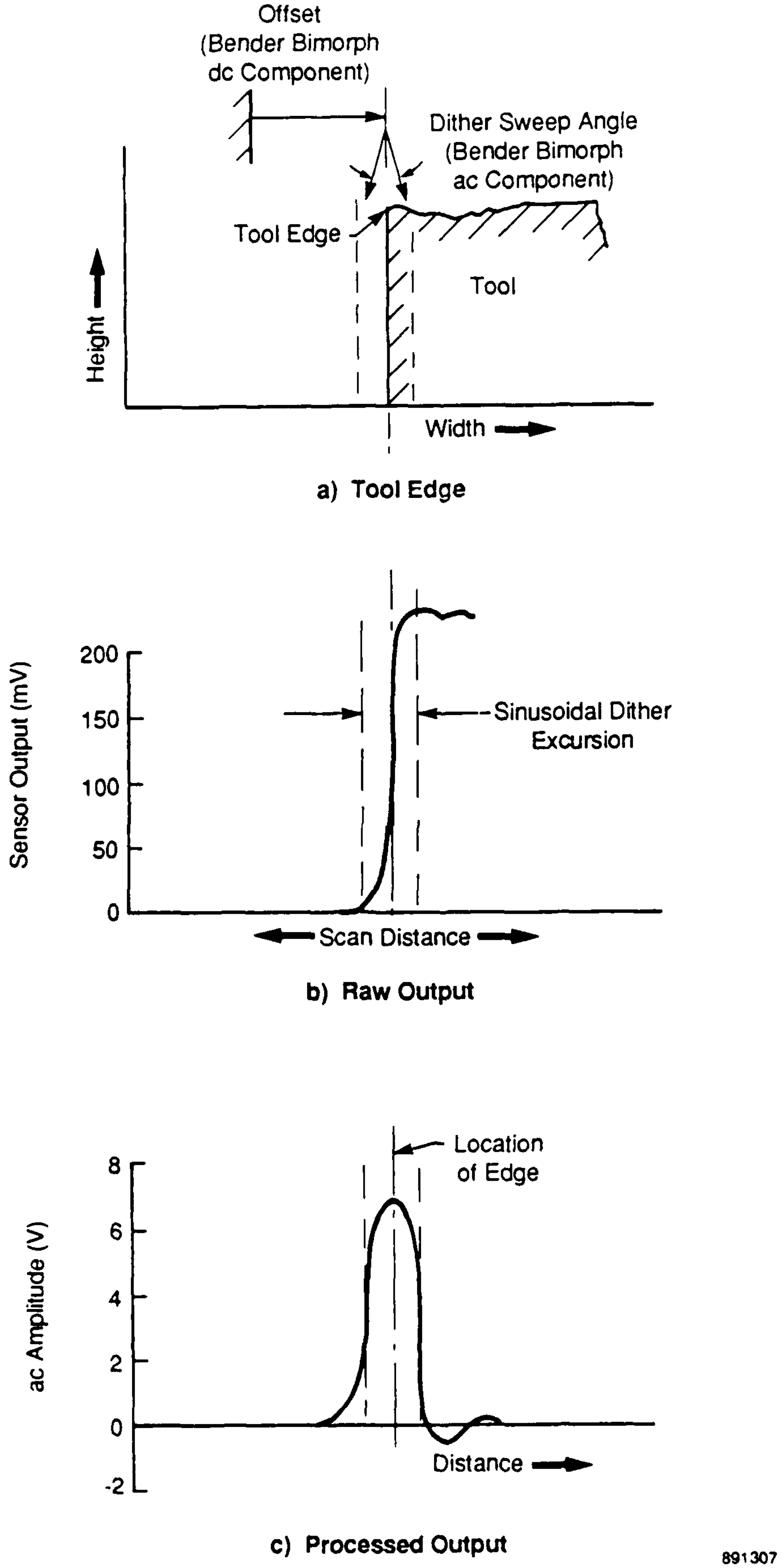
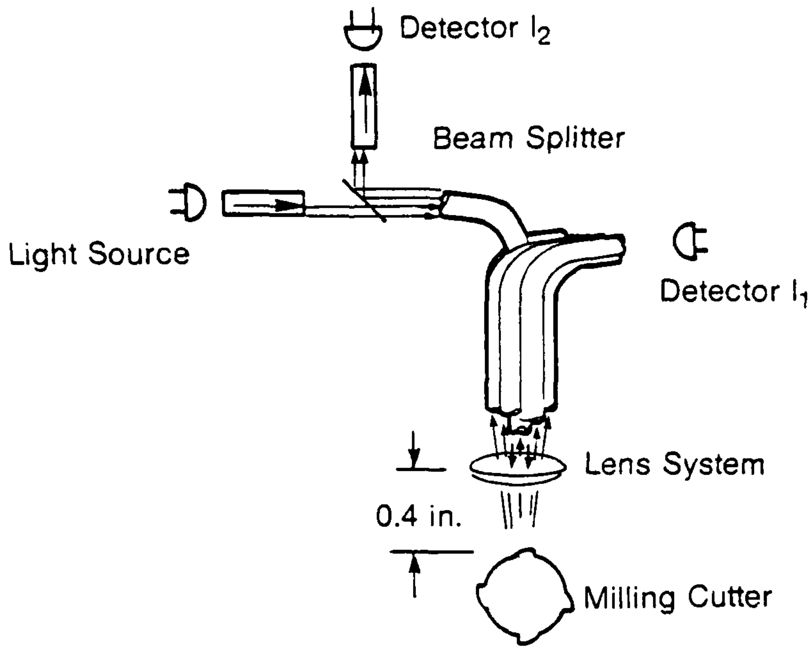
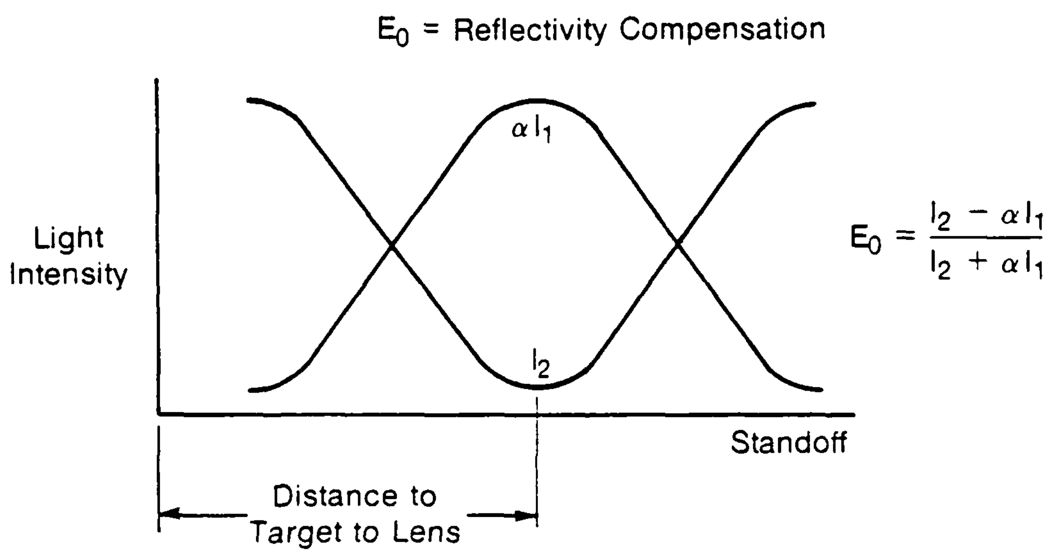


Figure 9. Sensitivity of fiber optic edge detector.



a) Configuration



b) Reflectivity-Compensated Measurement

Figure 10. Fiber optic proximity array concept.

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performed to ascertain the actual resolution and accuracy that can be obtained in its application to rotary tools.

3.4.3.3 Fiber Optic Surface Follower. Another variation on the fiber optic sensor developed by MTI, the fiber optic surface follower functions essentially as a noncontact surface profilometer [20]. Although not a candidate sensor type, this method is included in the discussion to provide a complete overview of the available fiber optic sensor technology.

As noted earlier, if an optical extender is placed in front of a fiber optic sensor, the response characteristic shown in Fig. 7c is produced. The right-hand portion of the response curve is similar to a standard curve without an optical extender, and the left-hand portion of the curve is almost a mirror image of the standard curve. The region where the curves join is characterized by a very sharp null point in the response output. The width of this null region is typically on the order of a few thousandths of an inch displacement. The distance from the lens to the target at the null point remains precisely fixed, even when target reflectivity variations cause the output amplitude to change.

When a sensor is operating at the null point, an image of the sensor face is projected onto the target. Light from the images of the transmitting fibers is reflected back along the same paths to their points of origin on the sensor face. In theory then, no light falls on the receiving fibers, which accounts for the minimum output. If the sensor-to-target distance is varied slightly in either direction, the image of the sensor face would defocus slightly, causing light from the transmitting fibers to be sensed by the receiving fibers. The sensor output would then rise rapidly as in the front slope region of a standard sensor without an optical extender (see Fig. 7c).

A fiber optic surface follower, however, provides the capability for continuously positioning a sensor to operate with a standoff precisely at the center of the null point. If the target surface moves towards or away from it, the sensor will stay locked on the null point and mirror the target movement. The target displacement is determined by measuring the sensor movement.

Fig. 11 shows the basic elements of this sensor type. A standard fiber optic sensor is configured with an optical extender to increase the standoff and to produce the characteristic response curve with a sharp null point. The fiber optic sensor electronics convert the optical information from the sensor fiber bundle into an electrical output using the relationship shown in Fig. 7c. A null detector circuit is used to determine whether or not the sensor is operating at the null point. If it is not, an error signal is generated that operates a rotary motor. The motor shaft is connected to a lead screw that repositions the sensor to the null position. The system operates as a closed loop, servo-controlled device that automatically positions the sensor to a fixed standoff. The actual system output is calibrated by measuring the displacement of the fiber optic sensor assembly with any conventional displacement sensor such as an LVDT or capacitance sensor.

In many applications, the sensor is capable of tracking a target displacement to resolutions of 10 μin. Spot size, that is, sensor footprint, can be as small as 0.005 in. in diameter. The sensor-to-target standoff is typically 0.15 in. and can be increased to 0.4 in. with special optics.

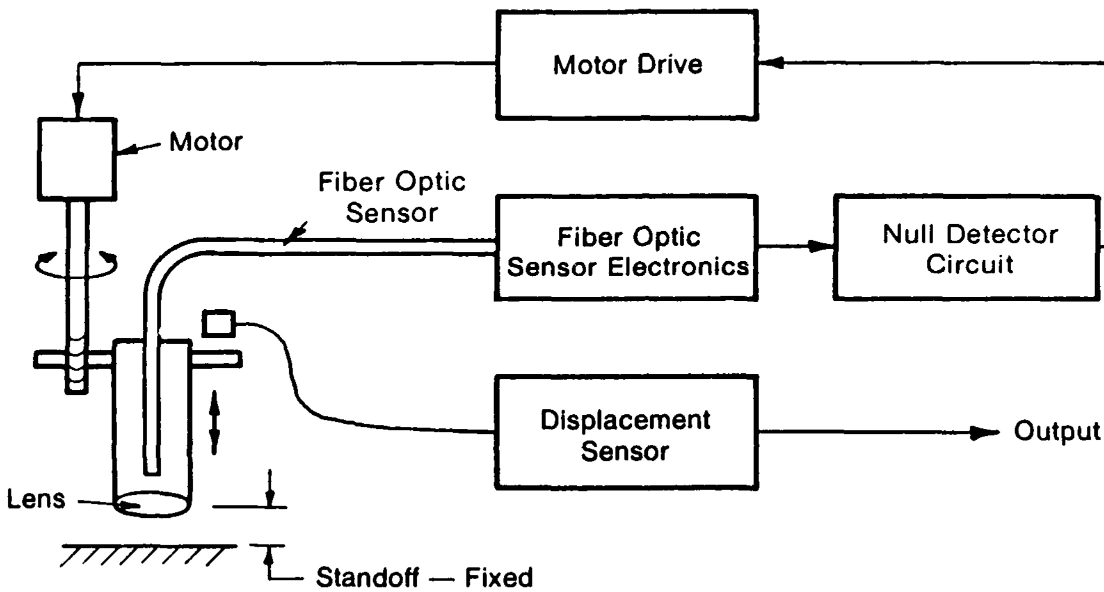

Figure 11. Fiber optic surface follower concept.

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The resolution and accuracy of this approach easily meets the requirements for flank wear land measurements on stationary tools. Since a fiber optic surface follower is essentially a point-type sensor, an additional linear positioning mechanism is required to provide the capability to profile the wear land area. Application to tool wear measurement requires a development effort to provide sufficient depth of focus to preclude the danger of servo runaway. Servo runaway is encountered when the target displacement is large such that the operating point is not on the "V"-shaped response curve that straddles the null point shown on Fig. 7c. Development of this sensor type would probably require design of custom optics and would be moderately risky.

3.4.4 Laser Interferometry

Although not a candidate sensor type, laser interferometry was considered to have potential for RIA applications during the early stages of the program and is included in the discussion for this reason. Conventional laser-based optical interferometers clearly have the resolution and accuracy required to measure tool wear. However, since they are point-type sensors that require a retroreflector mounted to the target being measured, upon closer examination they are not suitable for most RIA applications.

3.4.5 Laser Velocimeter

As with laser interferometry, the laser velocimeter was considered to have potential for the RIA application during the early stages of the program but has been eliminated from consideration for the reasons outlined below.

The laser Doppler velocimeter is an interferometric instrument (see Appendix A, pages A-20 through A-27). Through a beam splitter, a laser beam is aimed at two targets: one is moving and the other serves as a reference. In one of the two light paths, an acoustic-optic modulator introduces a frequency shift of 40 MHz. When the light reflected from the targets is superimposed and both targets are both motionless, the total light intensity shows a 40-MHz intensity modulation, which is measured with a photodiode. When the moving target vibrates, the 40-MHz frequency changes linearly with the target velocity, and a demodulator converts the shifted signal to an output signal proportional to the shift. Thus, an output proportional to target velocity is obtained. A second output proportional to target displacement is available and is generated by counting interference fringes that occur every time the target moves through a cycle of displacement.

Displacement measurement resolution is one-half wavelength or typically 10 μin. The sensor-to-target standoff is a function of the focal length of the lens and is typically 2 to 6 in. or greater if needed. The frequency response is also very high (1 MHz). The sensor weighs 0.2 to 2.5 lb, and the sensing head dimensions are 4 to 8 in. long and 1 to 3 in. in diameter, depending upon the lens used.

The sensor can be used to measure deflections caused by cutting forces. For rotary tools, the deflections are typically 100 to 1000 μin. However, depending upon where the sensing head is attached, other displacements can be added to the tool deflection. Therefore, the performance of this sensor type in measuring cutting forces is inferior to the direct methods of force sensing through load cells. An additional drawback is that, in practice, only a single sensor would be used, and thus only one force component would be sensed. The use of a two or more sensors in a differential sensing system that would compare the tool displacements to that of an adjacent object (the tool holder) would give more accurate force data. However, the greater complexity of the differential system renders it e en more unattractive than the single-sensor system.

For milling tools, the situation is even more complex. Deformation of the spindle and spindle bearings is added to deformation of the tool. Further, the sensor must be located such that it will see the deformation independent of how the cutter engages the workpiece. The information that can be obtained with a laser velocimeter can be measured with other proximity sensors or contacting sensors at a fraction of its cost and complexity. The applications which justify the high cost of this sensor are those that require high resolution, a large sensor head standoff distance, or a high frequency target.

3.4.6 Machine Vision

The state of the machine vision industry today is one of rapidly increasing maturity. Factory-usable hardware is emerging and is complemented by equally capable processing algorithms. This maturity is reflected in the increasing number of successful production line applications. Since a generalized approach to machine vision is not possible with today's hardware technology, solutions may well remain semicustom (at least in software) for some time in order to achieve acceptable table performance.

Fig. 12 shows the basic elements of a machine vision system. Cameras have either two-dimensional (2D) detectors, like a conventional television camera (see Appendix A, pages A-52 through A-58), with roughly 512 x 512 picture elements or pixels of resolution or one-dimensional (1D) detectors (line scan) with as many as 4096 pixels arranged in a linear array (see Appendix A, pages A-2 through A-5).

Illumination systems vary from conventional diffuse lighting, for example, ordinary room light, to structured patterns of light in the form of points or lines that are projected on the target. Lenses provide the necessary magnification or demagnification to focus the desired target area (field of view) onto the detector's sensor. Special vision processing hardware and software translate the large amount of raw data representing pixel gray-scale values into the desired measurement data, for example, the object's diameter. The choice between detector, illumination approach, optics, and specialized hardware and algorithms is usually governed by:

- Type and resolution of data to be extracted
- Required processing speed
- Surface and environmental properties of target such as temperature, reflectivity, texture, and motion
- Other environmental conditions such as ambient light, electrical noise, and others.

With a carefully designed and linearized system, resolution of 30 μin. at a standoff of 1 in. with overall accuracy better than 100 μin. has been achieved for inspection applications. Several variations of machine vision are appli-

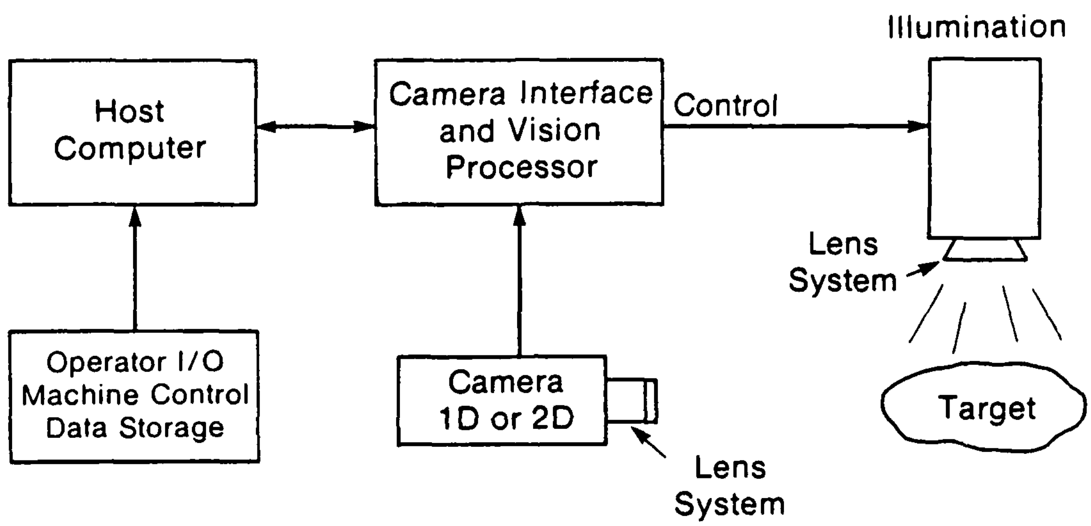

Figure 12. Basic machine vision system concept.

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cable for direct measurement of tool wear and are discussed in the following subsections.

3.4.6.1 Conventional Machine Vision. Conventional machine vision can be most likened to the human vision process. It responds to incoherent, diffuse, randomly oriented light sources and uses a two-dimensional sensor such as an eye with sensitivity to illumination level (gray scale) at each retinal site or pixel. A simple lens/iris combination provides the necessary focusing and control of light level. Sophisticated hardware and hierarchical processing algorithms permit efficient extraction of key information, for example, an object entering the field of view on a collision course. Unlike the human eye, most machine vision systems are not stereoscopic and cannot interpret color.

On the surface, application of conventional machine vision to the direct measurement of flank wear is straightforward. A field of view of approximately 0.2 x 0.2 in. with a 0.1-in. depth of field is required for typical tool inserts. Since the area of typical camera sensors is 2/3 x 1/2 in., a magnification of 3x is required for maximum resolution. Typical sensors have 512 pixels. Therefore, each pixel represents 0.0004 in. in the field of view described.

Due to the jagged appearance of flank wear lands, combined with large local variations in reflectivity due to noise sources such as a built-up edge, worn-away coating, scratches, etc., a lighting approach must be chosen to contrast the features of interest with the sources of scene noise. The degree of success in this regard often determines the accuracy that can be achieved. Researchers who have applied conventional machine vision have met with limited success due to scene noise [22]. More sophisticated feature recognition and extraction algorithms are needed to achieve the required accuracies at reasonable speed.

3.4.6.2 1D Projection Machine Vision. A machine vision technique which has recently been applied to commercial inspection tasks is 1D projection machine vision. Conventional imaging examines all points of a target at a particular instant in time, and features are then extracted from this snapshot. In 1D projection machine vision, the target is moved across the field of view of a 1D camera with the optical axis of the camera sensor oriented perpendicular to the motion. At the conclusion of the process, each camera pixel has integrated the light from those target surface elements that have passed in front of it. For instance, to determine that a package label is oriented correctly and has no tears or other defects, a properly illuminated container is passed in front of a 1D array. The ensemble of the final values of the camera's pixels will be a unique signature for a good label properly positioned. The advantages of this technique over conventional machine vision are the speed of image acquisition, which is approximately 1 ms compared to 33 ms for a conventional 2D camera, and a reduction in the number of pixels to be processed from 262,144 to 4,096.

A proposed extension to this technique is shown in Fig. 13. A tool is rotated in front of a 1D camera at a specified speed which is determined by desired resolution and camera scan rate. Illumination is selected to contrast the flank wear land from the remainder of the tool. Images are taken at approximately 1-ms intervals and saved in a first-in/first-out memory. When the

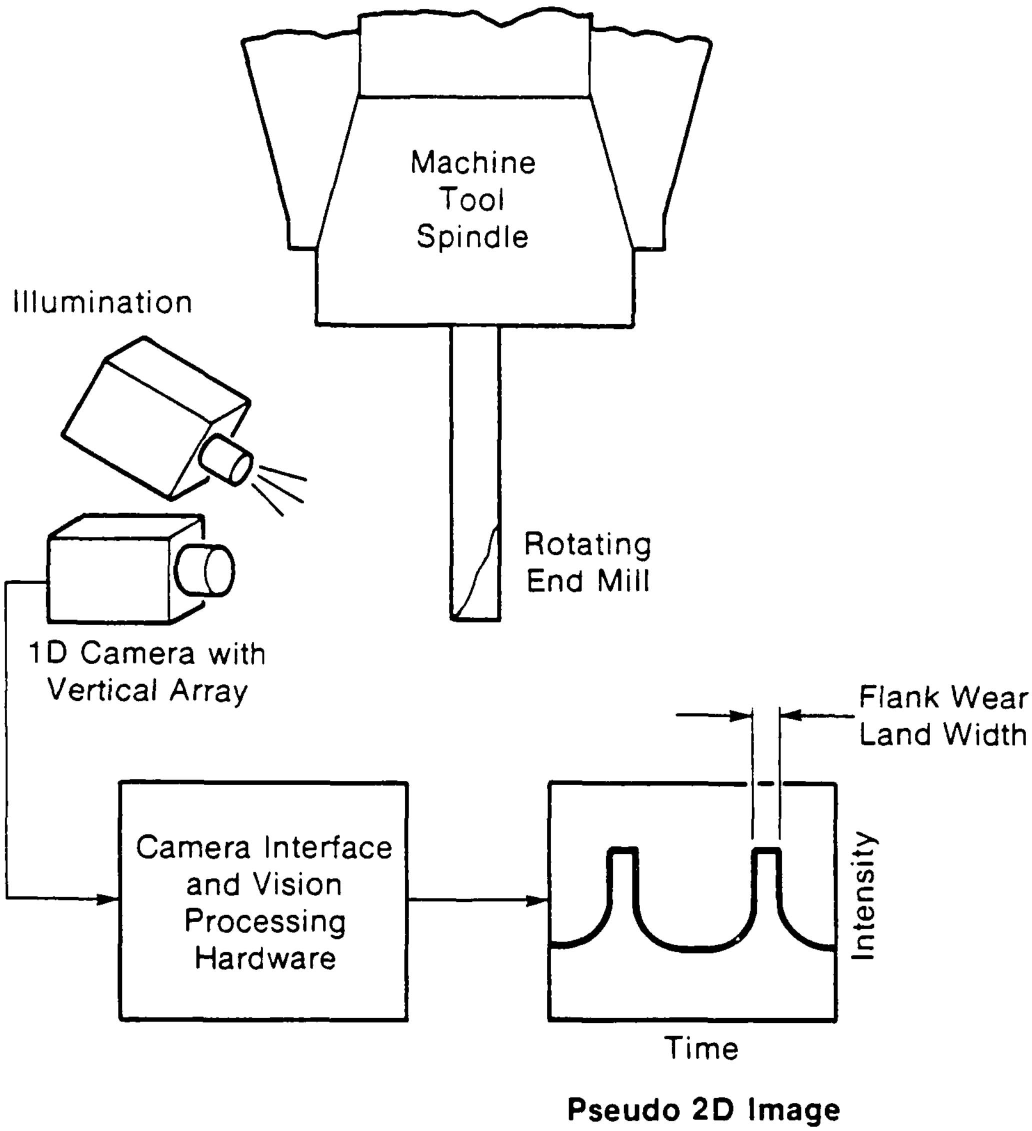


Figure 13. 1D projection machine vision concept.

rotation is complete, the series of 1D images are reconstructed into a pseudo 2D image. Based on geometry, the speed of tool rotation, and the frame rate of the camera, the flank wear land width can be determined. For the end mill tool shown in Fig. 13, a second camera and light source could be positioned to the end face of the cutter to provide a complete assessment of tool wear. A variation on this technique has been proposed by Takeyama for stationary tool applications [19].

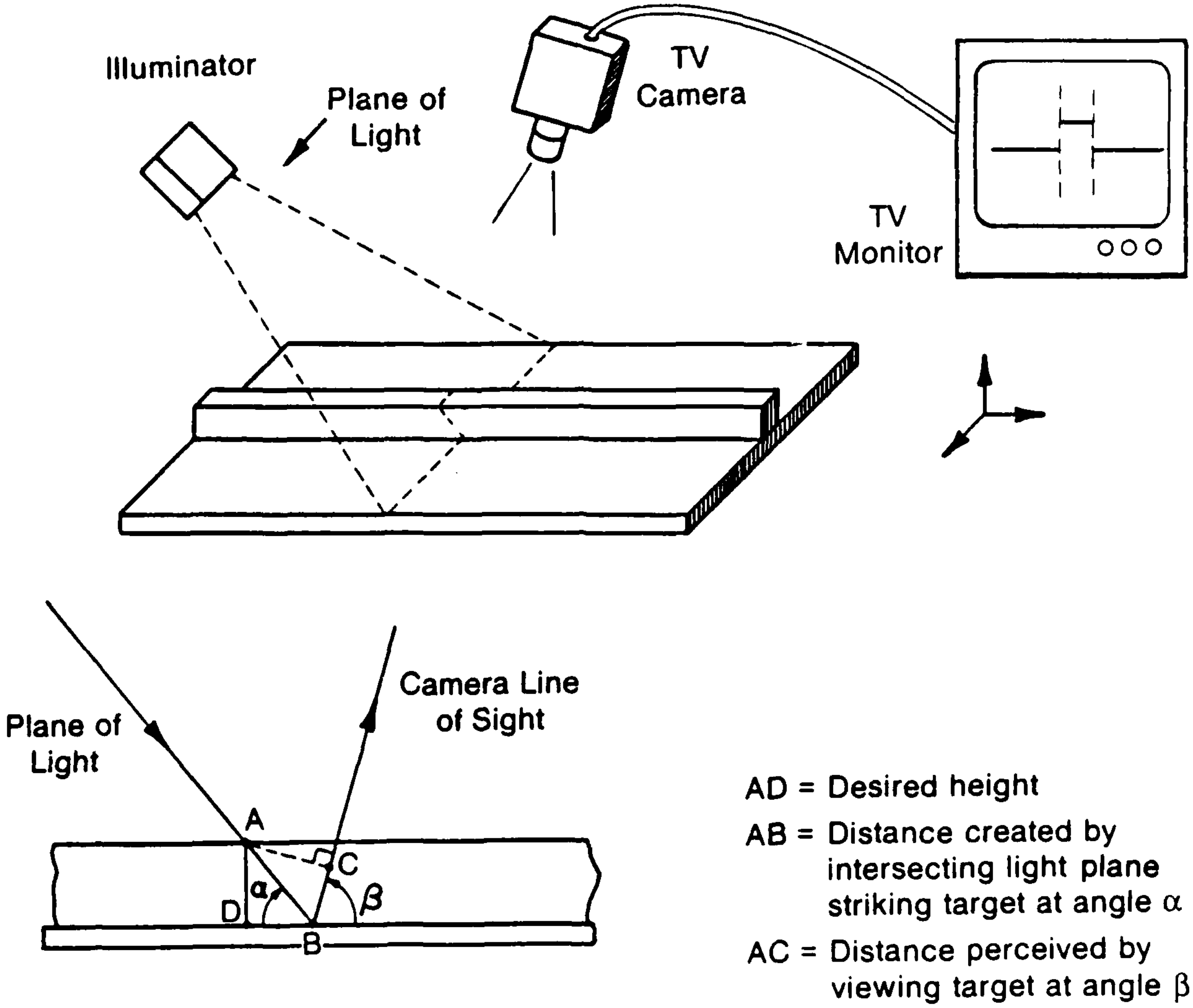
3.4.6.3 Structured Light Machine Vision. Structured light machine vision combines the television camera and monitor of machine vision technology with a specialized illuminator to permit surface profiling by optical triangulation (see Fig. 14). Typical structured light sources project regular arrays of points, parallel lines, or grids of lines onto a target. As such, structured light machine vision is an extension of the concept of optical triangulation described later in Section 3.4.7, where the structure is a single point of light. Under proper circumstances, the distance to any illuminated point on the target which is within the camera's field of view can be measured as shown on Fig. 14. The accuracies to which this can be carried out are dependent upon the spatial characteristics of the structured light, surface finish and optical texture of the target, and the maximum spatial rate of change of the feature being measured. In well-controlled situations, accuracies of 1 part in 5,000 or better in the field of view can be obtained. For the 0.2-in. field of view discussed earlier, this translates into 40 μin. Actual accuracies for typical surfaces are of the order of 200 to 400 μin.

Fig. 15 shows an example of structured light triangulation using a single line applied to the measurement of the flank wear land width on a stationary carbide tool. The break in the imaged line is due to a break in the surface at the flank wear land boundary. The image shown has been averaged to minimize video noise and thresholded to increase contrast. Further image processing would locate the centerline of the image of the structured line as shown on Fig. 15. From that point, the distance to each point on the computed centerline is determined by optical triangulation techniques (see Section 3.4.7 for discussion). In actual practice, several parallel lines would probably be projected across the length of the flank wear land in order to compensate for the jagged edge along the width dimension by averaging.

Rotary tools such as milling cutters require that each cutting edge be presented in turn to the machine vision system. As an alternative, synchronized stroboscopic illumination could be utilized to image the tool while it is rotating. Practical implementation of such a scheme may be difficult, however, and would require development.

3.4.7 Point Range Triangulation

Optical triangulation is a standard measurement technique widely used in precision surveying contexts. Recently, laser-based point range triangulation gages have become available and have been applied to on-machine or in-process inspection systems, especially in the automotive industry. As shown in Fig. 16, a laser light source generates a continuous or pulsed collimated point of light on the target surface. Most surfaces reflect and scatter some portion of the incident energy. For targets without mirror-like surfaces, sufficient scattered energy is available to be gathered by inexpensive photodiode arrays. As shown in Fig. 16, if a linear (1D) array is arranged and a



$AD = AB \sin \alpha$

$AC = AB \sin (180 - [\alpha + \beta])$

$AD = AC (\sin \alpha)/(\sin[\alpha + \beta])$

Figure 14. Structured light machine vision concept.

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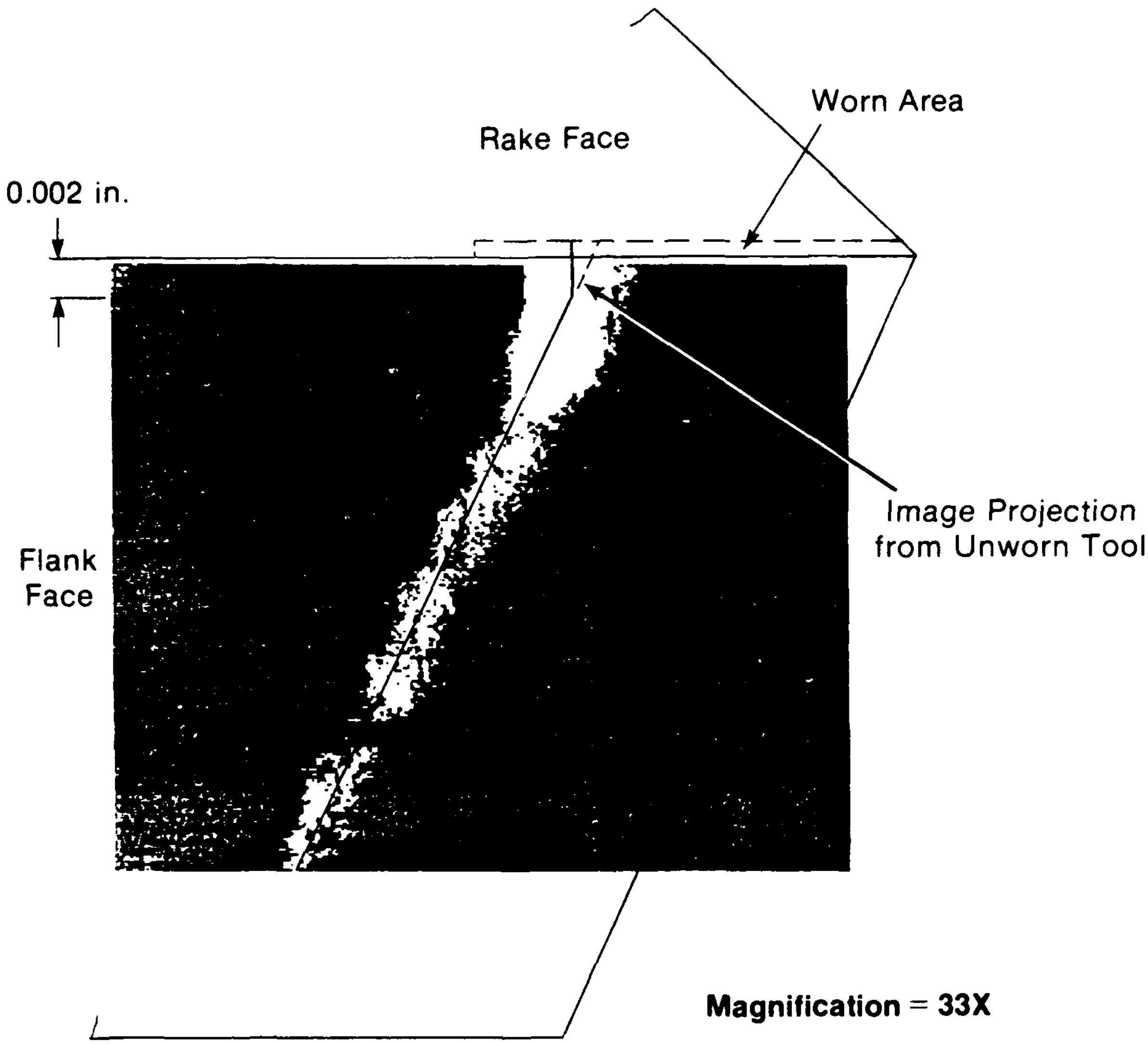

Figure 15. Direct measurement of flank wear land width using structured light machine vision.

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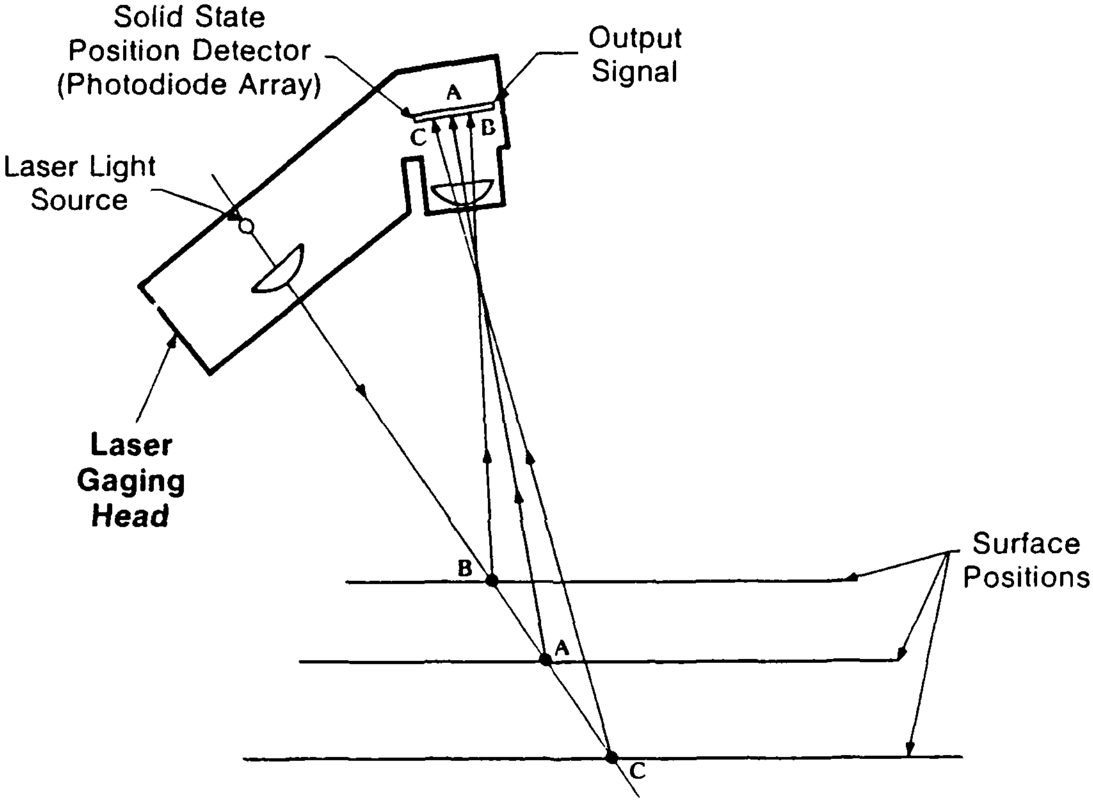

Figure 16. Point range triangulation concept.

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portion of the scattered energy is focused on the array, the position of the image on the array is dependent on the distance from the array to the target. The characteristics of the array determine many of the system parameters. Range is determined by array length, speed by the time to charge the photoreceptor elements, and resolution by the number of elements in the array. A state-of-the-art system using a pulsed laser light source (which provides some insensitivity to part motion) can achieve 0.00008-in. resolution and 0.0003-in. accuracy with a measurement range of 0.3 in. and a standoff of 3.7 in. (see Appendix A, pages A-40 through A-51).

From a functional standpoint, a point range triangulation gage is no different than a touch trigger probe in that both make point measurements. Therefore, to apply this sensor type to tool wear measurement, appropriate positioning devices must be added to the sensor to acquire the required data. Ultimate accuracy is strongly affected by the reflectivity, surface finish, and texture of the target. The ideal surface is a uniform, diffusely reflecting surface, such as the paper this report is printed on. Any mirror-like areas on the target may cause complete loss of useful data.

3.4.8 Projection Interferometry

A variant of this sensor type is available from Electro-Optical Information Systems (EOIS) and provides the capability of surface profiling with accuracies to 0.001 in. (see Appendix A, pages A-6 through A-11). This method uses a proprietary technique called white light projection interferometry and is applicable only to stationary tools at its present state of development. At this point, the amount and complexity of the optical and electronics systems required with this sensor type is a disadvantage. Environmental sensitivities of the types considered in Section 4.0, TABLE 3 would have to be investigated.

3.4.9 Touch Trigger Probe

Developed originally for use on coordinate measurement machines, the touch trigger probe has proven to be so universal a measurement tool that it has been adapted for use on machine tools. Because of its universality, it is included in this discussion even though it is strictly a binary transducer rather than a measurement device. The touch trigger probe does not possess the necessary performance for consideration as a candidate sensor.

As shown in Fig. 17, the stylus is held in place by a spring, allowing current to flow between a pair of pins and a set of balls on which the pins rest. When contact is made between the stylus tip and target and a 7 to 10 gm lateral force is applied to deflect the stylus, at least one of the balls will lose contact with its pins, creating an open circuit. A signal resulting from this open circuit condition begins within 5 to 10 ms, and latching circuits in the host machine record the position of each of the axes at that instant. Debounce protection has been incorporated to enhance repeatability which can be at the 20-µin. level. Some overtravel is permitted, and operational speeds are typically limited to avoid damage. The need to move to each measurement point, detect the surface, and then approach slowly enough for reliable measurement adds significant time to the measurement cycle and represents one of the major limitations of this sensor. Data rates are typically on the order of ten measurements per minute.

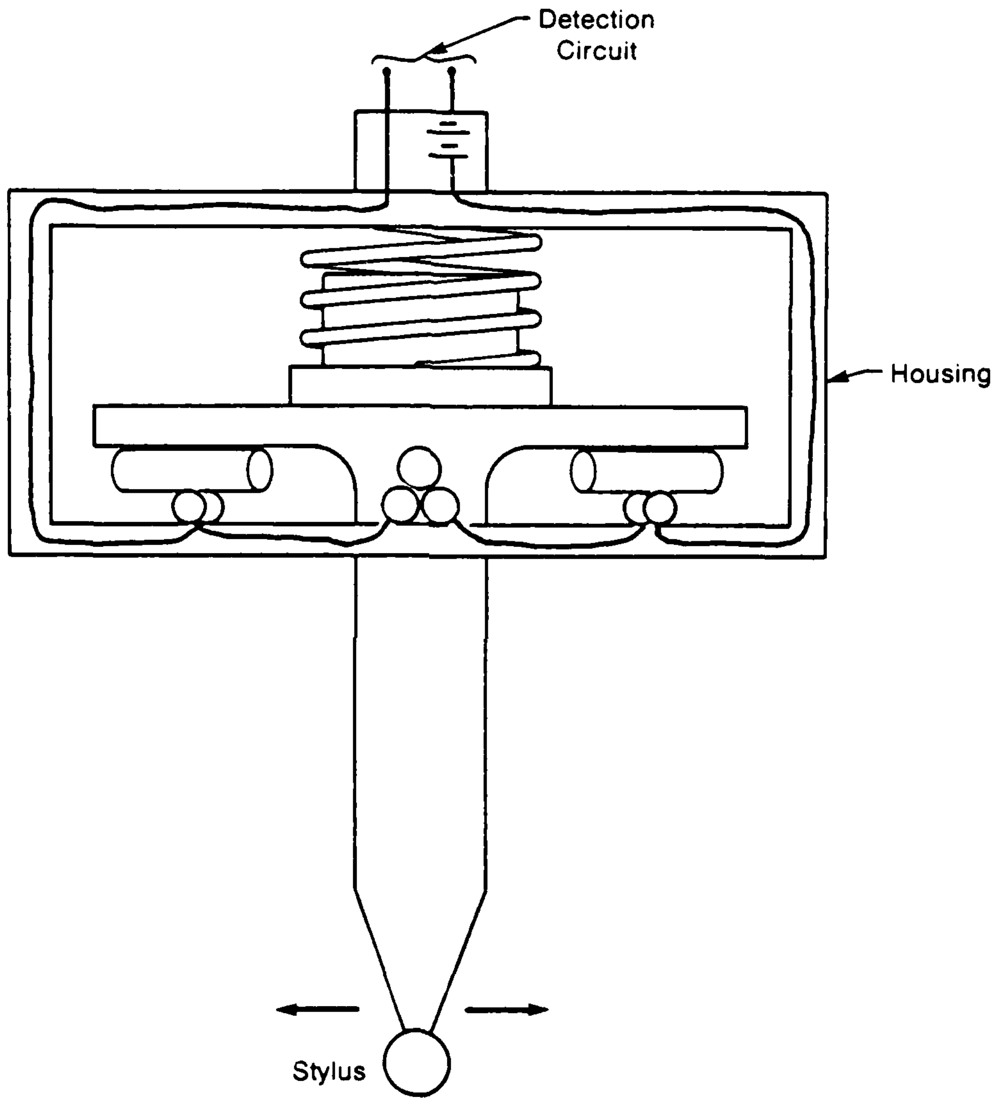

Figure 17. Touch trigger probe concept.

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Although the touch trigger probe is very sensitive, the accuracy of the target position measurement is dependent on other components. These components include the slides that move the probe to its touch position and the measurement systems that provide data on slide movements. Thus, the touch probe is limited by the inaccuracies and nonrepeatabilities of its slide/positioning system. This situation is basically different for sensor systems that measure changes in standoff distance, because these types of sensors can be readily calibrated whereas a similar calibration of the slide/positioning system is a complex undertaking.

The Renishaw HP and LP series of sensors have been designed for use on machining centers and lathes, respectively, to perform on-machine inspection and tool setting. For the case of the lathe, they could also be utilized to perform tool wear measurements. This application would, however, require the addition of a linear positioner to permit samples of the profile to be taken of the flank wear land area. Due to the jagged nature of the flank wear land and the fact that this type of sensor will sit on high spots, the accuracy of this application would have to be assessed experimentally. The touch probe was not designed to measure the surface topography of a worn tool.

3.5 Indirect Tool Wear Measurement Sensor Types

As with direct tool wear measurement, the methods for indirect tool wear measurement have changed little over the past 12 years. The indirect methods considered in the survey and discussed in the following subsections include:

- Acoustic emission
- Feed rate variation
- Force-related methods
- Sound measurement
- Temperature changes
- Vibration
- Workpiece surface finish changes.

3.5.1 Acoustic Emission

Many researchers have investigated acoustic emission in the 0.5 to 1.0 MHz region which is outside the human hearing range and is generated by stress waves emitted by materials undergoing deformation or fracture [25,26,27,28]. The signals are then taken as an indicator of tool wear.

Among the disadvantages reported for this technique are its sensitivity to formation and breaking of a built-up edge, chip form and chip breaking, workpiece vibration, and precise location of the sensor (waveguide effect). Two commercial systems are available for online detection of tool breakage (see Appendix A, pages A-12 through A-15 and A-59 through A-62).

3.5.2 Feed Rate Variation

In applications where the feed force is constant, such as hydraulic feed drilling, tool wear is observed to cause a decrease in feed rate. Since these situations are rather special cases, the subject has been little researched [5]. Therefore, feed rate variation detection was dropped from further consideration.

3.5.3 Force-Related Methods

Force-related methods are the most widely studied of the indirect methods and form the basis for most commercially available tool wear monitoring systems. Takeyama and others have reported essentially linear relationships between the cutting force and the flank wear land width [17,19,29]. Linear relationships have also been found to exist between the forces and the depth of cut, work material hardness, tool geometry angles, cutting speed, and feed rate over certain parts of the cutting operation. Others have reported relationships between force ratios such as feed to cutting and flank wear [30]. However, the presence of a built-up edge and work hardening have been found to influence the magnitude of the forces, and although the effects of tool material, stiffness, fixturing are as yet unknown, they are also expected to be significant. The situation which results is one in which an extensive amount of cutting tests with worn and unworn tools may be required to determine the effects of all the variables for any given machine/tool/workpiece combination. In this way, empirical limits can be established for tool end of life and breakage. In addition, many of the effects probably vary over time as wear occurs to machine parts. Thus, periodic verification of the empirical parameters would be necessary.

3.5.3.1 Load Cell Force Measurement. Sensors used to measure forces for lathe applications usually take the form of a turret or tool-post-mounted dynamometer. For machining centers, spindle-bearing-mounted, strain-gage-based systems are commercially available. These sensors are reliable and offer sufficient accuracy and resolution. In addition to the disadvantages for force sensors cited above, the primary disadvantage associated with this sensor type is the modification required to the machine tool to locate the sensor properly. Brochures of typical commercially available systems are provided in Appendix A, pages A-11 through A-19 and A-28 through A-31.

3.5.3.2 Bearing Deflectometer. A contacting sensor which permits accurate determination of bearing loads has been developed to measure the health of a bearing in an aerospace application [31]. Shown in Fig. 18, the bearing deflectometer consists of a threaded housing which contains a spring-loaded piezoelectric load sensing element that rests on a movable button. The movable button is preloaded by the spring and protrudes from the threaded housing. As the sensor is threaded into a bearing housing, the button is depressed when it contacts the bearing outer race. When the race surface deforms due to the applied load, the resulting displacement of the button causes a change in spring load which is sensed by the piezoelectric crystal. The load change results in an electrical charge which is measured with a charge amplifier.

This sensor is very efficient in converting outer race displacement into a good electrical signal. Typically the noise level in this measurement is one to two decades lower than that found in fiber optic proximity sensors, and the sensitivity is better than that obtained with conventional accelerometers. Sensors have been fabricated with resonant frequencies in the 9000-Hz range, which translates into a maximum usable spindle speed of approximately 40,000 rpm for the typical bearing.

3.5.3.3 Power. Although not a candidate sensor type, power sensors were considered in the survey. These sensor types are used to measure the power input to the spindle or feed motors (see Appendix A, pages A-63 through A-64).

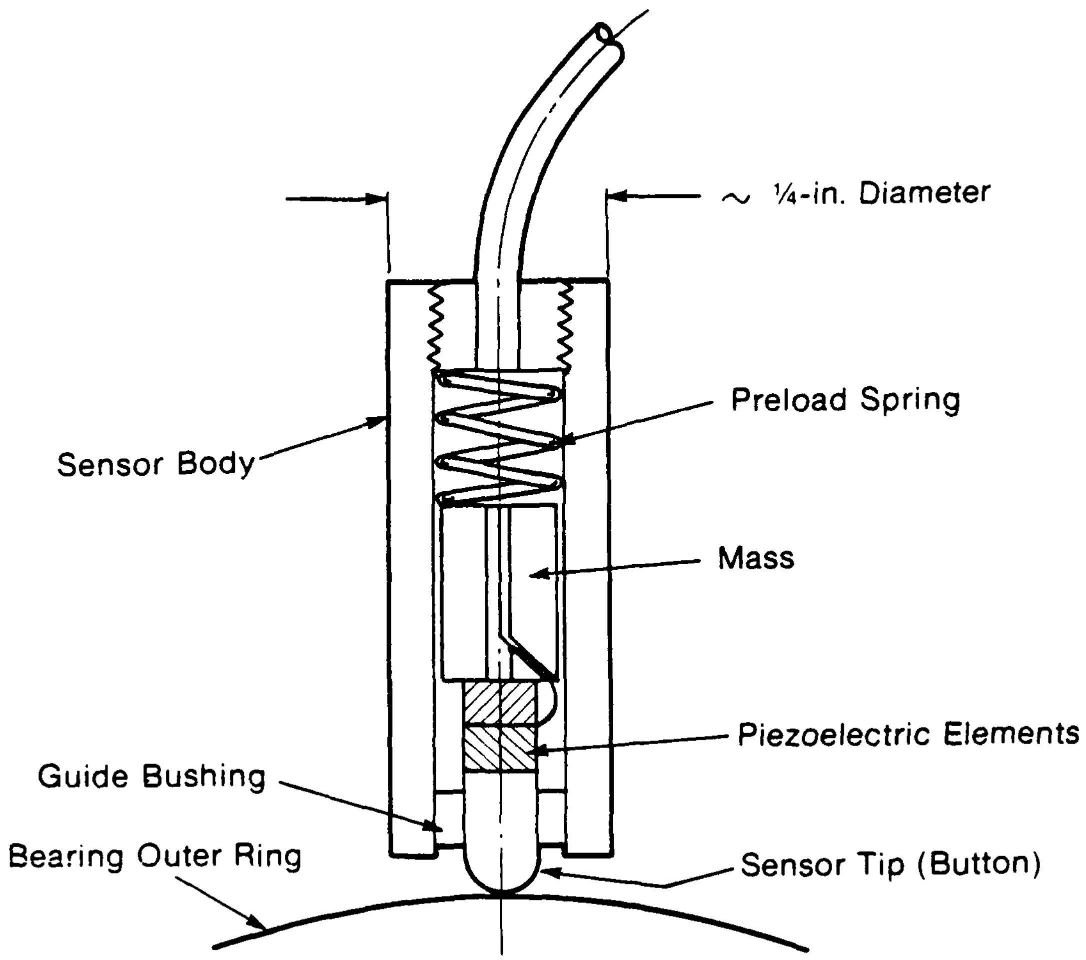

Figure 18. Bearing deflectometer concept.

They can report large increases in power draw just prior to breakage and smaller increases in conjunction with worn tools. The main disadvantages of this method are:

- Lack of discernible change when small tools are used on high horsepower machines
- Lack of generally discernible signal during the "normal wear" part of tool life
- Susceptibility to power fluctuations due to problems in the drive system which increase power draw (bearing friction variation, lack of lubrication, etc.).

3.5.3.4 Torque. Although not a candidate sensor type at this time, torque sensors were considered in the survey. In this approach, a torque sensor determines the net cutting torque by measuring horsepower and spindle speed [32]. The torque required to "cut air" is determined each time the spindle speed is changed and subtracted from the measured torque to produce the net cutting torque. This method has the same general disadvantages as power sensors and has been applied primarily to adaptive control schemes which attempt to limit the torque below some empirically established value. Feedrate is usually the controlled parameter in this scheme.

A new torque sensor is being developed by MTI for use in an in-process control system at RIA. The sensor is based on a piezoelectric crystal and will be mounted in a tool holder to monitor and control tapping torque. Early tests show its capability to handle a torque range from several in.-oz to 150 ft-lb. This sensor is being developed to detect wear when the torque magnitude, or rate of increase of the torque, indicates wear is causing tap breakage to be probable. In contrast, a rapid drop in torque indicates the tap has broken. This sensing system, which includes a data transmitting and receiving package, may become a viable component of a tool and workpiece sensing system in the near future.

3.5.4 Sound Measurement

Microphones placed near the cutting process have been reported to detect changes in the frequency distribution of emitted sound (audible to the human ear) due to the worn tool rubbing against the workpiece [3,23]. This method suffers the same disadvantages for indirect tool wear measurement as the vibration sensors discussed in Section 3.5.6 and has been dropped from further consideration.

3.5.5 Temperature Changes

Although not a candidate sensor type, significant research has been devoted to correlation of increases in cutting edge temperature to tool wear [4,33,34,35]. If the tool and workpiece materials are different, a built-in thermocouple exists. In other cases, thermocouples have been imbedded in or between the tool insert and tool holder. Recently, infrared sensors have been applied to detect the temperature at the cutting edge. While this method has been a valuable research tool, many practical problems limit its usefulness:

- Thermocouple calibrations must be made for each individual tool-workpiece combination

- For the tool-workpiece thermocouple, chip form can produce a very noisy signal because of the intermittent short circuit produced each time the chip touches the tool

- Infrared methods are hindered since the chips obscure the tool-workpiece interface and cause difficulty in focusing on the precise area of interest. Excessive time constants are seen in observing temperature changes remote from the tool-workpiece interface

- Use of coolant is expected to significantly alter observed temperature profiles.

3.5.6 Vibration

Workpiece or tool support vibrations, as detected by an accelerometer, have been used to produce characteristic signatures of the cutting process. Changes in the observed signature from the reference have been related to tool wear and breakage. The method usually employs frequency domain techniques, that is, either ratios of energy (in particular, frequency ranges) or overall power spectral density. The signatures obtained are usually characteristic of the particular machine employed and sensitive to process variable changes. Some success has been reported by NIST with this method as applied to drilling [24] and end milling.

3.5.7 Workpiece Surface Finish Changes

Although it is generally accepted that surface finish deteriorates as tools reach advanced state of wear, no published research was found characterizing the changes to be expected due to tool wear. In addition to tool wear, workpiece surface finish changes probably can be brought on by variations in overall stiffness of the workpiece, tool, machine, and fixtures. Since surface finish measurement is important to RIA as an indicator of workpiece quality, a means of dealing with this parameter in that context is described in Section 3.7.

3.6 Workpiece Dimension Sensors

For both in-process and between-cut workpiece dimension sensing, the state of the art is more highly evolved than that for tool wear sensing. Sensors mounted some distance behind the cutter but attached to the spindle structure or cross slide can view results of cutting in relative safety and achieve the desired accuracy. For point-type sensors, such as a point range triangulation gage, measurement accuracy will be limited by the volumetric errors of the machine tool positioning system. Higher accuracies can be achieved by providing machine-independent positioning or an independent coordinate system such as a camera frame. Examples of successful in-process workpiece dimension measurement have been demonstrated at RIA [1,2].

The RIA objectives for a workpiece dimension sensor require determination of workpiece dimensions to 0.001 in. for milling and 0.0001 in. for turning, as well as the ability to perform in-process measurement. Several sensor types have been identified as having the potential to meet these objectives:

- Conventional machine vision
- Optical shadowing
- Point range triangulation
- Structured light machine vision
- Touch trigger probe.

Note that the touch trigger probe is included in the following discussion to establish a baseline for comparison.

3.6.1 Conventional Machine Vision

This sensor type was described in detail in Section 3.4.6.1 as applied to tool wear measurement. As an illustration of what could be expected when it is applied to workpiece dimensional measurement, consider a requirement to measure the width of a 1.75-in. milled slot. Since the width of the camera sensor is 0.67 in., a magnification less than 0.38 is required to image the entire slot onto the camera frame. If a camera having a 512 × 512 pixel resolution is used, then each pixel will represent 1.75/512 or 0.0034 in., which falls short of the 0.001 in. desired for RIA applications. Since accuracy is a function of field of view, use of higher magnification will increase accuracy but the target must be correspondingly smaller. Although subpixel resolution is possible, it is felt that the tool wear problem may not allow accurate subpixelation.

A lighting arrangement that adequately contrasts the milled slot against the background with accuracies of better than 1 pixel is not easily attained. Standoff would have to be approximately 6 in. at the magnification specified and then maintained within 0.3 in. so as not to affect accuracy (since magnification varies with standoff). Note that the depth of the slot cannot be determined as easily with this method as it could be with a point range triangulation gage. Conventional machine vision is generally limited to measurement of features that lie in a plane. For repeatable results, the imaged feature should be free from burrs and chips, although image processing can reduce or eliminate their effect. Raw data acquisition speed is limited to 30 images/sec. Generally, two to four images must be averaged to eliminate video noise. The effective raw data rate is then of the order of 0.12 sec. Image processing may require anywhere from 0.1 to 1.0 sec depending on the complexity of the scene and the amount of scene noise (such as chips) which must be removed by processing.

While image processing times are constantly being reduced due to the development of higher performance hardware, it will be some time before it is cost effective to process complex image data in real time (<0.12 sec). Another difficulty that limits in-process application of conventional machine vision is associated with relative target-to-camera motion. For the example previously cited, vibration during the 0.033-sec image acquisition time may reduce accuracy. In some cases, strobe illumination can reduce this effect.

3.6.2 Optical Shadowing

Optical shadowing uses the shadow cast by a suitably backlit object to generate an image that allows determination of certain dimensions of the object when processed. Dimensions that can be measured are those that are cast as light/dark transitions in the image. There are two major variations on this method that have been commercially applied.

In the first variation, a laser beam is directed onto a rotating mirror that causes the beam to sweep repeatedly across an aperture (see Fig. 19). A target placed in the beam will intercept the laser energy and cause a temporary loss of signal at the receiver. The time duration of the signal loss is a measure of the external dimension of the part. Accuracy is improved by tracking the mirror rotation and compensating for any speed variations. Parts from 0.010 to 5 in. can be measured with typical resolutions of 0.0002 in. with comparable repeatabilities and accuracies (e.g., 0.0005 in.). Commercial products utilizing this technique are available from several manufacturers (see Appendix A), and specialized systems have been developed for particular applications. One system designed to measure crankshafts is reported to have an accuracy of 20 μin.

The second variation uses diffuse collimated light to backlight the target (see Fig. 20). A suitable lens images the desired light/dark transition(s) onto a linear array camera(s). This technique was applied by MTI in RIA Contract DAAA08-83-C-0052, and the results obtained indicate a resolution of 0.00005 in. and an accuracy of 0.0001 in. per edge [2]. Therefore, the accuracy associated with measurement of the diameter of a turned part is 0.0002 in. Part of this error is due to the positioning system that adjusts the spacing between the sensors for variable-sized parts. Accuracy of the sensor itself probably exceeds the desired accuracy of 0.0001 in.

For either of the above techniques, due to the nature of the measurement, accuracy is independent of the volumetric errors of the machine tool used to position the sensor for measurement. As described in Reference 2, this problem was eliminated by fitting the machine tool with high resolution linear electronic scales which determined the location of the sensor. The speed of measurement possible with this sensor type permits its use for in-process applications.

3.6.3 Point Range Triangulation

This sensor type was described in detail in Section 3.4.7 relative to direct tool wear measurement. For workpiece dimension measurement, a carriage-mounted point range triangulation gage has been applied to in-process workpiece measurements for RIA [1]. These include measuring thread profile dimensions and axial distances between edges. Using statistical methods to reduce the single-point data scatter (due to surface finish and reflectivity variations), accuracies on the order of 0.0002 in. have been achieved. Data rates ranging from 200 to thousands of data points per second are possible. Results are not affected by relative sensor-to-workpiece motions over a wide range of speeds.

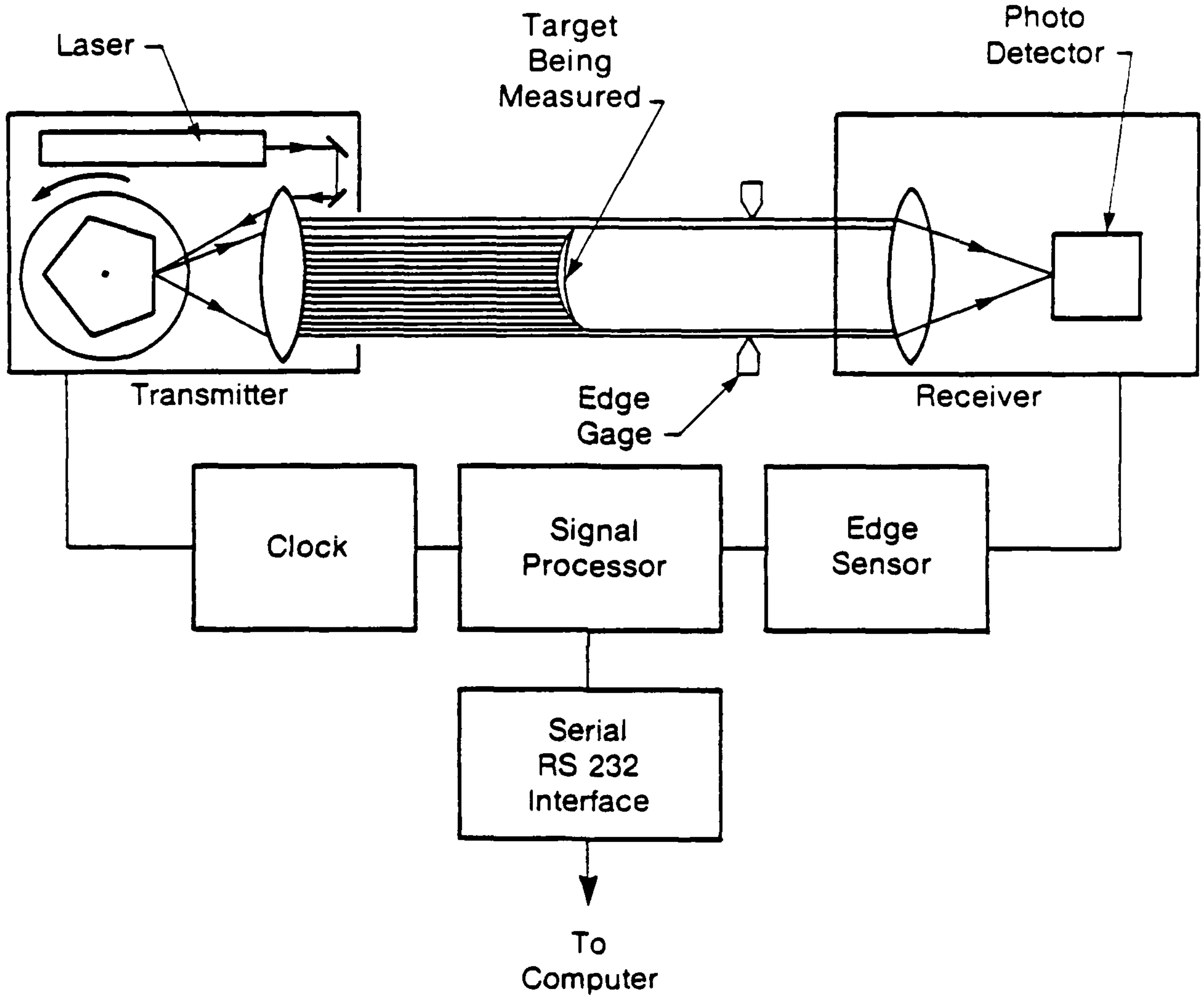

Figure 19. Optical shadowing concept no. 1.

87519 -1

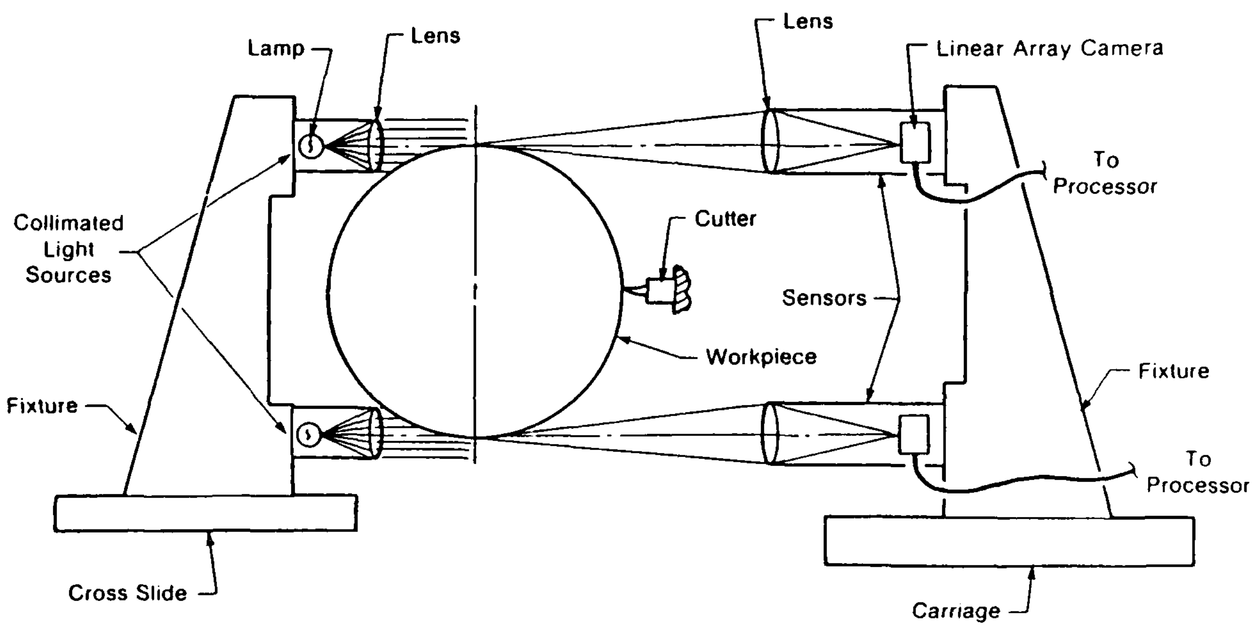

Figure 20. Optical shadowing concept no. 2.

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3.6.4 Structured Light Machine Vision

This sensor type was described in detail in Section 3.4.6.3 relative to direct tool wear measurement. When applied to workpiece dimension measurement, structured light machine vision offers several advantages over conventional machine vision. A typical structured light approach might use an individual or a series of parallel lines projected onto the workpiece. Usually, a laser is used to generate the lines since this is a relatively simple way to control the line length, width, and spatial profile. With this technique, accuracies on the order of 0.1 pixel in the field of view are possible. For the earlier example of a 1.75-in. milled slot imaged onto a 512 × 512 pixel camera, the accuracy could be as high as 0.0003 in., which exceeds the desired accuracy. Because of the geometric relationships that exist, feature depth can be determined by triangulation as shown earlier in Fig. 14. Use of a pulsed laser to produce the structured illumination would permit operation at high sensor-to-target relative motion. Due to the nature of the structured light image (a series of lines as opposed to irregular gray-scale patterns), it is anticipated that the required image processing may be reduced over what is required for conventional machine vision, thereby improving performance.

3.6.5 Touch Trigger Probe

This sensor type was described in detail in Section 3.4.9 relative to direct tool wear measurement. For high-precision, off-machine workpiece inspection, the touch trigger probe is still the current sensor of choice in coordinate measuring machine applications. In on-machine applications, measurements have to be made between cuts or after the process has been completed due to the fact that readings must be taken at extremely low relative sensor-to-target movement speeds. These sensors are very fragile and easily damaged by collision. Sensor tip wear and breakage is a problem as is the need for the workpiece to be free of chips and burrs. The slow data rate adds significantly to overall process time. The touch trigger probe is a mature technology and is not likely to undergo future improvements that are significant. For these reasons, it is not recommended for this advanced application.

3.7 Workpiece Surface Finish Measurement Sensor Types

Survey of the published literature did not yield any surface finish measurement approaches that could meet the range of 20 to 150 μin. R_a required by RIA [36,37,38,39,40,41,42]. However, NIST has produced soon-to-be published data on surface finish measurements based on optical and ultrasonic scattering techniques. This information was used as the basis for evaluation of the ultrasonic scattering method and also provided additional understanding of the optical scattering method [10,11,43,44,45].

However, at present, neither of those scattering methods nor any other available noncontact system exists which can determine surface finish over the required range independently of the detailed structure and orientation of the surface. In addition, all systems evaluated require development of an empirical data base to correlate the sensor output to standard parameters such as R_a. The resultant data are good only for the particular process, and process variables used to generate the correlation and analytical models to extend the data to other process situations are not yet available. The following sensor types were evaluated for application to workpiece surface finish measurement:

* Conventional machine vision
* Fiber optic sensor variation
* Microwave reflection
* Optical scattering
* Stylus profilometer
* Ultrasonic scattering.

Note that the stylus profilometer is included in the following discussion to establish a baseline for comparison.

3.7.1 Conventional Machine Vision

Conventional machine vision, as described in Section 3.4.6.1, has been applied to surface finish measurement [40]. For this application, the target is illuminated with grazing diffuse white light and imaged onto a camera using microscope optics. Grey-scale histograms are taken of the digitized image in a direction parallel to the roughness. It is found that the frequency distribution of the pixel grey-scale values changes with roughness. Specifically, the grey level associated with the maximum frequency and the variance of the distribution increase with increasing roughness. The method is very sensitive in the roughness range from 4 to 40 μin. but rapidly loses sensitivity above 40 μin. Actual data are a function of the surface topography, and, thus, empirical calibration must be made for each specific surface to be measured. The method also suffers from slow processing time (approximately 0.1 to 1 sec per measurement).

3.7.2 Fiber Optic Sensor Variation

A variation of the basic fiber optic sensor discussed in Section 3.4.3 has been applied to the measurement of the roughness of ground surfaces [37]. Relative to Fig. 7b, the sensor is operated at the optical peak which corresponds to a standoff of approximately 2 mm for the particular fiber optic configuration used. The light output at the optical peak was found to vary with variations in surface roughness over the range from 6 to 80 μin. and correlated well with profilometer measurements. MTI researchers have also noted this effect using the MTI Fotonic sensor product. It is felt that a fiber optic bundle configuration could be developed which provides sufficient resolution over the desired range from 20 to 150 μin. for this application, although a substantial development effort would be required.

3.7.3 Microwave Reflection

Although not a candidate sensor type, microwave reflection is included in this discussion for completeness. One published work described the use of time domain reflectometer techniques to correlate microwave effects to surface finish [38]. In this method, the workpiece is configured as the termination of a waveguide into which microwaves are injected. Surface finish variations change the characteristic impedance presented by the workpiece to the microwaves. This causes a change in the standing wave pattern which results in increased losses in the system as predicted by transmission line theory.

Reported results are inconclusive and show only overall trends in the losses for changes in surface finish [38]. The method is not suitable for on-machine use since the workpiece must be attached to the waveguide setup. The instrumentation and setup used in this method are suitable for laboratory use only.

3.7.4 Optical Scattering

This technique is based on the well-known and characterized scattering of light by rough surfaces [46]. If a beam of collimated light is incident upon a surface at an angle θ_o with respect to the surface normal, light is reflected at an equal angle θ in the plane of incidence (see Fig. 21). In addition, some light is scattered due to the roughness of the surface. If the area of the surface illuminated is large compared to the roughness wavelength, then the scattered light will be distributed about the reflection angle as shown in Fig. 21. For relatively smooth surfaces (R_a < 1μm), the dispersion about the reflection angle is small (<10°). For rougher surfaces, the dispersion angle increases rapidly. In addition, the light intensity pattern assumes a complex function of angle which is highly dependent on the detailed structure and orientation of the surface to the incident light.

Commercially available instruments typically have a small included angle (15 to 30°) between the incident light and the detector (see Appendix A, pages A-34 through A-39). This limits the useful range of the sensor to surfaces with roughness values below 80 μin. In addition, standoff distances of a few millimeters limit its versatility in the production environment. Lastly, the sensor data must be empirically calibrated to R_a by an independent means since a rigorous analytic model does not exist at present.

3.7.5 Stylus Profilometer

The stylus profilometer is the accepted standard by which other workpiece surface finish measurement methods are judged. In this sensor type, the sensing system consists of a steel ball stylus which contacts the workpiece and follows the surface profile. The stylus is connected to an inductive pickup mechanism which accurately converts the mechanical motion into an electrical output. Linear devices use a precision linear servo system to move the stylus, and rotary devices use a precision rotary table to rotate the workpiece. Stylus diameter can be as small as 0.0002 in. with accuracy to 1 μin. over a measuring range of 0.010 in. Maximum stylus speed is on the order of 4 in./sec with a gaging pressure of 2.5 g. The low gaging speed and delicate contacting sensor head make this method unsuitable for in-process measurement.

3.7.6 Ultrasonic Scattering

In soon-to-be-published work by NIST [11], correlations have been found between ultrasonic back-scattering amplitude and surface roughness using both fluid and air coupling techniques between sensor and workpiece. Pulsed ultrasound waves ranging in frequency between 1 and 30 MHz were used, and data were taken for both static and moving flat and round workpieces. At the highest frequency, resolution of 20 μin. was achieved over the roughness range from 40 to 1600 μin. Using filtered coolant as the coupling fluid, this method has the robustness and speed to be considered for in-process use. As with all sensor types investigated, the output must be calibrated empirically to the particular surface structure and roughness range of interest.

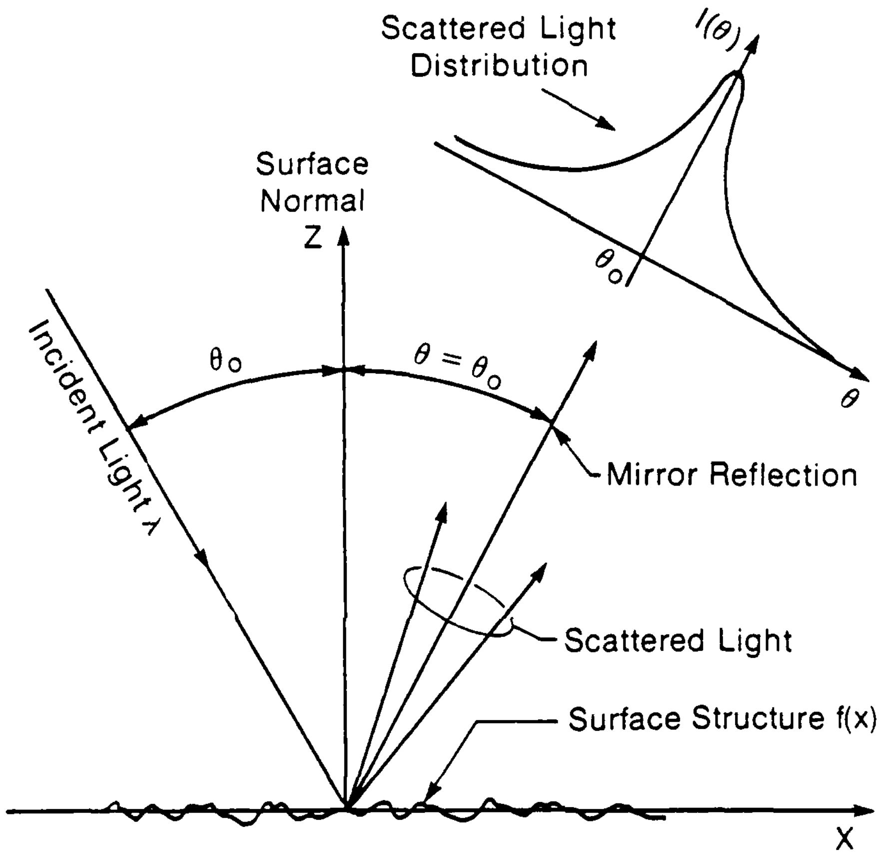

Figure 21. Optical scattering concept.

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4.0 SENSOR EVALUATION SUMMARY

This section summarizes the results of the evaluation of the sensor types described in Section 3.0. These sensors qualified for ranking based on their ability to meet RIA criteria for tool and workpiece sensing.

4.1 Evaluation Approach

At the beginning of the evaluation process, it became evident that many areas must be considered to properly evaluate the potential of a given sensor type within the context of RIA's application objectives. To meet this need and ensure a complete evaluation, a matrix approach was formulated. Eight evaluation categories with corresponding parameters were determined based on MTI's experience with sensor technology and discussions with RIA regarding their needs. The resulting evaluation categories and their parameters include:

- **Classification** - to evaluate the measurement approach and potential applications for a sensor type. Parameters include application versatility, computed parameter, measurement method, measurement mode, and measurement type.
- **Environmental Sensitivity** - to evaluate sensor sensitivity to environmental effects. Parameters include airborne pollutants, ambient light, ambient temperature, built-up edge, chip form, collisions, coolant, coolants or chips on tool or workpiece, coupling medium composition and purity, electrical noise, hardness, orientation to surface structure, speeds/feed/depth of cut, stiffness, surface finish, tool material, tool temperature, vibration, and workpiece material.
- **Suitability** - to evaluate sensor suitability for the RIA application. Parameters include acceptability to operators, calibration requirements, ease of use, expected life, requirements for process modifications or limitations, requirements for modifications to machines or tools, and predicted reliability. Two of these parameters require further definition: calibration requirements and predicted reliability. Calibration requirements include such factors as the complexity and frequency of calibration, requirements for special fixtures and instrumentation, and whether a sensor must be returned to the vendor for calibration. Predicted reliability is defined as an assessment of the overall complexity of the hardware plus the collision damage potential.
- **Cost** - to evaluate sensor cost. Parameters include adaptation, development, maintenance, and recurring costs. Adaptation costs are defined as the cost to adapt a system developed for one application (e.g., turning) to a different application (e.g., milling). Maintenance costs include cost of fixed life items and costs for periodic calibration, and recurring costs include the estimated cost of copying a sensor system after the development cycle is complete.
- **Performance** - to evaluate sensor performance. Parameters include accuracy, bandwidth, growth potential, repeatability for a single measurement, and resolution. Since these performance parameters can be interpreted in several ways, all require further definition. Accuracy is defined as the deviation of the mean of a number of measurements from the actual value. Bandwidth is defined as the number of measurement results a sensor can produce in unit time and not the sensor's raw data rate. For example, a two-dimensional camera can acquire 30 frames/sec, but the actual frame processing rate into requested measurements may be 0.5 sec/frame. Growth

potential is defined as the assessment of prospects for advances in performance, price reductions, and increasing suitability for factory use. Repeatability is defined as the scatter associated with a group of measurements under identical measurement conditions. Finally, resolution is defined as the minimum change in measurement quantity that can be repeatably detected by a sensor.

- **Safety** - to evaluate sensor safety. Although this category has no specific parameters, hazards such as the potential to cause eye damage and potential exposure to radiation were considered.
- **Technology** - to evaluate the level of risk for a given sensor. Parameters include measured physical quantity, maturity of model or algorithms relating sensor output to measured parameter, and technology maturity.
- **Interface Complexity** - to evaluate how a sensor will interface to and integrate with the overall system architecture. Parameters include ancillary requirements, hardware and processing requirement complexities, and the need for sensor positioning mechanisms.

Once the categories and parameters were determined, each category was assigned a weight number (W_n) from 1 to 3; 1 represents the lowest value and 3 the highest. This weighting reflects RIA's assessment of the importance of that category to their application. Values were also assigned to each parameter as shown in TABLE 3, which defines all values used for sensor evaluation. Due to the number of sensors evaluated, the completed matrices for each candidate sensor type are presented in Appendix B.

After the evaluation matrices were completed, the candidate sensor types were scored and ranked. Since each category contains a variable number of parameters, a scoring system was devised wherein the composite score for all parameters within a category must equal 10. Due to the variable number of parameters and the need to weight some parameters more than others, the actual raw score obtained by summing the scores of all parameters (V) was divided by a normalization factor (C) equal to the highest possible raw score divided by 10. The resulting raw scores were multiplied by the category weight and summed to give a total score. Thus,

$$\text{Total Score} = \sum_1^8 W_n * 1/C_n \sum_1^P Vp.$$

Under this system, a perfect sensor would receive the following scores for a given category.

Category	**Perfect Score**
Classification	30
Environmental Sensitivity	30
Suitability	30
Cost	20
Performance	20
Safety	20
Technology	20
Interface	10
Total	180

After the initial sensor evaluation, the candidate sensor types were then evaluated under two supplemental categories: potential and risk. These two categories and their parameters were selected by RIA to reflect their objec-

TABLE 3. Evaluation Matrix.

Category [Weight] [1]	Value Definition [2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both		
Computed Parameter	Give 1 point each SF, TB, TO, TW, WD.[3] Point range 0 to 5.		
Measurement Method	3 = indirect, 5 = direct		
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process		
Measurement Type	2 = contact, 5 = noncontact		
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.		
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category, 0, 1 = low; 2, 3 = medium; 4, 5 = high		
Acceptability to Operators			
Calibration Requirements			
Ease of Use			
Expected Life			
Machine/Tool Modifications Required			
Modifications Required or Process Limitations			
Predicted Reliablity			

[1] Numbers in brackets designate category weights assigned to reflect RIA application objectives.

[2] The values defined and assigned herein reflect the intent and objectives of the RIA application and are not intended to be applied to or interpreted in any other context.

[3] SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.

TABLE 3. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K		
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K		
Maintenance	0 = high, 1 = medium, 2 = low		
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K		
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.		
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms		
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high		
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.		
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.		
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard		
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]		
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high		
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high		
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	*Deduct 1 point for each ancillary. Point range 0 to 5.*		
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high		
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high		
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none		

[4]No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[5]Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

tives to advance the state of the art, enable unattended machining and on-machine inspection, monitor tool wear, predict tool end of life, and provide application versatility. Definitions of these categories follow:

- **Potential** - to evaluate sensor potential to meet RIA objectives. Parameters include adaptation flexibility, classification summary, computed parameter, and growth potential.
- **Risk** - to evaluate the application risk associated with a given sensor. Parameters include accuracy, environmental sensitivity, model maturity, number of parameters without confirming data, predicted reliability, process modification or limitation, repeatability, resolution, and technology maturity.

The values assigned to each parameter for the supplemental evaluation are shown in TABLE 4. With the exception of the value definitions for the classification summary, number of parameters without confirming data, and process modification or limitation parameters, all values are identical to those shown on the sensor evaluation matrix (TABLE 3).

4.2 Initial Scoring Results

After the evaluation matrices were completed, several sensor types were eliminated from further consideration. Total scores were not calculated for these sensor types for the reasons given below:

- Capacitance - unique fixture required and impractical
- Contact LVDT family - inadequate performance and little growth potential
- Projection interferometry - inadequate performance, may not be cost effective, and needs to be proven in factory environment.

After these sensor types were eliminated, the initial scores for the remaining ones were calculated.

The category scores and total scores for the candidate sensor types are presented on TABLE 5 for tool wear sensors, TABLE 6 for workpiece dimension sensors, and TABLE 7 for workpiece surface finish sensors. As stated in Section 4.1, the values assigned to the evaluation categories were determined based on RIA objectives. Thus, a sensor type which might receive a high score in another context may have received a lower score in this evaluation because of its limited suitability to RIA applications. Note that the completeness gained by thorough evaluation of each sensor type is more significant than the scores themselves. The ratings presented below are based on the initial sensor evaluation and do not include the results of the supplemental evaluation for potential and risk. The results and recommendations of the supplemental evaluation are presented in Section 4.3.

4.2.1 Tool Wear Sensor Types

As shown in TABLE 5, sensor types using optical technologies scored highest for both stationary and rotary tool wear applications. Note that as a group, the indirect sensors for tool wear received lower scores than the direct sensors, as would be expected from the discussion in Section 2.1. For

TABLE 4. Supplemental Evaluation Matrix.

Category	Value Definition[1]	Value Assigned[2]
POTENTIAL		
Adaptation Flexibility	The value assigned to the application versatility parameter plus double the value assigned to the adaptation cost parameter and then the sum divided by 2. Point range 0 to 4.5.	Value range for potential = 0 to 23.5.
Classification Summary	Give 1 point each: direct, noncontact, in-process, rotary tool milling and drilling. Point range 0 to 4.	
Computed Parameter	Same value definition as TABLE 3.	
Growth Potential	Same value definition as TABLE 3.	
Bandwidth	Same value definition as TABLE 3.	
RISK		
Accuracy	Same value definition as TABLE 3.	Risk = highest possible value - value assigned.[3]
Environmental Sensitivity	Same value definition as TABLE 3.	
Model Maturity	Same value definition as TABLE 3.	
Number of Parameters without Confirming Data	5 minus the number of parameters or 0 if number of parameters > 5.	Value range for risk = 0 to 57.
Predicted Reliability	Same value definition as TABLE 3.	
Process Modification or Limitation	The average of the values assigned to the machine/tool modifications required parameter and the modifications required or process limitations parameter.	
Repeatability	Same value definition as TABLE 3.	
Resolution	Same value definition as TABLE 3.	
Technology Maturity	Same value definition as TABLE 3.	

[1] The values defined herein reflect the intent and objectives of the RIA application and are not intended to be applied to or interpeted in any other context.
[2] For actual assigned values, see completed sensor evaluation matrices in Appendix B.
[3] For example, the risk associated with accuracy could be as follows: highest possible value for accuracy from TABLE 3 is 5. Assume the assigned value is 3, then the risk value is 5 - 3 = 2.

TABLE 5. Tool Wear Sensor Types Initial Scoring Summary.

Sensor Type (Application)[1]	Evaluation Category Scores: Classification	Environmental Sensitivity	Suitability	Cost	Performance	Safety	Technology	Interface Complexity	Total Scores
Fiber Optic Proximity Array (S,M)[2]	19.2	24.7	24.9	16	16	20	12	7	140
Fiber Optic Edge[2] Detector (S)	16.8	23.8	24.9	15	15.2	20	14	6.5	136
Structured Light Machine Vision (S,M,D)[2]	18	25.6	25.7	10	15.2	16	16	7	134
1D Projection Machine Vision (S,M,D)	21.6	26.5	26.6	10	15.2	16	10	7	133
Point Range Triangulation (S)	18	22.9	25.7	10	13.6	16	16	5.5	128
Conventional Machine Vision (S,M,D)[3]	20.4	22.9	25.7	7	9.6	20	16	5.5	127
Touch Trigger Probe (S)	15.6	24.7	22.3	11	9.6	20	16	6.5	126
Bearing Deflectometer (S,M,D)	18	12	21.4	17	13.6	20	14	8.5	125
Load Cell Force Measurement (S,M,D)	15.6	12	20.6	14	12	20	14	9	117
Acoustic Emission (S,M,D)	20.4	16	18	14	8	20	10	8	114

[1]S = stationary tool application, M and D = milling and drilling, respectively, of rotary tool application.
[2]Requires additional positioning mechanism for stationary tool application.
[3]Retained as baseline.

TABLE 6. Workpiece Dimension Sensor Types Initial Scoring Summary.

Sensor Type (Application)[1]	Evaluation Category Scores: Classification	Environmental Sensitivity	Suitability	Cost	Performance	Safety	Technology	Interface Complexity	Total Scores
Optical Shadowing (S)	20.4	26.5	25.7	13	14.4	20	18	9	147
Point Range Triangulation (S,M,D)	25.2	23.8	25.7	10	13.6	16	18	5.5	138
Structured Light Machine Vision (S,M,D)	20.4	26.5	25.7	10	15.2	16	16	7	137
Touch Trigger Probe (M,D)[2]	18	24.7	22.3	11	9.6	20	20	6.5	132
Conventional Machine Vision (S,M,D)	22.8	22.9	25.7	7	9.6	20	16	5.5	130

[1] S = stationary tool application, M and D = milling and drilling, respectively, of rotary tool application.
[2] Retained as baseline.

TABLE 7. Workpiece Surface Finish Sensor Types Initial Scoring Summary.

Sensor Type (Application)[1]	Evaluation Category Scores: Classification	Environmental Sensitivity	Suitability	Cost	Performance	Safety	Technology	Interface Complexity	Total Scores
Ultrasonic Scattering (S,M)	22.8	19.4	23.1	13	14.4	20	12	7.5	132
Conventional Machine Vision (M)[2]	22.8	22.9	25.7	7	9.6[2]	20	12	5.5	126
Optical Scattering (S,M)[2]	22.8	21.2	24	12	13.6[2]	16	8	7	125

[1] S = stationary tool application, M and D = milling and drilling, respectively, of rotary tool application.
[2] Available implementations do not meet RIA measurement requirement of 20 to 150 μin. R_a.

stationary tool applications, the tool wear sensor types with the highest scores were:

- Fiber optic proximity array
- Fiber optic edge detector
- Structured light machine vision
- 1D projection machine vision.

Note that the fiber optic proximity array, 1D projection machine vision, and fiber optic edge detector types require an additional incremental linear positioner when used in a stationary tool application.

For rotary drilling applications, the tool wear sensor types with the highest scores were:

- Structured light machine vision
- 1D projection machine vision
- Conventional machine vision.

For rotary milling applications, the tool wear sensor types with the highest scores were:

- Fiber optic proximity array
- 1D projection machine vision.

4.2.2 Workpiece Dimension Sensor Types

As shown in TABLE 6, the highest scores obtained overall were those received by the workpiece dimension sensor types which reflects the maturity of these technologies. It should be noted that these sensor types have already been successfully applied to related programs for RIA [1,2]. For stationary tool applications, the workpiece dimension sensor types with the highest scores were:

- Optical shadowing
- Point range triangulation.

For rotary tool applications, the workpiece dimension sensor types with the highest scores were:

- Point range triangulation
- Structured light machine vision.

4.2.3 Workpiece Surface Finish Sensor Types

For stationary tool applications, the workpiece surface finish sensor types with the highest scores were:

- Ultrasonic scattering
- Optical scattering.

For rotary tool applications, the workpiece surface finish sensor types with the highest scores were:

* Ultrasonic scattering
* Conventional machine vision
* Optical scattering.

Note that the optical scattering and conventional machine vision sensor types have yet to be proven over the full measurement range of interest to RIA (20 to 150 μin. R_a).

4.3 Supplemental Scoring and Sensor Recommendations

As discussed in Section 4.1, the initial sensor evaluation was supplemented by two evaluation categories (potential (P) and risk (R)) added by RIA. Acoustic emission did not receive supplemental evaluation because it had inadequate performance characteristics that include the need for a unique fixture and setup. TABLES 8, 9, and 10 present the supplemental evaluation scores for each candidate sensor type.

To determine a value for the risk category, the number given to the risk category parameter "number of parameters without confirming data" (see TABLE 4) is an estimate influenced by the amount of judgment necessary to fill out the evaluation matrix, as well as an assessment of the risk associated with the determination of that data. In order for the value of the risk category to reflect a higher score for higher risk, the sense of the factors as derived from the evaluation matrices was inverted by subtraction from the highest possible score. Thus, 12 on a scale of 30 would become 18. In addition, the normalized ratio of the potential-to-risk score was calculated as follows to provide a measure of risk normalized benefit for a given sensor type:

$$P/R = (P*N)/R) \text{ where } N = 57/23.5 \text{ (see TABLE 4).}$$

Sensors were selected from those with the highest computed potential-to-risk score and recommended to RIA as shown in TABLE 11 for tool and workpiece sensing in general.

4.4 Recommended System Configuration

Based on the scores and recommendations given above, the results of the sensor evaluation specifically for integrated tool and workpiece sensor systems are shown as preliminary concepts in Figs. 22 and 23. Note that an indirect sensor type discussed in Section 3.5 is also included in each system concept to provide tool breakage and tool wear progression information in between direct sensor measurements. MTI feels that the recommended sensors offer the best balance between the RIA objectives and the development risk.

The method for performing the sensor fusion step shown in Figs. 22 and 23 is currently under evaluation by MTI. An alternative means for processing sensor information using neural networks has recently been shown to have potential application for detecting tool wear [48]. The hardware and software to implement this approach is relatively new. However, the approach offers the potential to parallel process large quantities of information very rapidly and, through a teaching process, to quickly reach conclusions on the state of tool wear that are close to the conclusions reached by an experienced machinist. These assets may prove to be essential for assessing the meaning of

TABLE 8. Tool Wear Sensors Supplementary Evaluation.

Sensor Type (Application)[1]	Potential to Meet RIA Objectives	Risk per RIA Definition	Normalized P/R Ratio
Structured Light Machine Vision (S,M,D)	15.5	10.5	3.6
1D Projection Machine Vision (S,M,D)	15.5	11.5	3.3
Fiber Optic Proximity Array (S,M)	16.5	15.5	2.6
Point Range Triangulation (S)	10.5	10.3	2.4
Fiber Optic Edge Detector (S)	12.5	15.5	2.0
Bearing Deflectometer (S,M,D)	14.5	21.5	1.6
Conventional Machine Vision (S,M,D)	10.5	15.5	1.6
Load Cell Force Measurement (S,M,D)	14.5	26	1.4
Touch Trigger Probe (S)[2]	5.5	13	1.0

[1] S = stationary tool application, M and D = milling and drilling, respectively, of rotary tool application.
[2] Retained as baseline.

TABLE 9. Workpiece Dimension Sensors Supplementary Evaluation.

Sensor Type (Application)[1]	Potential to Meet RIA Objectives	Risk per RIA Definition	Normalized P/R Ratio
Point Range Triangulation (S,M,D)	14.5	9.5	3.7
Structured Light Machine Vision (S,M,D)	14.5	9.5	3.7
Optical Shadowing (S)	10.5	7.5	3.4
Conventional Machine Vision (S,M,D)	10.5	15.5	1.6
Touch Trigger[2] Probe (M,D)	6.5	11	1.4

[1]S = stationary tool application, M and D = milling and drilling, respectively, of rotary tool application.
[2]Retained as baseline.

TABLE 10. Workpiece Surface Finish Sensors Supplementary Evaluation.

Sensor Type (Application)[1]	Potential to Meet RIA Objectives	Risk per RIA Definition	Normalized P/R Ratio
Ultrasonic Scattering (S,M)	18.5	16.5	2.7
Optical Scattering (S,M)	15.5	17	2.2
Conventional Machine Vision (M)	13	17.5	1.8

[1]S = stationary tool application, M and D = milling and drilling, respectively, of rotary tool application.

TABLE 11. Recommended Sensor Types.

Tool Wear

Stationary Tool Applications	Rotary Tool Applications
• Structured Light Machine Vision	• 1D Projection Machine Vision
• 1D Projection Machine Vision[1]	• Fiber Optic Proximity Array
• Fiber Optic Proximity Array[1]	
• Fiber Optic Edge Detector[1]	

Workpiece Dimension

Stationary Tool Applications	Rotary Tool Applications
• Point Range Triangulation	• Structured Light Machine Vision
• Optical Shadowing	• Point Range Triangulation

Workpiece Surface Finish

Stationary Tool Applications	Rotary Tool Applications
• Ultrasonic Scattering	• Ultrasonic Scattering
• Optical Scattering	• Optical Scattering[2]
	• Conventional Machine Vision[2]

[1]Requires additional positioning mechanism when used in this application.

[2]Not proven over full range of interest to RIA (20 to 150 μin. R_a).

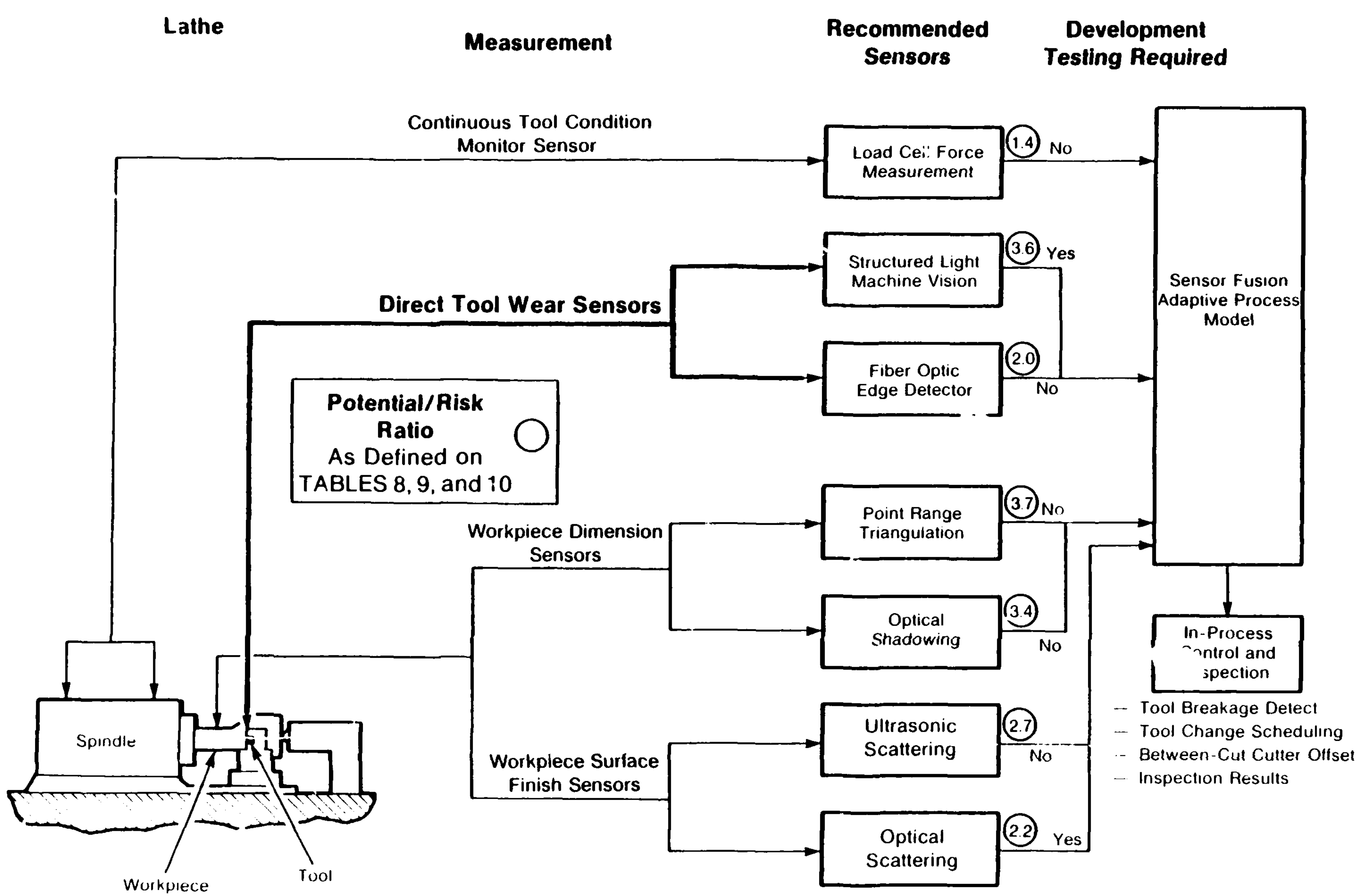

Figure 22. Stationary tool sensor system concept.

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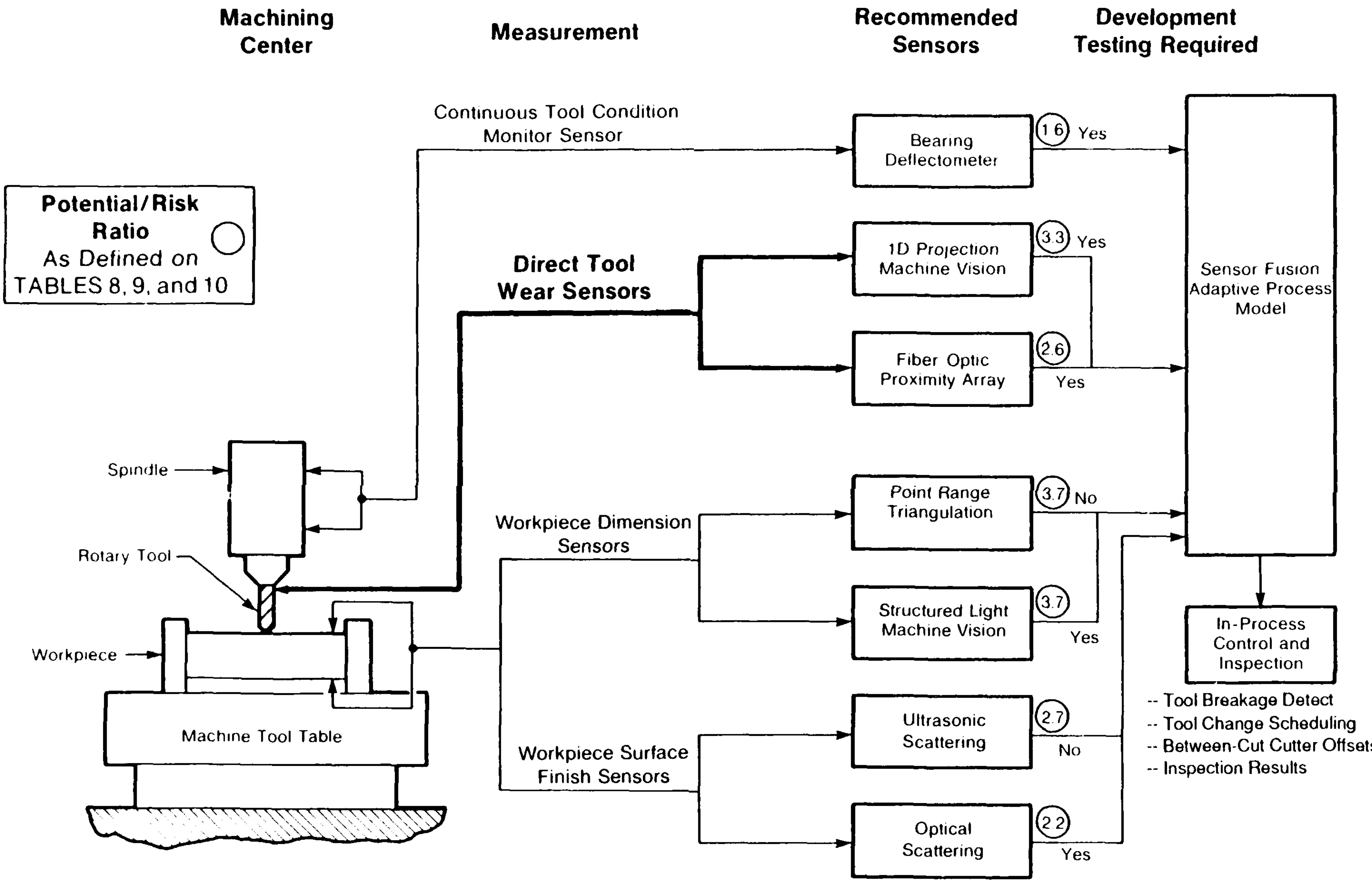

Figure 23. Rotary tool sensor system concept.

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light-based data from worn tools. Therefore, MTI will consider neural network technology when developing the conceptual designs for this project.

For those sensors that require development testing, test plans with estimated costs are presented in Section 5.0. In these plans, development testing means tests to prove the feasibility of the sensor for meeting RIA requirements. The "yes" listed under "Development Testing Required" in Figs. 22 and 23 means the sensor has the highest score among its competitors and MTI recommends proof-of-feasibility testing if these sensors are selected by RIA for integrated systems.

5.0 SENSOR TEST PLANS

This section presents the test plans proposed to demonstrate the performance of those sensors selected by RIA where feasibility cannot be ensured solely by extrapolation of published or available test data from other similar applications.

MTI recommended a load cell as the continuous monitoring sensc · selection for the stationary tool system shown in Fig. 22, since the hypothesis that cutting forces could be detected adequately by monitoring bearing reactions in a multispindle lathe headstock has not been proven. RIA, however, chose to test the bearing deflectometer in this instance to evaluate the hypothesis, to achieve greater commonality between the rotary and stationary tool sensing system concepts, and to test a new sensor applied in a unique way. In addition, the bearing deflectometer should give information on the health of the various machine elements, paving the way for machine tool diagnostics and preventive maintenance forecasting.

The following test plans include descriptions of the experimental configurations and the testing to be accomplished. Bench-top setups (breadboard testing) will be performed using equipment available at MTI and fabrication of prototype sensors where necessary. The testing will involve two basic categories: basic performance tests and sensitivity tests.

The basic performance tests will demonstrate if the sensor system possesses the accuracy, repeatability, resolution, and speed necessary for the RIA applications. Test articles will consist of simulated flank wear lands, as well as worn and unused tools supplied by RIA. Independent measurements of flank wear lands will be made using conventional measuring microscope techniques on all worn tools used for testing.

The sensitivity tests will demonstrate the effect on sensor performance due to coolant, built-up material on the cutting edge, and different tool coatings and workpiece materials.

TABLE 12 lists these sensors and provides labor-hour estimates for each category of testing. Note that in the case of the bearing deflectometer, a basic testing effort is given for the rotary tool application and that the effort for the stationary tool application is an increment to that effort.

5.1 Structured Light Machine Vision Testing

A structureu light machine vision sensor will be evaluated for its suitability to measure flank wear land width on stationary tools. The basic sensor configuration, including components, working distances, and mounting arrangements, will be specified according to the measurement requirements for each tool tested. The equipment will be assembled as shown in Fig. 24.

Computer software will be provided to analyze the image data acquired by the video camera and to determine the flank wear land width measurement. This software includes image processing to locate the structured light and numerical processing to calculate the actual size of the flank wear land in inches. Calibration software will also be provided. Much of the software will be adapted from existing MTI software.

TABLE 12. Labor-Hour Estimates for Sensor Testing.

Sensor[1]	Tool Application	Measured Parameter	Basic Performance Test (Hr)[2]	Sensitivity Test (Hr)[3]
Structured Light Machine Vision (6)	Stationary	Flank Wear Land Width	310	100
1D Projection Machine Vision (2)	Rotary	Flank Wear Land Width	440	100
Fiber Optic Proximity Array (4,5)	Rotary and Stationary	Flank Wear Land Width	460	140
Bearing Deflectometer (1)	Rotary	Cutting Force Components	470	Not Recommended
Bearing Deflectometer (3)	Stationary	Cutting Force Components	90	Not Recommended
TOTAL			1770	340

[1]Numbers in parentheses indicate priority of test.
[2]Hours include any required fabrication and setup.
[3]Expressed as increment to basic performance test effort.

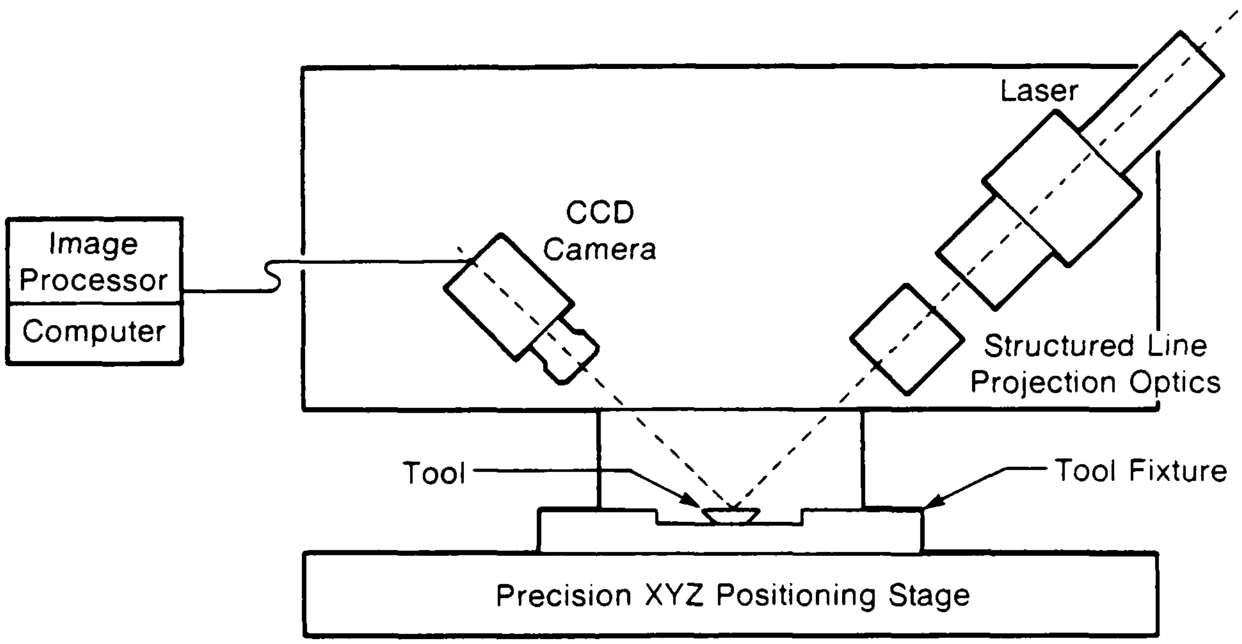

Figure 24. Structured light test configuration.

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5.1.1 Basic Performance Tests

5.1.1.1 Test 1 - Functional Capability. Functional capability will be evaluated using a test sample that is representative of flank wear lands found on typical worn tools. Simulated wear will be achieved by grinding flank wear land widths in a range from 0.001 to 0.015 in. The actual dimensions of the machined flank wear land will be determined by measuring microscope techniques. Using a linear positioning stage, the test sample will be translated so that the simulated flank wear land area is presented to the sensor at equally spaced locations. At each location, ten measurements will be taken consecutively and then analyzed to determine the mean value and standard deviation. The mean values for all locations will be plotted to show the correlation with the measuring microscope data. Existing MTI data will be used to predict the expected resolution and repeatability of the technique.

Based on the imaging strategy selected for this test, the image processing and analysis requirements will be determined and the total processing time to produce an output will be calculated to establish the measurement bandwidth.

5.1.1.2 Test 2 - Tool Wear Measurement. The sensor will be tested using worn tools provided by RIA. Using a linear positioning stage, the tools will be translated so that the flank wear land is presented to the sensor at equally spaced locations. At each location, ten measurements will be taken consecutively and then analyzed to determine the mean wear at the measurement location. For at least one measurement, a photograph will be provided to identify three key items: the structured light projection line from which the measurement data are taken, both sides of the flank wear land, and the implied flank wear land width (see Fig. 25).

5.1.2 Sensitivity Tests

5.1.2.1 Test 3 - Sensitivity to Tool Material. The sensor will be tested using two cutting tools provided by RIA. These tools will be made with materials and/or coatings that are different from the tools used in Test 1. The same basic test procedure as described in Test 2 will be performed for each tool.

5.1.2.2 Test 4 - Sensitivity to Workpiece Material on Built-Up Edge. The sensor will be tested using tools provided by RIA with workpiece material built up on the edge. The same basic test procedure as described in Test 2 will be performed.

5.1.2.3 Test 5 - New Tool Measurement. The sensor will be tested with an unused tool provided by RIA. To ensure that the sensor system confirms the absence of tool wear, the same basic test procedure as described in Test 2 will be performed.

5.2 1D Projection Machine Vision Testing

A 1D projection machine vision sensor will be evaluated for its suitability to flank wear land width measurement on rotary tools. The basic sensor configuration, including components, working distances, and mounting arrangements, will be specified according to the measurement requirements. The equipment will be assembled on a test bench as shown in Fig. 26. To eliminate the need for a custom interface board, a standard 512 x 512 charge-coupled device (CCD)

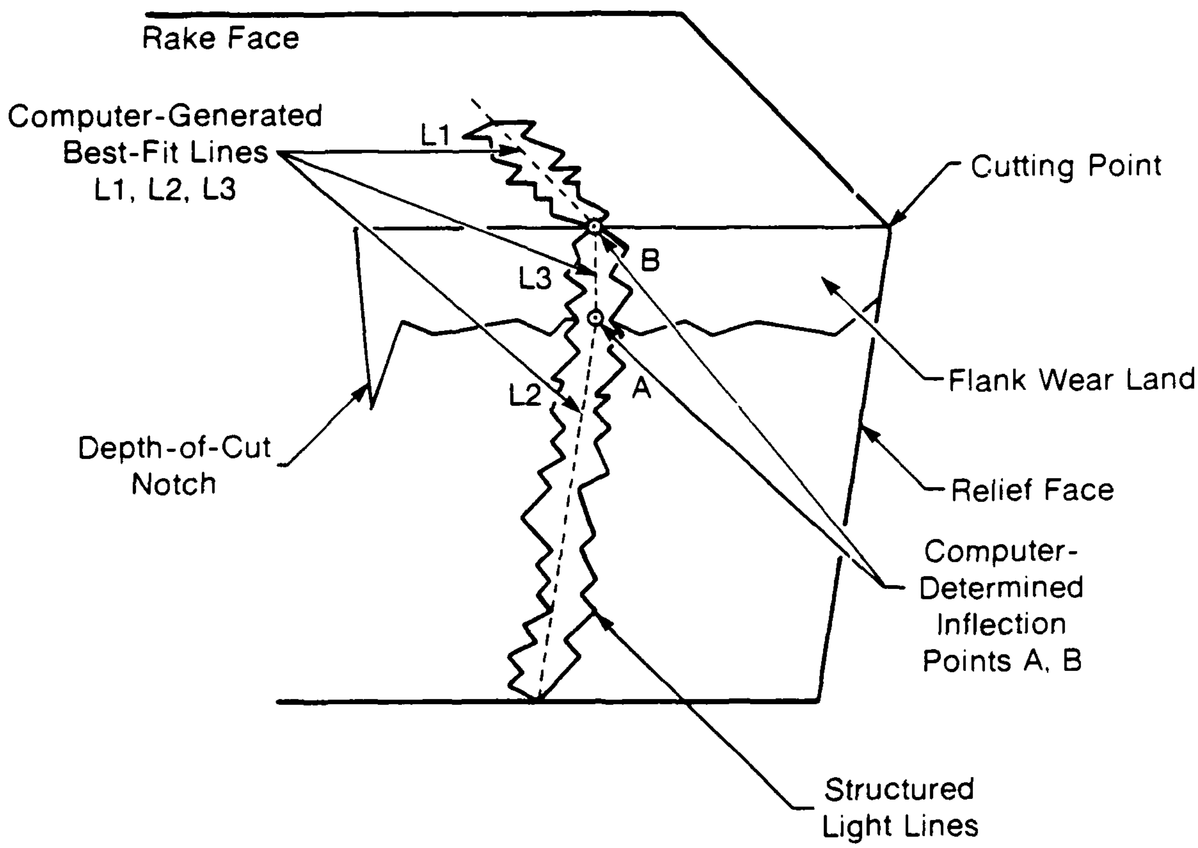

Image Processing Summary

- Average Four Frames
- Apply Low-Pass Filter
- Compute Best-Fit Lines L1, L2, L3
- Compute Intersection Points A, B
- Repeat Above Steps for Several Positions along Flank Wear Land Length

Figure 25. Structured light image processing.

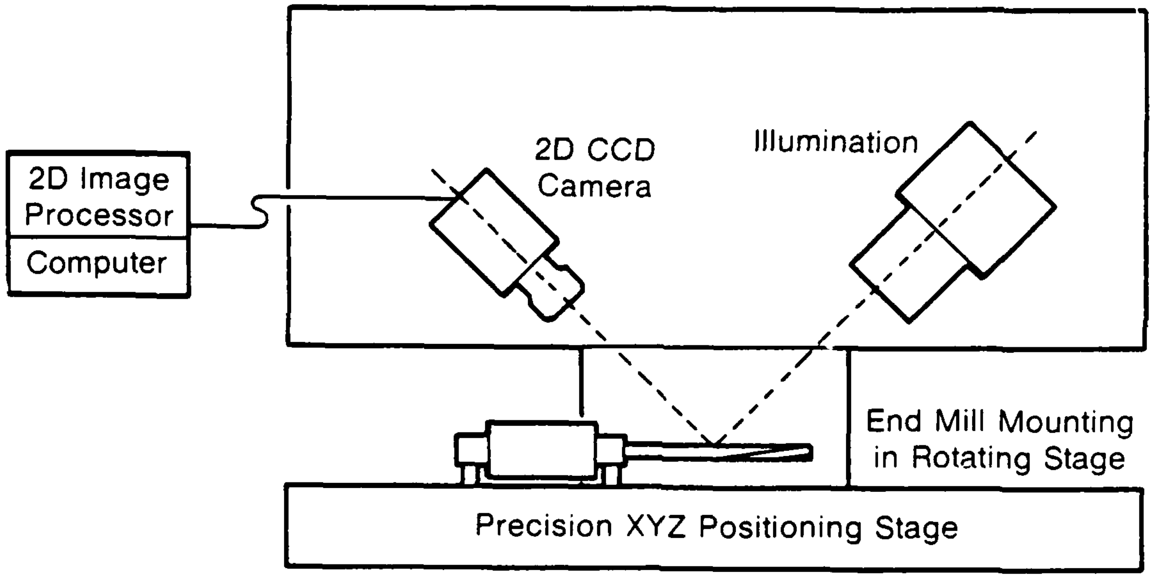

Figure 26. 1D projection machine vision test configuration.

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camera will be utilized instead of a 1D camera. One row of data from the area camera will be used to properly simulate the 1D sensor.

Computer software will be provided to analyze the image data acquired by the video camera and to perform the tool wear measurement calculations. This includes both image processing software to emulate the behavior of a 1D camera system, as well as numerical processing to calculate the actual size of the wear land in inches. Calibration software will also be provided for scaling. The software will be verified using optical test target standards.

5.2.1 Basic Performance Tests

5.2.1.1 Test 1 - Functional Capability. Functional capability will be evaluated using a test sample that has a machined area representative of flank wear lands found on typical worn tools. The machined area will have a simulated flank wear land width ranging from 0.001 to 0.015 in. Using a linear positioning stage, the test sample will be translated so that the machined area is presented to the sensor at equally spaced locations. At each location, ten measurements will be taken consecutively and then analyzed to determine the mean value and standard deviation. The mean values for all locations will be plotted to show the ability to correlate sensor output to tool wear over the required range.

To establish measurement bandwidth, the expected total measurement time, which includes image acquisition plus data processing, will be determined from the results of testing. The effect of using a 1D camera will be taken into account. MTI will draw on 1D application data available from other sources to assist in these calculations.

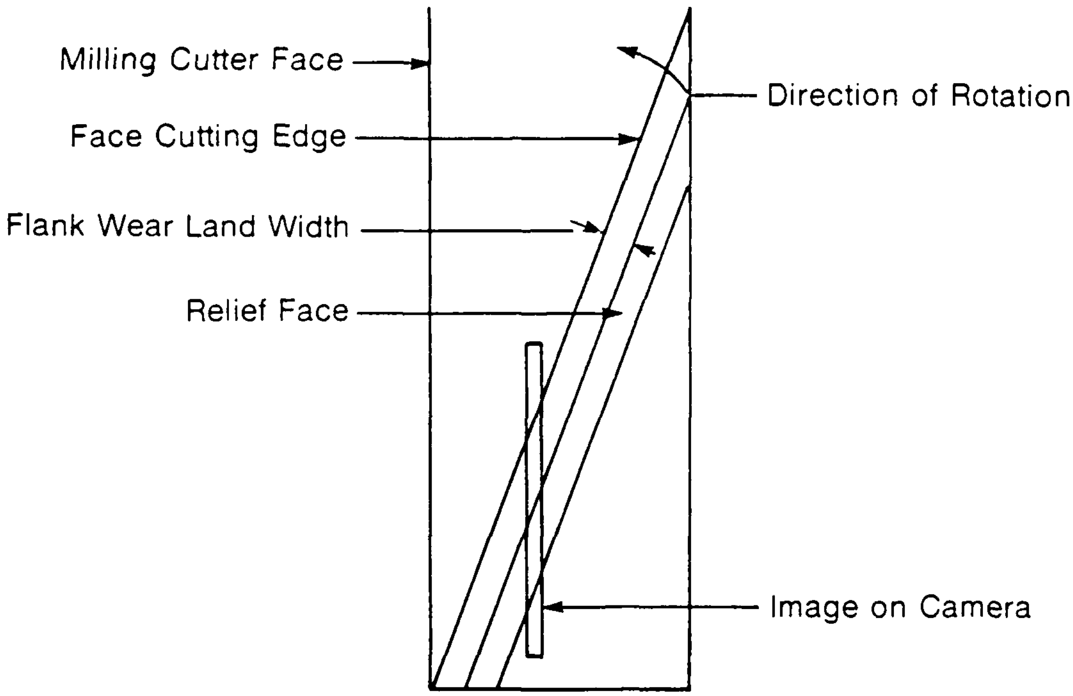
5.2.1.2 Test 2 - Tool Wear Measurement. The sensor will be tested using worn tools provided by RIA. Using a rotary positioning stage, the tool will be rotated so that the flank wear land is presented to the sensor at equally spaced locations. At each location, ten measurements will be taken consecutively and then averaged to determine the mean wear. For at least one measurement, a photograph will be provided to identify three key items: a 1D projection line from which the measurement data are taken, both sides of the flank wear land, and the implied flank wear land width (see Fig. 27).

5.2.2 Sensitivity Tests

5.2.2.1 Test 3 - Sensitivity to Tool Material. The sensor will be tested using two cutting tools provided by RIA. These tools will be made with materials and/or coatings that are different from the tools used in Test 1. The same basic test procedure described in Test 2 will be performed for each tool.

5.2.2.2 Test 4 - Sensitivity to Workpiece Material on Built-Up Edge. The sensor will be tested using tools provided by RIA with workpiece material built up on the edge. The same basic test procedure as described in Test 2 will be performed.

5.2.2.3 Test 5 - New Tool Measurement. The sensor will be tested with an unused tool provided by RIA. To ensure that the sensor system confirms the absence of tool wear, the same basic test procedure described in Test 2 will be performed.



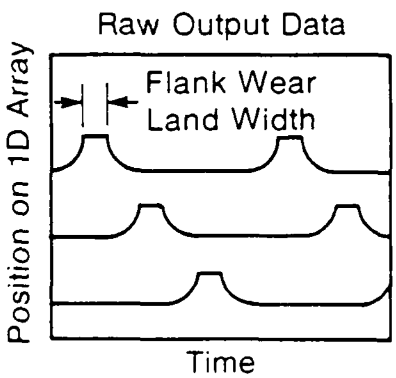


Image Processing Summary

- Capture Raw Images for 1 Revolution of Tool
- Low-Pass Filter Images
- Superimpose Equivalent Images from Separate Frames
- Average Images
- Compute Flank Wear Land Width

Figure 27. 1D projection machine vision image processing.

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5.3 Fiber Optic Proximity Array Testing

The fiber optic proximity array will be evaluated for its suitability to measure the flank wear land width on rotary and stationary tools. Part of this effort will involve fabrication of a breadboard sensor.

Fig. 28 shows two schematics of the proposed test configuration; schematic A will be utilized to establish basic feasibility. Simulated flank wear lands will be constructed from shim stock and will cover the flank wear land width ranging from 0.001 to 0.015 in. The test specimens will be mounted on a precision ball slide, and relative position with respect to the sensor will be measured with a calibrated LVDT. The raw sensor output will be processed to produce the desired measurement and this measurement will be reflectivity compensated, if necessary. This signal will be used to determine the distance from the sensor to the simulated flank wear lands.

Software is not required for these tests because processing will be accomplished using standard signal processing instrumentation.

5.3.1 Basic Performance Tests

5.3.1.1 Test 1 - Functional Capability. Correlation between the sensor output and a set of shims will be determined by a precision micrometer. After satisfactory correlation has been established, additional measurements will be taken on a stationary cutter. These cutters will have simulated flank wear lands generated by hand lapping. The flank wear land will be measured with a measuring microscope. After satisfactory correlation is established in this experiment, tests will be run on rotary milling cutters (Fig. 28, schematic B).

To establish measurement bandwidth, data from the performance tests and consideration of the final implementation approach will be used to estimate the measurement speed of the sensor.

5.3.1.2 Test 2 - Tool Wear Measurement. Representative milling cutters provided by RIA will be mounted on a lathe spindle and centered using a contacting gage.

The fiber optic proximity array will be mounted on the tool post and set up radially so that the output level is minimum when the worn flat is in view of the sensor. The face of the cutter will be rotated at low speed (50 to 100 rpm), and an oscilloscope record will be made of the output as the tool is rotated in front of the sensor. This test will be repeated for the end of the cutter if appropriate.

Application of this sensor to a stationary tool simply requires the addition of a positioning mechanism to cause the flank wear land to be moved in front of the sensor. Since this mechanical arrangement will not add to the sensor data base, no additional testing is required for this application.

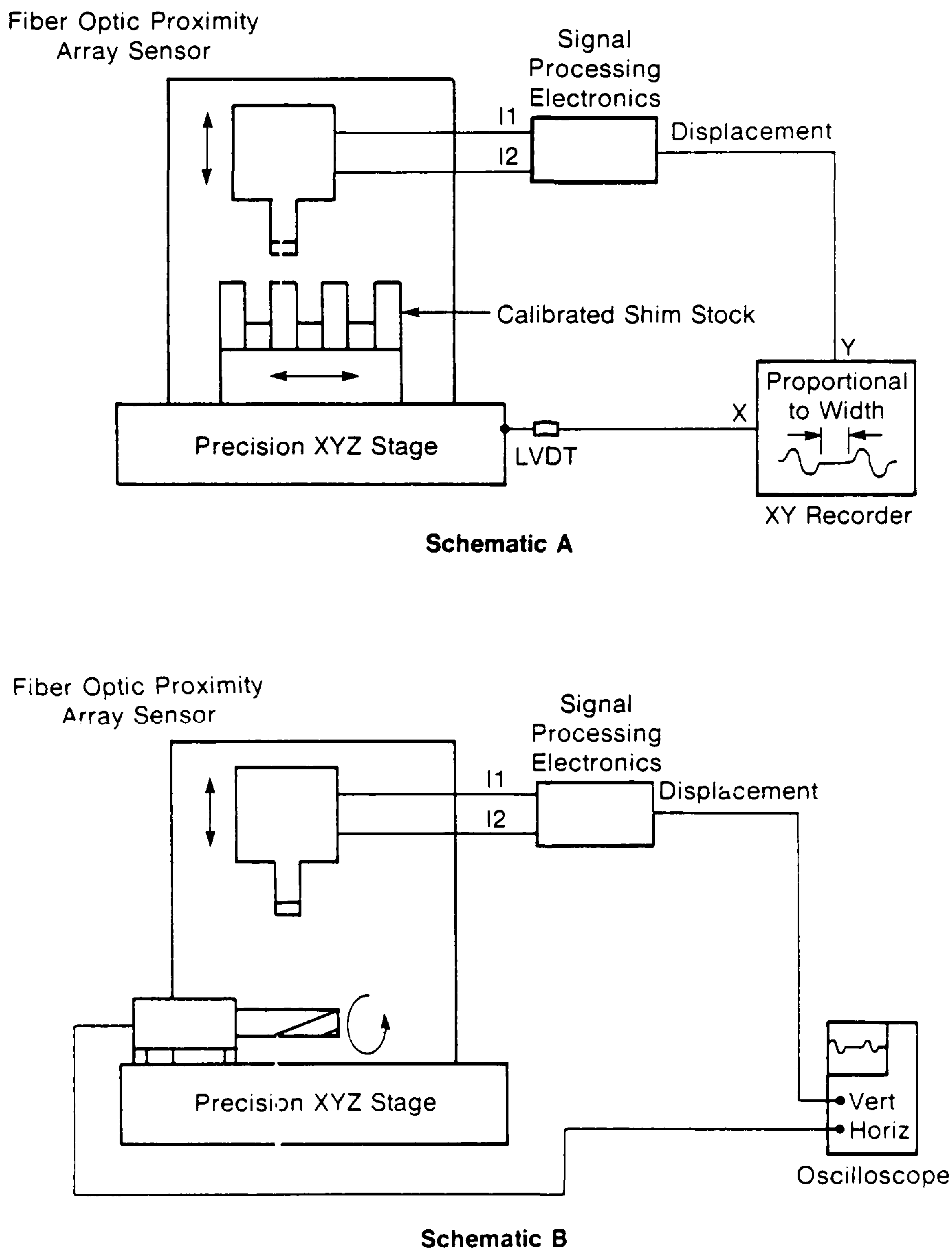

Figure 28. Fiber optic proximity array test configuration.

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5.3.2 Sensitivity Tests

5.3.2.1 Test 3 - Sensitivity to Tool Material. Due to the reflectivity compensation feature of the sensor, it is expected that the measurements will be insensitive to tool material. Using the setup shown in Fig. 28, schematic B, this expectation will be verified with tools supplied by RIA.

5.3.2.2 Test 4 - Sensitivity to Workpiece Material on Built-Up Edge. Flank wear land measurements are expected to be affected by the presence of a built-up edge on the cutting tool. The flank wear land will be indicated as larger than it actually is by the width of the built-up edge. An extension of the basic approach, which adds an additional sensor in the unworn area of the tool, will allow compensation for the built-up edge. Data from the basic sensor will also be used to establish the profile of the cutting edge of an unused tool. These data will be saved and used later to correct data taken on worn tools that have a built-up edge.

5.3.2.3 Test 5 - New Tool Measurement. The sensor will be tested with an unused tool provided by RIA. To ensure that the sensor system confirms the absence of tool wear, the same basic test procedure as described in Test 2 will be performed.

5.4 Bearing Deflectometer Testing

Bearing deflectometer tests will be conducted for both rotary and stationary tools. The basic objective of the performance testing is to demonstrate the ability to obtain the components of the cutting forces using sensors in contact with the outer race of the spindle bearing. Two sensors will be mounted at 90° on the outer race of each bearing assembly to acquire force information.

An existing Clausing-Colchester 13-in. lathe will serve as the test bed. Fixtures to apply and measure radial and axial forces will be installed on the cross slide and tailstock, respectively (Fig. 29). This will permit data to be taken for both rotary and stationary tool applications.

For the rotary tool application, a cylindrical blank will be chucked to simulate a milling cutter and thrust and feed forces will be simulated through the tail stock quill shaft. For the stationary tool application, a cylindrical workpiece will be used, and forces will be applied through a quill shaft near the tailstock end of the workpiece to ascertain whether the forces can be detected at the headstock bearing. Each sensor will be calibrated statically prior to testing.

Software is not required for these tests because processing will be accomplished in hardware.

5.4.1 Basic Performance Tests (Rotary Tool)

5.4.1.1 Test 1 - Functional Capability. Axial, radial, and combined loads similar to those expected in milling will be applied. The sensor outputs will be analyzed to separate the force components from the composite sensor signals that contain components of radial, axial, preload, and ball pass modulation forces. Sensor outputs will be compared to the values indicated by calibrated

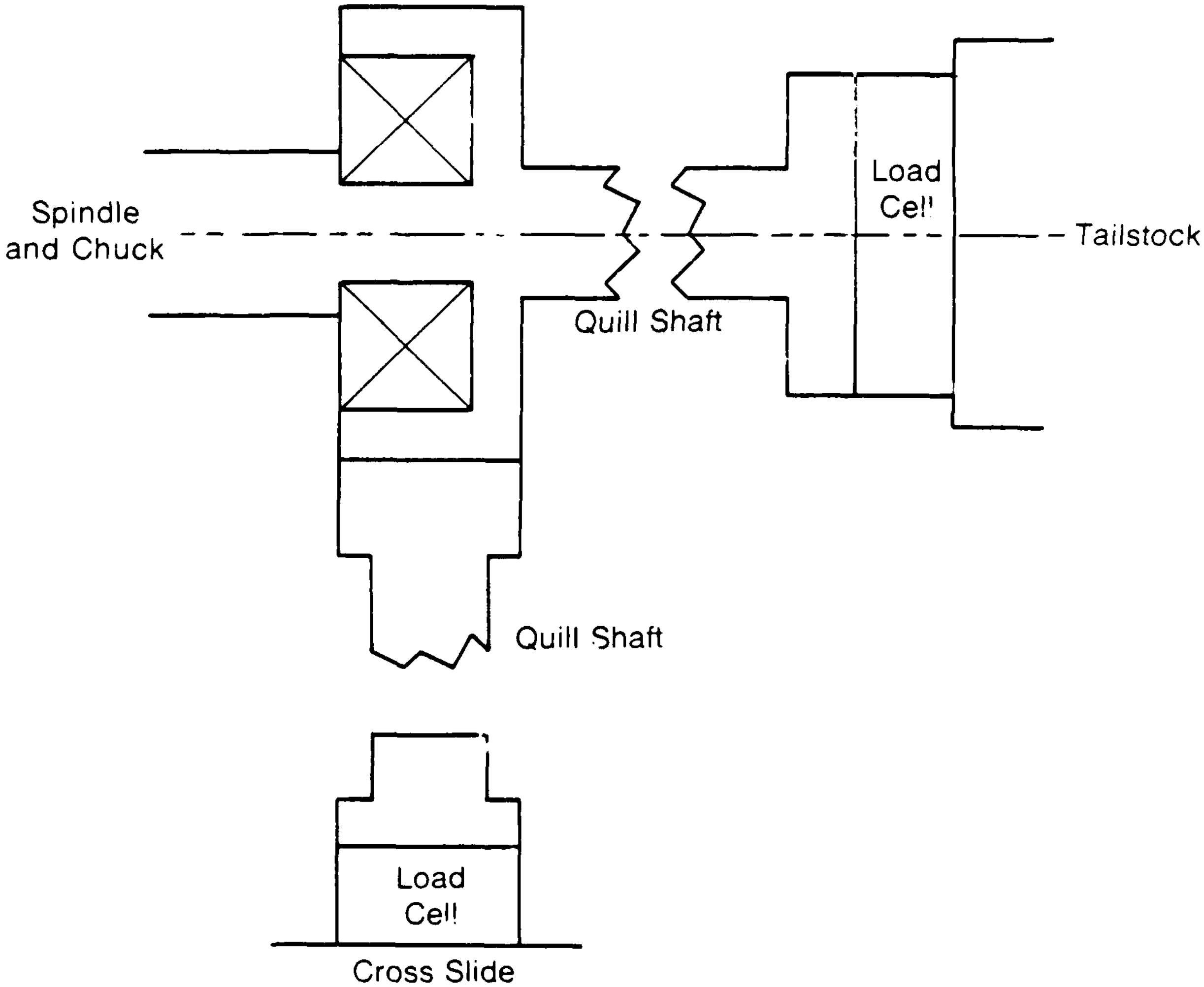

Figure 29. Bearing deflectometer test configuration.

load cells to establish correlation. Published data will be utilized to quantity the force differences that result from the wear progression from a rew to a worn tool.

To establish measurement bandwidth, estimates will be made of signal processing requirements to extract the force components from the raw deflectometer signal.

5.4.1.2 Test 2 - Sensitivity Tests. The ability to resolve the forces in the presence of varying preload, spindle vibration, and other machine defects can be investigated. However, these tests are not recommended at this time due to risk of damage to the test machine and the perceived high cost.

5.4.2 Basic Performance Tests (Stationary Tool)

The functional capability tests described above for a rotary tool will be repeated for a configuration similar to a normal lathe application. The ability to resolve the forces that are meaningful to assessing tool wear and are transmitted through all interfaces between the tool and the sensor will be investigated.

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6.0 SURVEY OF COMMERCIALLY AVAILABLE SENSORS

To provide a complete overview of the sensing technologies applicable to tool and workpiece sensing, a survey was made of the commercially available sensors for tool condition monitoring. This survey consisted of review of a previously published survey of commercial tool monitoring systems [47], obtaining vendor literature and making calls to selected vendors, and discussions with vendors at Sensors '87 Expo.

In all, 17 systems from 14 vendors were considered (see TABLE 13). All of these systems are after-market items that are not built into the original machine tool. The systems can be grouped into the following categories based on sensing technology; the numbers in parentheses indicate the number of systems surveyed for a given sensor type:

- Accelerometer (2)
- Acoustic emission (1)
- Electric power/torque (4)
- Inductive sensor (1)
- Infrared detector (1)
- Instrumented bearing (spindle or leadscrew) (4)
- Piezoelectric force sensors (fixed-point application) (2)
- Touch trigger probe (2).

Of these systems, only the touch trigger probes and the force-related systems have found general application. None of the above methods offer complete surveillance of machine tools to provide end-of-life prediction, wear estimation, and breakage detection for cutting tools.

Since the published literature indicated that the piezoelectric force sensors held the most promise of the indirect methods [16], vendors of these systems were contacted for more information to determine the degree of application sensitivity which exists. As expected, the contacts revealed that the customer's application is considered in detail by vendor personnel before purchase is recommended. It should be noted that force-related systems should not be used when substantial crater wear is expected. Published work [16] has shown that force increase due to wear is partially or totally compensated for by reduction in force due to the weakened rake face.

At the request of RIA, commercially available acoustic emission systems were also investigated further (see Appendix A). This revealed one acoustic emission system capable of early warning or actual breakage detection in systems using small tools, that is, less than 1/2-in. diameter. As with the force-related systems, a great deal of "learning" by an acoustic emission system is required for reliable operation.

TABLE 13. Commercially Available Sensors for Tool Monitoring.

Manufacturer	Type	Sensed Parameter	Comments
BILZ	Electric power/ torque	Torque	Adaptive control for drilling and tapping.
Digital Techniques	Electric power/ torque	Feed or cutting forces or torque	
Digital Techniques	Touch trigger probe	Cutting forces	
Euchner	Inductive sensor	Breakage	Detects presence of tool at extremes of travel
HBM	Instrumented bearing	Bearing loads	Measures through envelope detection.
Kennametal	Acoustic emission	Changes in acoustic emission signature	Breakage detection through signature analysis.
Kennametal	Piezoelectric force	Cutting forces	Tool wear/breakage by signature analysis.
Kruppwidia	Piezoelectric force	Cutting forces	20-ms response, 16 sensors or tools programmable.
Leure	Infrared detector	Breakage	
OKA	Accelerometer	Vibration	Programmable limits for adaptive control.
Pera	Accelerometer	Vibration	Breakage and wear through vibration analysis.
Promess	Instrumented bearing	Feed or cutting forces	
QUE	Acoustic emission	Vibration changes	Uses real-time acoustic emission analysis.
Renishaw	Touch trigger probe	Cutting forces	Cutting edge recession and offsets.
Sandvik - Coromant	Electric power/ torque	Feed or cutting forces or torque	Breakage and wear. Programmable limits for adaptive control.
Sandvik Coromant	Instrumented bearing	Feed or cutting forces	

TABLE 13. (Continued).

Manufacturer	Type	Sensed Parameter	Comments
SKF	Instrumented bearing	Feed or cutting forces	Applied to milling, drilling, turning. 3-ms response time.
Valerite	Electric power/ torque	Feed or cutting forces or torque	

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APPENDIX A
VENDOR BROCHURES

This appendix presents a list of vendors who have brochures for commercial products applicable to tool and workpiece sensing. These include key components for sensing systems, e.g., cameras for machine vision sensors.

- EG&G Reticon Modular Line Scan Camera (1D Machine Vision)
- EOIS MK VII Series (Projection Interferometry)
- Kennametal Rotating Tool Monitor Breakage System (Acoustic Emission)
- Kennametal Tool Condition Sensor (Load Cell Force Measurement)
- Polytek Fiber Optic Laser Vibrometer (Laser Velocimeter)
- Promess Tool Condition Monitor (Strain Gage Force Measurement)
- Rodenstock RM 600 Laser Stylus (Point Range Triangulation)
- Rodenstock Optical Surface Finish Measuring System RM 400 (Surface Finish)
- Selcom Optocator Gage (Point Range Triangulation)
- Systemes SUD Video Micro-Camera (2D Machine Vision)
- QUE Computers, Inc. Cimtec AE100 Acoustic Emission Tool Monitoring System (Acoustic Emission)
- Valeron Division, Digital Tecniques, Tool Sense™ Machine Tool Monitor (Power Draw Monitor)
- VIDISPEC Electric Speckle Pattern Interferometer (Laser Interferometry)
- Zygo Laser Shadow Gages (Optical Shadowing).

Because some of the brochures have registered trademarks, this appendix has been published separately under "A Critical Review for Tool and Workpiece Sensing, Appendix A, Vendor Brochures," authorized to U.S. Government agencies only.

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APPENDIX B
CANDIDATE SENSOR EVALUATION MATRICES

This appendix presents the completed evaluation matrices for the candidate sensor types that qualified for ranking based on their ability to meet RIA criteria for tool and workpiece sensing.

B.1 Evaluation Approach

At the beginning of the evaluation process, it became evident that many areas must be considered to properly evaluate the potential of a given sensor type within the context of RIA's application objectives. To meet this need and ensure a complete evaluation, a matrix approach was formulated. Eight evaluation categories with corresponding parameters were determined based on MTI's experience with sensor technology and discussions with RIA regarding their needs. The resulting evaluation categories and their parameters include:

- **Classification** - to evaluate measurement approach and potential applications for a sensor type. Parameters include application versatility, computed parameter, measurement method, measurement mode, and measurement type.
- **Environmental Sensitivity** - to evaluate sensor sensitivity to environmental effects. Parameters include airborne pollutants, ambient light, ambient temperature, built-up edge, chip form, collisions, coolant, coolants or chips on tool or workpiece, coupling medium composition and purity, electrical noise, hardness, orientation to surface structure, speeds/feed/depth of cut, stiffness, surface finish, tool material, tool temperature, vibration, and workpiece material.
- **Suitability** - to evaluate sensor suitability for the RIA application. Parameters include acceptability to operators, calibration requirements, ease of use, expected life, use requires process modifications or limitations, modifications required to machines or tools, and predicted reliability. Two of these parameters require further definition: calibration requirements and predicted reliability. Calibration requirements include such factors as the complexity and frequency of calibration, requirements for special fixtures and instrumentation, and whether a sensor must be returned to the vendor for calibration. Predicted reliability is defined as an assessment of the overall complexity of the hardware plus the collision damage potential.
- **Cost** - to evaluate sensor cost. Parameters include adaptation, development, maintenance, and recurring costs. Adaptation costs are defined as the cost to adapt a system developed for one application (e.g., turning) to a different application (e.g., milling). Maintenance costs include cost of fixed life items and costs for periodic calibration, and recurring costs include the estimated cost of copying a sensor system after the development cycle is complete.
- **Performance** - to evaluate sensor performance. Parameters include accuracy, bandwidth, growth potential, repeatability for a single measurement, and resolution. Since these performance parameters can be interpreted in several ways, all require further definition. Accuracy is defined as the deviation of the mean of a number of measurements from the actual value. Bandwidth is defined as the number of measurement results a sensor can produce in unit time and not the sensor's raw data rate. For example, a two-dimensional camera can acquire 30 frames/sec, but the actual frame processing rate into requested measurements may be 0.5 sec/frame. Growth

potential is defined as the assessment of prospects for advances in performance, price reductions, and increasing suitability for factory use. Repeatability is defined as the scatter associated with a group of measurements under identical measurement conditions. Finally, resolution is defined as the minimum change in measurement quantity that can be repeatably detected by a sensor.

- **Safety** - to evaluate sensor safety. Although this category has no specific parameters, hazards such as the potential to cause eye damage and potential exposure to radiation were considered.
- **Technology** - to evaluate the level of risk for a given sensor. Parameters include measured physical quantity, maturity of model or algorithms relating sensor output to measured parameter, and technology maturity.
- **Interface Complexity** - to evaluate how a sensor will interface to and integrate with the overall system architecture. Parameters include ancillary requirements, hardware and processing requirement complexities, and the need for sensor positioning mechanisms.

Once the categories and parameters were determined, each category was assigned a weight number from 1 to 3; 1 represents the lowest value and 3 the highest. This weighting reflects RIA's assessment of the importance of that category to their applications. Values were also assigned to each parameter as defined in the matrices.

B.2 Evaluation Matrices

The evaluation matrices for the sixteen candidate sensor types are presented on the following pages in alphabetical order:

- Acoustic Emission (Table B-1)
- Bearing Deflectometer (Table B-2)
- Capacitance (Table B-3)
- Contact LVDT Family (Table B-4)
- Conventional Machine Vision (Table B-5)
- Fiber Optic Edge Detector (Table B-6)
- Fiber Optic Proximity Array (Table B-7)
- Load Cell Force Measurement (Table B-8)
- 1D Projection Machine Vision (Table B-9)
- Optical Shadowing (Table B-10)
- Optical Scattering (Table B-11)
- Point Range Triangulation (Table B-12)
- Projection Interferometry (Table B-13)
- Structured Light Machine Vision (Table B-14)
- Touch Trigger Probe (Table B-15)
- Ultrasonic Scattering (Table B-16).

TABLE B-1. Acoustic Emission Evaluation Matrix.

Category [weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	5	
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	2	TB, TW
Measurement Method	3 = indirect, 5 = direct	3	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	5	
Measurement Type	2 = contact, 5 = noncontact	2	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	9	Built-up edge (-1), chip form (-1), hardness (-1), speeds/feed/depth of cut (-1), stiffness (-1), tool material (-1), vibration (-1), workpiece material (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category,		
Acceptability to Operators	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Calibration Requirements		2	Uncertain stability.
Ease of Use		2	Sensor must be positioned empirically.
Expected Life		3	
Machine/Tool Modifications Required		4	Sensor must be attached to machine/workpiece.
Modifications Required or Process Limitations		4	Sensor position may be function of work piece.
Predicted Reliablity		3	

[1]Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2]The values defined and assigned herein reflect the intent and objectives of the RIA applicaiton and are not intended to be applied to or interpreted in any other context.
[3]SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.

TABLE B-1. (Continued).

Category [weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	1	
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	2	
Maintenance	0 = high, 1 = medium, 2 = low	1	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	10	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	2	Estimates for wear detection; good results for TB only.
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	3	Built-up edge, chip breaking, and wave guide effects limit applicability to wear measurement.
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	1	
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	2	Estimate.
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	2	Estimate.
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]	Ultrasonic stress waves	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	1	No analytic model, incomplete empirical data, only proven for breakage detection.
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	Deduct 1 point for each ancillary. Point range 0 to 5.	5	
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	5	

[4]No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[5]Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-2. Bearing Deflectometer Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	3	Applicability to stationary tool must be demonstrated.
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	2	TB, TW
Measurement Method	3 = indirect, 5 = direct	3	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	5	
Measurement Type	2 = contact, 5 = noncontact	2	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	7	Built-up edge (-1), chip form (-1), coolant (-1), electrical noise (-1), hardness (-1), speed/feed/depth of cut (-1), stiffness (-1), tool material (-1), vibration (-1), workpiece material (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category, 0, 1 = low; 2, 3 = medium; 4, 5 = high		
Acceptability to Operators		3	
Calibration Requirements		3	Periodic to quantify any machine/process-related changes that affect output.
Ease of Use		2	May require cutting tests to establish parameters for each process change.
Expected Life		4	
Machine/Tool Modifications Required		4	Access holes must be drilled in spindle housing.
Modifications Required or Process Limitations		5	
Predicted Reliablity		4	

[1] Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2] The values defined and assigned herein reflect the intent and objectives of the RIA appliicaiton and are not intended to be applied to or interpreted in any other context.
[3] SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.

TABLE B-2. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	1	
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	4	
Maintenance	0 = high, 1 = medium, 2 = low	2	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	10	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	2	Estimate.
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	5	
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	3	May be restricted to specific applications.
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	3	Estimate.
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	
SAFETY [2]	0 = *unreconcilable hazard*, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]	Cutting forces	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	Deduct 1 point for each ancillary. Point range 0 to 5.	5	
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 - high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = *none*	5	

[4]No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[5]Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-3. Capacitance Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	1	TW
Computed Parameter	Give 1 point each: SF, TB, TO, TW,	1	
	WD.[3] Point range 0 to 5.	5	
Measurement Method	3 = indirect, 5 = direct	2	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process		
Measurement Type	2 = contact, 5 = noncontact	5	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	14.5	Coolants or chips on tool/workpiece (-1/2), tool material (-1), tool temperature (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category,		
Acceptability to Operators	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	Refixturing required for different relief angles.
Calibration Requirements		4	Positioning accuracy must be checked.
Ease of Use		5	
Expected Life		5	
Machine/Tool Modifications Required		5	
Modifications Required or Process Limitations		5	
Predicted Reliablity		5	

[1]Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2]The values defined and assigned herein reflect the intent and objectives of the RIA applicaiton and are not intended to be applied to or interpreted in any other context.
[3]SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.

TABLE B-3. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	0	
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	4	Ultraprecise positioning repeatability required.
Maintenance	0 = high, 1 = medium, 2 = low	2	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	0	Probably not better than 5 mil.
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	5	Ultraprecise positioning repeatability impractical.
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	1	
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	2	
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	1	
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]	Volumetric loss of tool	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	Deduct 1 point for each ancillary. Point range 0 to 5.	3	Special enclosure, tool cleaning required.
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	0	Ultraprecise positioning required.

[4] No numerical value is assigned as this item is a variable, e.g., *cutting force, tool geometry, etc.*, and is specific to given sensor type.

[5] Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-4. Contact LVDT Family Evaluation Matrix.

Category [weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	1	
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] *Point range 0 to 5.*	2	TW, WD
Measurement Method	3 = indirect, 5 = direct	5	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	2	
Measurement Type	2 = contact, 5 - noncontact	2	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. *Point range 0 to 17.*	14	Built-up edge (-1/2), collisions (-1), *coolants or chips on tool/workpiece* (-1/2), surface finish (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category, 0, 1 = low; 2, 3 = medium; 4, 5 = high		
Acceptability to Operators		5	
Calibration Requirements		5	
Ease of Use		5	
Expected Life		4	
Machine/Tool Modifications Required		5	
Modifications Required or Process Limitations		5	
Predicted Reliablity		5	

[1]Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2]The values defined and assigned herein reflect the intent and objectives of the RIA application and are not intended to be applied to or interpreted in any other context.
[3]SF = surface finish, TB = tool breakage, TO - tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.

TABLE B-4. (Continued).

Category [weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	0	Not really applied to rotary tools
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	4	
Maintenance	0 = high, 1 = medium, 2 = low	2	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	3	Limited by positioning mechanism.
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	3	
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	0	
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	3	Limited by positioning mechanism.
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	3	Limited by positioning mechanism.
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]	*Surface profile*	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	Deduct 1 point for each ancillary. Point range 0 to 5.	3	Special enclosure (-1), tool cleaning (-1).
Hardware Requirements	0, 1 = low; 2, 3 = *medium*; 4, 5 = high	5	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	3	

[4] No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.

[5] Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-5. Conventional Machine Vision Evaluation Matrix.

Category [weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	1 (TW)[4], 3 (SF), 3 (WD)	
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	4	TO, TW, SF, WD
Measurement Method	3 = indirect, 5 = direct	5	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	2	
Measurement Type	2 = contact, 5 = noncontact	5	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	13	Airborne pollutants (-1/2), ambient light (-1/2), coolants or chips on tool/workpiece (-1/2), electrical noise (-1/2), surface finish (-1), tool material (-1/2), vibration (-1/2).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category,		
Acceptability to Operators	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
Calibration Requirements		4	Special calibration fixtures and lighting compensation required.
Ease of Use		5	
Expected Life		4	Light sources have limited life.
Machine/Tool Modifications Required		5	
Modifications Required or Process Limitations		4	1 to 5 sec addition to cycle time
Predicted Reliablity		3	Complex electronics of uncertain factory suitability.

[1] Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2] The values defined and assigned herein reflect the intent and objectives of the RIA application and are not intended to be applied to or interpreted in any other context.
[3] SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.
[4] Multiple values indicate sensor scores for more than one application.

TABLE B-5. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	0	
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	2	
Maintenance	0 = high, 1 = medium, 2 = low	0	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	2	
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	0	1 to 5 sec to process data.
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	4	Shows trends towards lower hardware cost, faster processing speed, and better algorithms.
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	2	
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[5]	Physical dimensions	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	Needs more sophisticated feature recognition algorithms.
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	3(SF) 5(TO, TW, WD)	
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[6]	Deduct 1 point for each ancillary. Point range 0 to 5.	1	Air, power, special enclosure, tool cleaning required.
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	2	
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	5	

[5] No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[6] Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-6. Fiber Optic Edge Detector Evaluation Matrix.

Category [Weight] [1]	Value Definition [2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	1	TW
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WO.[3] Point range 0 to 5.	1	
Measurement Method	3 = indirect, 5 = direct	5	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	2	
Measurement Type	2 = contact, 5 = noncontact	5	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	13.5	Airborne pollutants (-1/2), ambient light (-1/2), coolants or chips on tool/workpiece (-1/2), tool material (-1), vibration (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category,		
Acceptability to Operators	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
Calibration Requirements		3	Uncertain stability over long periods of time.
Ease of Use		5	
Expected Life		3	Delicate sensor.
Machine/Tool Modifications Required		5	
Modifications Required or Process Limitations		4	Addition of seconds to cycle time.
Predicted Reliablity		4	

[1] Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2] The values defined and assigned herein reflect the intent and objectives of the RIA applicaiton and are not intended to be applied to or interpreted in any other context.
[3] SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WO = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.

TABLE B-6. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	0	Possible application to milling.
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	4	
Maintenance	0 = high, 1 = medium, 2 = low	1	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	10	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	3	Estimate.
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	5	
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	3	
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]	Physical dimensions	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	Performance needs to be proven.
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	New application of established fiber optic technology.
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	Deduct 1 point for each ancillary. Point range 0 to 5.	2	Air, special enclosure, and tool cleaning required.
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	5	

[4]No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[5]Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-7. Fiber Optic Proximity Array Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	3	Requires additional positioning mechanism for stationary tool.
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	1	TW
Measurement Method	3 = indirect, 5 = direct	5	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	2	
Measurement Type	2 = contact, 5 = noncontact	5	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	14	Airborne pollutants (-1/2), ambient light (-1/2), coolants or chips on tool/workpiece (-1/2), tool material (-1/2), vibration (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category,		
Acceptability to Operators	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
Calibration Requirements		4	
Ease of Use		5	For rotary tool.
Expected Life		3	
Machine/Tool Modifications Required		5	
Modifications Required or Process Limitations		4	May add seconds to cycle time.
Predicted Reliablity		3	Delicate sensor assembly at close stand-off.

[1] Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2] The values defined and assigned herein reflect the intent and objectives of the RIA application and are not intended to be applied to or interpreted in any other context.
[3] SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.

TABLE B-7. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	1	
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	4	
Maintenance	0 = high, 1 = medium, 2 = low	1	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	10	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	3	Estimate.
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	5	
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	4	May be applicable to variety of tool types.
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	4	
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	4	
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]	Physical dimensions	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	Algorithms/performance needs to be proven.
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	New application of established technology.
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	Deduct 1 point for each ancillary. Point range 0 to 5.	2	Air, special enclosures, and tool cleaning required.
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	5	For rotary tools only.

[4]No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[5]Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-8. Load Cell Force Measurement Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	1	
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	2	TB, TW
Measurement Method	3 = indirect, 5 = direct	3	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	5	
Measurement Type	2 = contact, 5 = noncontact	2	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	7	Built-up edge (-1), chip form (-1), coolant (-1), electrical noise (-1), hardness (-1), speeds/feed/depth of cut (-1), stiffness (-1), tool material (-1), vibration (-1), workpiece material (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category, 0, 1 = low; 2, 3 = medium; 4, 5 = high		
Acceptability to Operators		3	
Calibration Requirements		3	Periodic checks required to verify stability.
Ease of Use		2	Requires cutting tests to establish parameters for each process change.
Expected Life		4	
Machine/Tool Modifications Required		3	Dynamometer must be fit/retrofit to machine.
Modifications Required or Process Limitations		5	
Predicted Reliablity		4	

1 Numbers in brackets designate category weights assigned to reflect RIA application objectives.
2 The values defined and assigned herein reflect the intent and objectives of the RIA application and are not intended to be applied to or interpreted in any other context.
3 SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.

TABLE B-8. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	1	
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	6	
Maintenance	0 = high, 1 = medium, 2 = low	2	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	
PERFORMANCE [4]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	2	Estimate. May be acceptable in certain cases
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	4	
Growth Potential	0,1 = low; 2, 3 - medium; 4, 5 = high	3	May be restricted to special applications where process is constrained.
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	2	Estimate. May be acceptable in certain cases.
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	4	Marginal for small tools/cuts in soft materials.
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]	Cutting forces	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	2	No comprehensive analytical model exists, only empirical data.
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	Deduct 1 point for each ancillary. Point range 0 to 5.	5	
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	For lookup methods.
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	5	

[4] No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[5] Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-9. 1D Projection Machine Vision Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	5	
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	1	TW
Measurement Method	3 = indirect, 5 = direct	5	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	2	
Measurement Type	2 = contact, 5 = noncontact	5	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	15	Airborne pollutants (-1/2), built-up edge (-1/2), coolants or chips on tool/workpiece (-1/2), electrical noise (-1/2).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category,		
Acceptability to Operators	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	
Calibration Requirements		5	
Ease of Use		5	
Expected Life		5	
Machine/Tool Modifications Required		5	
Modifications Required or Process Limitations		4	Adds a few seconds to cycle time.
Predicted Reliablity		4	

[1]Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2]The values defined and assigned herein reflect the intent and objectives of the RIA applicaiton and are not intended to be applied to or interpreted in any other context.
[3]SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.

TABLE B-9. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	1	
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	2	
Maintenance	0 = high, 1 = medium, 2 = low	2	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	3	Estimate.
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	5	Much faster than conventional machine vision.
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	5	Capable with much less electronics and more straightforward processing of wide range of cutter profiles than conventional machine vision.
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	Estimate.
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	3	Estimate.
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	8	Class IIIb laser requires enclosure. May be able to use conventional illumination.
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]	Physical dimensions	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	Requires development.
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	May require custom processing hardware.
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	Deduct 1 point for each ancillary. Point range 0 to 5.	1	Air, power, special enclosure, tool cleaning required.
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	5	

[4] No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[5] Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-10. Optical Shadowing Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	1	
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD[3] Point range 0 to 5.	1	WD
Measurement Method	3 = indirect, 5 = direct	5	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	5	
Measurement Type	2 = contact, 5 = noncontact	5	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	15	Coolants or chips on tool/workpiece (-1), vibration (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category, 0, 1 = low; 2, 3 = medium; 4, 5 = high		
Acceptability to Operators		3	
Calibration Requirements		5	
Ease of Use		5	
Expected Life		4	
Machine/Tool Modifications Required		4	Mounting may be difficult for large sensor heads.
Modifications Required or Process Limitations		5	
Predicted Reliablity		4	

1 Numbers in brackets designate category weights assigned to reflect RIA application objectives.

2 The values defined and assigned herein reflect the intent and objectives of the RIA application and are not intended to be applied to or interpreted in any other context.

3 SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.

TABLE B-10. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	0	Limited to rotationally symmetric parts available off the shelf.
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	6	
Maintenance	0 = high, 1 = medium, 2 = low	2	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	4	0.3 mil
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	4	
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	2	
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	4	0.5 mil or better with averaging (to 1 mil).
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	4	0.2 mil
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	For white-light versions only, laser devices would receive a lower score of 6.
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]	Workpiece diameter	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Technology Maturity	0, 1 = low, 2, 3 = medium; 4, 5 = high	5	
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	Deduct 1 point for each ancillary. Point range 0 to 5.	4	Enclosure required.
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	5	

[4]No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[5]Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-11. Optical Scattering Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	5	Must be oriented with respect to lay of finish.
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	1	SF
Measurement Method	3 = indirect, 5 = direct	3	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	5	
Measurement Type	2 = contact, 5 = noncontact	5	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	11	Airborne pollutants (-1/2), ambient light (-1/2), coolant (-1), coolants or chips on tool/workpiece (-1/2), electrical noise (-1/2), orientation to surface structure (-1), speeds, feed, depth of cut (-1), vibration (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Orientation to Surface Structure			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
SUITABILITY [3]	For all parameters in this category, 0, 1 = low; 2, 3 = medium; 4, 5 = high		
Acceptability to Operators		5	
Calibration Requirements		1	Empirical calibration for each workpiece/process.
Ease of Use		5	
Expected Life		5	Light sources.
Machine/Tool Modifications Required		4	May require bulky structural support.
Modifications Required or Process Limitations		4	
Predicted Reliablity		4	

[1] Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2] The values defined and assigned herein reflect the intent and objectives of the RIA application and are not intended to be applied to or interpreted in any other context.
[3] SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.

TABLE B-11. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	2	
Development	2 = >150K, 4 = 50K to 150K, 6 - <50K	4	
Maintenance	0 = high, 1 = medium, 2 = low	1	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	Adequate in range 40 μin. < R_a < 80 μin.
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	3	
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	4	Good with more robust model and orientation-independent algorithms.
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	2	To be proven.
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	8	Class II laser.
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]	Scattered light	
Model Maturity	0, 1 = low; 2, 3 = medium, 4, 5 = high	2	Performance needs to be proven.
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	2	At research stage.
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	Deduct 1 point for each ancillary. Point range 0 to 5.	3	Special enclosure and workpiece cleaning required.
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	Complex optics and electronics.
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	General algorithms may be computation intensive.
Sensor Transport Mechanism	0 = three-dimensional (3D) 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 low-precision 1D, 4 = solenoid, 5 = none	5	Assume positioning by machine tool.

[4] No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[5] Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-12. Point Range Triangulation Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	1 (TW)[4], 4 (WD)	
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	2	TW, WD
Measurement Method	3 = indirect, 5 = direct	5	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	2 (TW), 5 (WD)	
Measurement Type	2 = contact, 5 = noncontact	5	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	13 (TW)	Airborne pollutants (-1/2), built-up edge (-1/2), coolants or chips on tool/workpiece (-1/2), electrical noise (-1/2), surface finish (-1), tool material (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece		13.5 (WD)	Workpiece material (-1), coolants or chips on tool/workpiece (-1/2), surface finish (-1), airborne pollutants (-1/2), electrical noise (-1/2).
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category, 0, 1 = low; 2, 3 = medium; 4, 5 = high		
Acceptability to Operators		3	
Calibration Requirements		4	
Ease of Use		5	
Expected Life		[illegible]	
Machine/Tool Modifications Required		5	
Modifications Required or Process Limitations		5	
Predicted Reliablity		4	

[1] Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2] The values defined and assigned herein reflect the intent and objectives of the RIA applicaiton and are not intended to be applied to or interpreted in any other context.
[3] SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.
[4] Multiple values indicate sensor scores for more than one application.

TABLE B-12. (Continued).

Category [weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	0	Difficult to apply to rotary tool.
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	4	
Maintenance	0 = high, 1 = medium, 2 = low	1	Electronics maintenance.
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	4	
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	2	
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	3	
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	Limited by positioning mechanism.
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	8	Class IIIb infrared laser. Requires local shielding.
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[5]	Surface topography	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	3 (TW), 4 (WD)	Reflectivity/texture variations may be a problem.
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[6]	Deduct 1 point for each ancillary. Point range 0 to 5.	2	Special enclosure, tool cleaning, and air.
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	Needs better spot-centroid algorithms.
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	3	

[5]No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[6]Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-13. Projection Interferometry Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	3 (TW)[4]; 3 (WD)	May be adaptable to milling.
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	3	TO, TW, WD
Measurement Method	3 = indirect, 5 = direct	5	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	2	
Measurement Type	2 = contact, 5 = noncontact	5	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	11.5	Airborne pollutants (-1/2), ambient light (-1), coolants or chips on tool/workpiece (-1/2), electrical noise (-1/2), surface finish (-1), tool material (-1), vibration (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category, 0, 1 = low; 2, 3 = medium; 4, 5 = high		
Acceptability to Operators		3	Noncompact.
Calibration Requirements		3	Precise alignments must be maintained and verified.
Ease of Use		3	
Expected Life		3	Light sources have limited life.
Machine/Tool Modifications Required		4	Possibly for structural support of sensor system.
Modifications Required or Process Limitations		3	Slows process.
Predicted Reliablity		2	Complex electronics, optics, and light.

[1] Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2] The values defined and assigned herein reflect the intent and objectives of the RIA applicaiton and are not intended to be applied to or interpreted in any other context.
[3] SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.
[4] Multiple values indicate sensor scores for more than one application.

TABLE B-13. (Continued).

Category [weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	1	
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	2	
Maintenance	0 = high, 1 = medium, 2 = low	0	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	3	1 mil claimed.
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	0	Estimate > 1 sec.
Growth Potential	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	Capabilities should increase [illegible] years.
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	3	Estimate.
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	3	Estimate approximately 1 mil
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[5]	Physical dimensions	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	2	Needs to be proven in factory environment
Technology Maturity	0, 1 = low, 2, 3 = medium; 4, 5 = high	3	New proprietary product.
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[6]	Deduct 1 point for each ancillary. Point range 0 to 5.	1	Air, power, special enclosure, and [illegible] cleaning required.
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	2	Several elements with precise alignment required.
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	3	Complex [illegible]
Sensor Transport Mechanism	0 = three dimensional (3D), 1 = two dimensional (2D), 2 = high precision, one dimensional (1D), 3 = low precision 1D, 4 = [illegible], 5 = none	5	

[5] No numerical value is assigned as [illegible] variable, e.g., [illegible] force, [illegible] and [illegible] given sensor type.
[6] Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-14. Structured Light Machine Vision Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	3 (WD).[4] 1 (TW)	
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	2	TW, WD
Measurement Method	3 = indirect, 5 = direct	5	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	2	
Measurement Type	2 = contact, 5 = noncontact	5	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	14.5 (TW)	Airborne pollutants (-1/2), built-up edge (-1/2), coolants or chips on tool/workpiece (-1/2), electrical noise (-1/2), surface finish (-1/2).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise		15 (WD)	Airborne pollutants (-1/2), coolants or chips on tool/workpiece (-1/2), electrical noise (-1/2), surface finish (-1/2).
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category, 0, 1 = low; 2, 3 = medium; 4, 5 = high		
Acceptability to Operators		3	
Calibration Requirements		5	
Ease of Use		5	
Expected Life		5	
Machine/Tool Modifications Required		5	
Modifications Required or Process Limitations		4	Several seconds added to process time.
Predicted Reliablity		3	Complex electronics required.

[1]Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2]The values defined and assigned herein reflect the intent and objectives of the RIA applicaiton and are not intended to be applied to or interpreted in any other context.
[3]SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.
[4]Multiple values indicate sensor scores for more than one application.

TABLE B-14. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	1 (TW), 0 (WD)	
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	2	
Maintenance	0 = high, 1 = medium, 2 = low	2	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	
PERFORMANCE [2][5]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	4	
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	2	33 ms/frame to take data, approximately 1 sec to process.
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	5	Trends toward lower hardware cost, higher processing speed, and better algorithms.
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	3	Frame averaging required to eliminate video noise.
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	5	
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	8	Class IIIb laser requires enclosure to shield beam (enclosure also required to shield sensor).
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[6]	Physical dimensions	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	Many successful commercial applications.
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	Pulsed Gaussian laser beam, multistripe gratings available.
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[7]	Deduct 1 point for each ancillary. Point range 0 to 5.	1	Air, power, special enclosure, tool cleaning required.
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	5	

[5]Researched implementations do not have sufficient range to meet RIA requirements for surface finish measurement.
[6]No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[7]Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-15. Touch Trigger Probe Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	1 (TW)[4] 3 (WD)	
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	3	TW, WD, 10
Measurement Method	3 = indirect, 5 = direct	5	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	2	
Measurement Type	2 = contact, 5 = noncontact	2	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	14	Built-up edge (-1/2), collisions (-1), coolants or chips on tool/workpiece (-1/2), surface finish (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolant			
Coolants or Chips on Tool/Workpiece			
Electrical Noise			
Hardness			
Speeds/Feed/Depth of Cut			
Stiffness			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category, 0, 1 = low; 2, 3 = medium; 4, 5 = high		
Acceptability to Operators		5	
Calibration Requirements		5	
Ease of Use		5	
Expected Life		4	Derated for collision sensitivity.
Machine/Tool Modifications Required		4	
Modifications Required or Process Limitations		0	Adds estimated 10 min to cycle.
Predicted Reliablity		3	Easily damaged.

[1] Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2] The values defined and assigned herein reflect the intent and objectives of the RIA applicaiton and are not intended to be applied to or interpreted in any other context.
[3] SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification summary parameter used in Table 4, Supplemental Evaluation Matrix.
[4] Multiple values indicate sensor scores for more than one application.

TABLE B-15. (Continued).

Category [weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	0	Impractical for rotary tool.
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	4	
Maintenance	0 = high, 1 = medium, 2 = low	2	Tip replacement required.
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	Probe, linear slide, electronics.
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	Limited by positioning mechanism.
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	0	Very slow (10 points/min)
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	0	
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	Limited by positioning mechanism.
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 μin., 4 = 100 to 400 μin., 5 = <100 μin.	4	Limited by positioning mechanism.
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[5]	Physical profile	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	3 (TW), 5 (WD)	Needs algorithms to relate trigger points through tip radius into profile information.
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	5	
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[6]	Deduct 1 point for each ancillary. Point range 0 to 5.	3	Tool cleaning (-1), special enclosure (-1)
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one-dimensional (1D), 3 = low-precision 1D, 4 = solenoid, 5 = none	2	High-precision linear slide.

[5]No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is specific to given sensor type.
[6]Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

TABLE B-16. Ultrasonic Scattering Evaluation Matrix.

Category [Weight][1]	Value Definition[2]	Value Assigned	Comment
CLASSIFICATION [3]			
Application Versatility	1 = stationary, 3 = rotary, 5 = both	5	SF
Computed Parameter	Give 1 point each: SF, TB, TO, TW, WD.[3] Point range 0 to 5.	1	
Measurement Method	3 = indirect, 5 = direct	3	
Measurement Mode	0 = off-machine, 2 = between cut, 5 = in-process	5	
Measurement Type	2 = contact, 5 = noncontact	5	
ENVIRONMENTAL SENSITIVITY [3]	For all parameters in this category, deduct 1 point for each sensitivity that cannot be compensated. Deduct 1/2 point for each that can be compensated. Point range 0 to 17.	11	Chip form (-1), coolants or chips on tool/workpiece (-1), coupling medium composition/purity (-1), orientation to surface structure (-1), speeds/feed/depth of cut (-1), vibration (-1).
Airborne Pollutants			
Ambient Light			
Ambient Temperature			
Built-up Edge			
Chip Form			
Collisions			
Coolants or Chips on Tool/Workpiece			
Coupling Medium Composition/Purity			
Electrical Noise			
Hardness			
Orientation to Surface Structure			
Speeds/Feed/Depth of Cut			
Surface Finish			
Tool Material			
Tool Temperature			
Vibration			
Workpiece Material			
SUITABILITY [3]	For all parameters in this category,		
Acceptability to Operators	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Calibration Requirements		1	Must be calibrated for each surface finish/tool/process combination or coupling fluid change.
Ease of Use		3	Needs coupling fluid.
Expected Life		5	
Machine/Tool Modifications Required		4	Control of coupling fluid (on/off), if cutting fluid is not used or cut is made dry.
Modifications Required or Process Limitations		5	
Predicted Reliablity		5	

[1]Numbers in brackets designate category weights assigned to reflect RIA application objectives.
[2]The values defined and assigned herein reflect the intent and objectives of the RIA applicaiton and are not intended to be applied to or interpreted in any other context.
[3]SF = surface finish, TB = tool breakage, TO = tool offset, TW = tool wear, WD = workpiece dimension. Although consideration of TO and TB was not required, they were incorporated to measure additional capability. Sensors with these capabilities will receive a higher score for the classification *summary parameter* used in Table 4, Supplemental Evaluation Matrix.

TABLE B-16. (Continued).

Category [Weight]	Value Definition	Value Assigned	Comment
COST [2]			
Adaptation	0 = >100K, 1 = 10K to 100K, 2 = <10K	2	Adapt to different conditions of surface production.
Development	2 = >150K, 4 = 50K to 150K, 6 = <50K	4	Quantification of sensitivities.
Maintenance	0 = high, 1 = medium, 2 = low	2	
Recurring	0 = >100K, 5 = 10K to 100K, 10 = <10K	5	
PERFORMANCE [2]			
Accuracy	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	3	Range determined by frequency at 15 MHz - 32 to 125 µin.
Bandwidth	0 = >1 sec, 2 = 0.1 to 1 sec, 3 = 10 to 100 ms, 4 = 1 to 10 ms, 5 = <1 ms	5	1000 readings/sec.
Growth Potential	0,1 = low; 2, 3 = medium; 4, 5 = high	5	May be expandable into tool wear.
Repeatability	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	2	Needs average of ten 10^6 measurements to produce realiable reading.
Resolution	0 = >5 mil, 2 = 1 to 5 mil, 3 = 400 to 1000 µin., 4 = 100 to 400 µin., 5 = <100 µin.	3	50 µin.
SAFETY [2]	0 = unreconcilable hazard, 3 = hazard can be compensated at high cost or is nonlocal in effect, 6 = hazard correctable at moderate cost, 8 = hazard correctable at low cost, 10 = no hazard	10	
TECHNOLOGY [2]			
Measured Physical Quantity	Variable[4]	Scattered acoustic energy	
Model Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	2	Empirical at this point. Research needed to develop analytical prediction from known surface profile.
Technology Maturity	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
INTERFACE COMPLEXITY [1]			
Ancillary Requirements[5]	Deduct 1 point for each ancillary. Point range 0 to 5.	3	Cutting fluid source, [illegible]
Hardware Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	
Processing Requirements	0, 1 = low; 2, 3 = medium; 4, 5 = high	4	Real-time solution of analytic [illegible] may present challenge.
Sensor Transport Mechanism	0 = three-dimensional (3D), 1 = two-dimensional (2D), 2 = high-precision, one dimensional (1D), 3 = low precision 1D, 4 = solenoid, 5 = none	5	

[4]No numerical value is assigned as this item is a variable, e.g., cutting force, tool geometry, etc., and is [illegible] given sensor type.
[5]Ancillaries defined as special enclosures, power, air, tool cleaning requirements, etc.

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A CRITICAL REVIEW OF OPTIONS FOR TOOL AND WORKPIECE SENSING
R. W. Gamache and John T. McCabe

Report SE 89-01, 150 p. incl. illus. tables,
(AMS Code 3297.06.8248) Unclassified Report

The first interim report of a two-phase project identifies and analyzes existing and emerging state-of-the-art sensors for assessing and forecasting the condition of cutting tools and for measuring the dimensions and surface finish of workpieces. The goal of the project is to provide a versatile means to use the sensor data for reducing manufacturing costs and improving the quality of parts in production at the Rock Island Arsenal and other similar facilities. The study concludes that to minimize the number of sensors and the frequency of their use, an integrated system is needed in which the sensor outputs are fused by an algorithm and used in a mathematical model that automatically adapts to the changing process, tool, and workpiece conditions.

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