PNL--8352

DE93 002976

A Comparison of Surface Topography Characterization Technologies for Use in Comparing Spent Bullet and Cartridge Case Signatures

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November 1992

Prepared for
The Federal Bureau of Investigation
under a Related Services Agreement
with the U. S. Department of Energy
Contract DE-AC06-76RLO 1830

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PREFACE

DRUGFIRE is a program initiated by the Federal Bureau of Investigation (FBI). The program's objective is to establish a limited regional network of databases which would expedite comparison and matching of spent bullets and cartridge cases found at the scenes of drug-related crimes. Bullets and cases would be compared both among those suspected of being fired from the same weapon and with the extensive FBI collection. The intent is to associate crimes in which the same weapons were used, thus increasing the amount of information related to a specific crime, and potentially increasing the probability of identifying suspects. A related benefit is that bullets and cases within the collection can be screened to identify those which might have been fired from the same weapon, thus associating crimes previously not known to be connected.

In January, 1991, the FBI published FBISS#1, FBISS#2, and FBISS#3, requests for information, in the Commerce Business Daily. These were for information from vendors having capabilities related to the needs of the FBI's DRUGFIRE Program. FBISS#1 focused on technologies capable of image acquisition and comparison, and FBISS#2 focused on surface topography characterization. Automated comparison of bullets and cartridge cases for fast screening of large numbers of samples was the ultimate goal of both.

The Department of Energy's Pacific Northwest Laboratory (DOE/PNL) offered, as a sister agency, to assist the FBI in evaluating the nearly 80 vendor packages received by providing the automated instrumentation expertise needed to compare technologies. The Electro-Optical Systems Group of PNL's Automation and Measurement Sciences Department was tasked to support the FBI in evaluating and ranking technologies capable of meeting the FBI's need for a surface topology comparison system.

This document describes the technologies investigated, the sources of information used to support the evaluation, the method followed in evaluating the technologies, and the results and recommendations.

SUMMARY

The Pacific Northwest Laboratory was tasked by the U. S. Department of Energy to provide technical assistance to the Federal Bureau of Investigation in evaluating and ranking technologies potentially useful in high-speed comparison of unique spent bullet and cartridge case surface signatures. Information sources included vendor input, current relevant literature, vendor phone contacts, other FBI resources, relevant PNL reports, and personal contact with numerous PNL technical staff.

A comprehensive list of technologies was reduced to a list of 38 by grouping very similar methodologies, and further reduced to a short list of six by applying a set of five minimum functional requirements. A total of 14 primary criteria, many having secondary criteria, were subsequently used to evaluate each technology.

The ranked short list results are reported and supported in this document, and their scores normalized to a hypothetical ideal system are as follows:

(1) confocal microscopy	82.13
(2) laser dynamic focusing	72.04
(3) moire interferometry	70.94
(4) fringe field capacitance	68.39
(5) laser triangulation	66.18
(6) structured/sectioned light	65.55
(7) contact stylus methods (FAILED MINIMUM)	54.81

Contact stylus surface contouring, the seventh ranked technology, was included since it provides a well-known baseline, even though it failed two minimum criteria, including the requirement that the technology be non-contacting.

Information available within the time/budget constraints which was used for the evaluation and ranking was not sufficiently detailed to evaluate specific implementations of the technologies. Each of the technologies in the short list was judged <u>potentially</u> capable of meeting the minimum requirements.

Clever, novel engineering solutions resulting in a more cost-effective system, or a closer fit to the "ideal system," could result in a reordering of the short list when actual technical proposals are evaluated. Therefore, it is recommended that a Request for Proposal not be limited to only the highest ranked technology, but include all six technologies in the short list.

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INTRODUCTION

DRUGFIRE is a program initiated by the Federal Bureau of Investigation (FBI). The program's objective is to establish a limited regional network of databases and characterization capability which would expedite high-speed comparison and matching of spent bullets and cartridge cases found at the scenes of drug-related crimes. Bullets and cases would be compared both among those suspected of being fired from the same weapon and with the extensive FBI collection. The intent is to associate crimes in which the same weapons were used, thus increasing the amount of information related to a specific crime, and potentially increasing the probability of identifying suspects. A related benefit is that bullets and cases within the collection can be screened to identify those which might have been fired from the same weapon, thus associating crimes previously not known to be connected.

Pacific Northwest Laboratory was tasked by the U. S. Department of Energy to provide technical assistance to the FBI in evaluating and ranking technologies potentially useful in high-speed comparison of unique spent bullet and cartridge case surface signatures. The scope was specifically limited to comparing technologies rather than specific implementations, with the emphasis on those technologies capable of high-precision surface topography characterization.

The work was conducted by staff in the Electro-Optical Systems Group and the Electronics and Instrumentation Group, within the Automation and Measurement Sciences Department.

This document describes the technologies investigated, the sources of information used to support the evaluation, the method followed in evaluating the technologies, results, and recommendations.

CONCLUSIONS

A comprehensive list of technologies was reduced to a short list of six, which were ranked using a set of 14 primary criteria, many having secondary criteria.

The ranked short list results (highest to lowest) are as follows:

(1) confocal microscopy

(2) laser dynamic focusing

(3) moire interferometry

(4) fringe field capacitance

(5) laser triangulation

(6) structured/sectioned light

Information used for the evaluation and ranking was not sufficiently detailed to evaluate specific implementations of the technologies. Each of the technologies in the short list was judged potentially capable of meeting the minimum requirements. Clever, novel engineering solutions resulting in a more cost-effective system, or a closer fit to the "ideal system", could result in a reordering of the short list when actual proposed implementations are evaluated.

DISCUSSION

OBJECTIVE

The objective of this study was to evaluate and rank a set of technologies identified by nearly eighty vendors in response to an FBI Sources Sought request. Vendors provided information on image acquisition and surface topographical characterization for comparison of spent bullets and cartridge cases, in support of the DRUGFIRE Program. The evaluation and ranking included additional technologies identified by PNL staff from other FBI resources and PNL's own resources.

SYSTEM REQUIREMENTS

Traditionally, bullet mark comparison consists of visually matching marks on one bullet against those on another using a comparison microscope. The FBI provided PNL with technical information on this traditional method, including information on the most important characteristics, and a variety of technical papers describing proposed methods of automating and/or improving comparison. The FBI also provided detailed characterization information including dimensional and other requirements. Other requirements included descriptions of the physical geometry of spent bullets and cases, operator issues, system implementation cost issues, functional objectives for the system, overall system information, and more.

From this information, PNL derived a set of minimum essential requirements and an additional set of criteria. The minimum requirements were used to reduce the comprehensive list of technologies to a short list of six. The entire set of criteria, including the minimum requirements, were then used to evaluate and rank the short list. The software used for evaluation and ranking provided a means for applying relative weights to the criteria. Appendix A is a complete listing of all criteria with their relative weights.

Minimum Requirements

The five minimum requirements used to reduce the comprehensive list to a short list of six are shown in Table 1.

MINIMUM REQUIREMENTS	
• Lateral Resolution	≤ 5 μm
• Vertical Resolution	≤ 5 μm
• Depth of Field	≥ 150 μm
• Nondestructive	
• Data Rate	≥ 500 points/sec

TABLE 1. Minimum Requirements

Lateral Resolution

Based on information provided by the FBI on characteristics of marks imparted to bullets and cases when fired, we determined that minimum lateral and depth resolution needed to be no worse than 5 μm. In evaluating the short list technologies for resolution, each was evaluated relative to an "ideal" range of 1 μm to 5 μm. Resolution poorer than 5 μm was not acceptable, and resolution much finer than 1 μm is to be avoided for a variety of reasons including increased signal-to-noise ratio, artifacts, increased amount of data, increased scanning time, greater system complexity, greater sensitivity to external noise, and others.

Vertical Resolution

As with lateral resolution, the surface features of interest require a resolution of 5 μm or better. Like lateral resolution, a window of 1 μm to 5 μm is preferred, for the same reasons as stated above.

Depth-of-Field

The step depth-of-field criterion is aimed at maintaining adequate focus for the sensor passing over a 150 μm step. This might be a crack, scratch, etc. In detailed evaluation, each technology was evaluated relative to a total depth of 2.5 mm. Background information suggests that this is a safe, but reasonable, maximum for features on the case head, in the vicinity of the primer, where most of the characteristic signature is expected.

Non-Destructive

The requirement for a non-destructive method needs no further explanation as a minimum requirement. In detailed evaluation, each technology was evaluated according to whether damage is certain, uncertain, or there is effectively no probability for damage.

Data Acquisition Rate

A minimum data acquisition rate was based on resolution required and a reasonable time to scan the head of a shotshell case. A data acquisition rate of 500 data points per second is very slow for this application, and thus this is not a very stringent minimum requirement. However, it applied a necessary test at a level which would not eliminate a technology that couldn't be significantly improved by clever engineering.

Additional Criteria for Evaluation

The additional criteria used to evaluate the short list of six technologies is shown in Table 2. Most of the criteria are readily understood by those in the surface topography and/or inspection community. A few require additional explanation. The following discussion briefly describes each criterion, and Appendix A contains a listing of all criteria with the scale used to evaluate each technology according to that criterion. In some cases, criteria can be applied numerically, for example, initial purchase price. In others, the evaluation is more subjective, for example, ease of operation. In a later section of this report, the software tool used for comparison and ranking will be described. This tool facilitated establishing user-defined scales which could accommodate either numerical or subjective verbal ratings.

Life-Cycle Cost - Initial Purchase Price

Since the networked system is intended for use by regional municipalities, most having limited budgets, purchase price could exclude some municipalities from participation. Low cost is better.

Life-Cycle Cost - General Ease of Operation

This subjective factor includes many considerations. Positive factors include operation by a relatively low-cost technician versus a highly educated

ADDITIONAL CRITERIA FOR EVALUATION OF SHORT LIST

- Life Cycle Cost
  - Initial Purchase Price
  - General Ease of Operation
- Robustness
  - Sensitivity to Changing Room Light
  - Sensitivity to Air Currents or Temperature
  - Sensitivity to Humidity
  - Sensitivity to Vibration
- Applicable to Side of Case/Bullet
  - 150 μm Step
  - 80 mm FOV/Scan
- Applicable to End of Case
  - 2.5 mm Step
  - View/Scan 19 mm Circular Case End
  - Occlusion Angle (from normal)
  - Sensitivity to Marking Orientation or Distribution
- Applicable to Material
  - Sensitivity to Conductivity
  - Sensitivity to Reflectivity
  - Sensitivity to Changes in Conductivity or Reflectivity
- Inherent Sources of Error
  - 2π Depth Ambiguities
  - Cumulative Errors
  - Reference Surface Errors
  - Repeatability
  - Alignment/Leveling/Translation Errors
- Ease of Use
  - Ease of Calibration
  - Frequency of Calibration
  - Reliability
  - Sensor Ruggedness
  - Standoff Distance
- Flexibility
  - Shape of Scan
  - Adjustability of Parameters
- Acceptability
  - Commercial Availability
  - Correlation with Other Methods
  - Aspect Ratio
  - Bytes per 3-D Data Point
  - Contact Versus Non-Contact
  - Simplicity of Design

TABLE 2. Additional Criteria for Evaluation of the Short List

professional, graceful versus catastrophic failure, ease of maintenance by local technicians versus vendor technicians, and others.

Robustness - Sensitivity to Changing Room Light

This is the first of several operating environment sensitivity factors. Many optical technologies could be affected by varying ambient light conditions. Some may be compensatable, some not.

Robustness - Sensitivity to Air Currents or Temperature

Some very high sensitivity technologies are less stable in the presence of air currents which can induce vibration or changing temperatures. Some technologies require a carefully controlled temperature and shielding from air currents.

Robustness - Sensitivity to Humidity

Humidity can affect some technologies, for example those relying on conductivity.

Robustness - Sensitivity to Vibration

At the resolution of interest, many technologies are sensitive to vibration, however, many can be compensated or damped.

Applicable to Side of Case/Bullet - 150 μm Step

In topographic mapping of the side of the case or bullet, radius of curvature is an important consideration. This criterion relates to the technology's ability to accommodate a step change of 150 μm.

Applicable to Side of Case/Bullet - 80 mm Field of View/Scan

Since the system will be applied to a wide range of samples, from .22 caliber (possibly smaller) to large caliber, including shotshell cases, 80 mm is a comfortable upper end of the length range.

Applicable to End of Case - 2.5 mm Step

Since the end of the case is nominally flat, one would expect a reduced requirement compared to the case/bullet side. However, most of the microstructure of interest is in the vicinity of the primer, or in the case of rimfire cases, at the location of the firing pin impact. A 2.5 mm maximum criterion ensures some latitude.

Applicable to End of Case - View/Scan 19 mm Circular Case End

This criteria was aimed at an ability to scan or image the end of a 12 gauge shotgun case. In retrospect, this is probably extreme, and was reduced from a minimum requirement to a less important criterion due to most of the detail of interest being in the immediate vicinity of the primer and/or firing pin mark.

Applicable to End of Case - Occlusion Angle from Normal

This criterion was included to favor those technologies which could accommodate not only pristine cases (and bullets), but also those which may have been damaged and badly deformed. For example, a case may have been ejected along a paved highway and subsequently damaged by vehicles.

Applicable to End of Case - Sensitivity to Marking Orientation of Distribution

This criterion is intended to favor those technologies which can accommodate arbitrary orientation and distribution of either manufacturing marks (manufacturer's head stamps) or features of interest (rimfire firing pin depressions). Technologies which cannot accommodate arbitrary alignment or distribution would result in an increased amount of sample preparation and/or mounting/alignment.

Applicable to Material - Sensitivity to Conductivity

Some technologies can accommodate conductive materials, but have problems with non-conductive materials, or with non-uniform conductivity.

Applicable to Material - Sensitivity to Reflectivity

Some optical technologies are very sensitive to optical reflectivity. Some work well with diffuse surfaces (bullets) but require surface preparation (dusting) for specular reflective surfaces (cases). Some require strong reflections favoring light colors while others can tolerate lower reflectivity.

Applicable to Material - Sensitivity to Changes in Conductivity or Reflectivity

This criterion favors those technologies which do not require uniform conductivity or reflectivity. Samples cannot be expected to be uniform in any way since they have not necessarily been pampered as could be the case with bullets fired in a controlled lab situation. Bullets may have traces of tissue, blood, fabric, or other material clinging to them which may need to remain intact, but should not preclude surface characterization.

Inherent Sources of Error - 2π Depth Ambiguities

These errors are typical of the various forms of interferometry. Some technologies (or implementations) may accommodate compensation, others not.

Inherent Sources of Error - Cumulative Errors

All systems are expected to have some sensitivity to cumulative errors. This criterion favors those less susceptible, which are typically less complex systems.

Inherent Sources of Error - Reference Surface Errors

This criterion favors those technologies which do not require a reference surface, or which require a reference surface, but for which significant errors introduced by that surface are compensated. While it is recognized that a differential measurement in which a reference is used can provide much greater precision (due to reduced dynamic range, resolution) and accuracy, this additional source of error must be controlled to ensure a net, useful gain.

Inherent Sources of Error - Repeatability

Repeatability is essential for comparing samples over long periods of time and among multiple nodes of the network.

Inherent Sources of Error - Alignment/Leveling/translation Errors

This criterion recognizes the great variety which is inevitable among numerous technologies in sample handling. Some technologies lend themselves to high resolution over a wide field of view (FOV), eliminating the need for scanning (translation). Others require mechanical or opto-electronic scanning. All require precision alignment to ensure that FOVs being compared are relevant and in registration. Some require careful leveling to ensure precision mechanical handling.

Ease of Use - Ease of Calibration

This subjective criterion favors technologies not needing complicated, National Institute of Standards and Technology (NIST)-traceable calibration. Since the objective is high-speed, reliable screening, rather than detailed and precise feature matching, extensive calibration is not a positive factor.

Ease of Use - Frequency of Calibration

The same description applies as for Ease of Calibration, above.

Ease of Use - Reliability

This subjective criterion relates to the potential for system malfunction and the resulting operator training requirements for minimizing malfunction, and for system troubleshooting and repair.

Ease of Use - Sensor Ruggedness

This criterion favors technologies requiring sensors which are electronically, mechanically, thermally, optically, or otherwise fragile. Since the system is intended for operation by relatively low-level technicians, fragile sensors invite excessive, costly downtime and repair.

Ease of Use - Standoff Distance

This criterion favors those technologies in which the sample is relatively accessible. Scanning electron microscopy would be at a disadvantage due to the required vacuum chamber, but some contact or near contact technologies (mechanical stylus, eddy current, etc.) might also preclude easy access to the sample due to the probe proximity. These might also increase the probability of sample damage.

Flexibility - Shape of Scan

The shape of the scan can favor selected feature geometries. A long, narrow detector footprint might give excellent resolution in one direction, but poor resolution in the other.

Flexibility - Adjustability of Parameters

This criterion emphasizes that this is not a development system, but a "production-like" system. Adjustability adds to operational complexity, potential sources of error, and operator training requirements. Technologies offering flexibility could be useful if their normal operation locks out parameter change functions. However, those requiring changes to accommodate the range of samples would rate lower than those not requiring such flexibility.

Acceptability

This set of criteria is a catchall for subjective criteria, as well as some less subjective. It provides a way to accommodate "intuitive feel" of the evaluators, based on their experience and judgement.

Acceptability - Commercial Availability

This criterion strongly favors systems which are commercially available, or which can be readily adapted from commercially available products. DRUGFIRE is not a hardware development program, but rather a methodology development program implemented by hardware and software integration, with the emphasis on cost effectiveness of commercially available subsystems.

Acceptability - Correlation with Other Methods

While this methodology is not intended for highly calibrated, absolute measurements, a feeling of confidence will be inspired within the community if results can be "certified" by positive correlation with accepted, traditional methodologies.

Acceptability - Aspect Ratio

This numerical criterion favors technologies whose detector footprint has an aspect ratio of 1.00. For various reasons alluded to above, elongated footprints complicate comparison, particularly when the comparison is overseen and checked visually.

Acceptability - Bytes per 3-D Data Point

This criterion favors technologies which require reasonable amounts of data storage. While data compression is acceptable, its impact on data acquisition rate may impact its acceptability.

Acceptability - Contact Versus Non-Contact

This criterion goes a step beyond a non-destructive requirement in favoring technologies which do not contact the surface, thereby ensuring freedom from damage to the sample, as well as eliminating long-term changes due to mechanical wear.

Acceptability - Simplicity of Design

This subjective, catchall criterion favors systems which are intrinsically simple. Positive factors are reliability, operator training, life cycle costs, community acceptance, and many more which are more difficult to apply separately.

Global and Other DRUGFIRE System Requirements

Taken in the context of the entire DRUGFIRE Program, there are many additional requirements relating to (1) interfacing with the computer system, database, and expert/knowledge-based system, and (2) analysis, evaluation, interpretation, and reporting of the surface characteristics data (i.e., correlation algorithms). In initially studying the vendor packages, it was clear that the packages divided into several categories as follows:

- Two-Dimensional (2-D) video imaging technology
- Three-Dimensional (3-D) surface topography technologies
- image processing (in support of 2-D video technologies)
- expert/knowledge-based systems
- database management systems
- general capabilities (systems integration, R&D, ballistics, forensics, etc.)

Given the overall magnitude of the DRUGFIRE system development, PNL focused only on the 3-D surface topography evaluation. The reasons for doing so relative to the two sets of requirements and the content of vendor packages described above are addressed in the following paragraphs.

Further, given the diversity of technologies and the limited amount of detailed information provided by the vendors regarding specific implementations of the technologies, it was impossible to evaluate issues involving compatibility with other DRUGFIRE computer and database subsystems. Rather, the technologies were evaluated independent of compatibility issues, under the assumption that a Request for Proposal (RFP) for a surface topography system would include compatibility requirements. It would then be the responsibility of the bidder to address compatibility issues in the context of his unique implementation.

Perusal of the vendor package suggested that 2-D video imaging solutions proposed involved no new technology that wouldn't be included in evaluating surface topography technologies. An RFP for a video comparison microscope system for comparison imaging would primarily focus on the user interface, cost, hardware and file compatibility with the system computer and database, and other issues that will only be detailed by proposing vendors responding to an RFP. That RFP will necessarily include system compatibility requirements relative to which vendor proposals will be evaluated.

Image processing was judged to be too broad a category to be evaluated at this point. It logically applies to 2-D video issues so that it cannot be evaluated independent of 2-D video imaging proposals. The nature and degree of video image enhancement could be considered prior to writing an RFP. However, because of implementation variations likely to be proposed by vendors, allowing them the freedom to propose their strongest combination of hardware and software should result in the best field of candidates from which to select.

There are some 3-D technologies for which image processing would be essential, for example, stereo microvideography. However, the algorithms in these cases are relatively unique to the technology so that procuring general-purpose video image processing capability from another vendor would be counterproductive.

Correlation algorithms and software will be essential, whether applied to video images or surface topography data. It may be more productive to acquire this capability from a vendor having strong statistical software capability since video and surface topography technology vendors are not likely to have first-rate expertise in this area, and since it is less dependent on the exact source of the data to be correlated. However, defining the requirements for correlation capability will be heavily dependent on data set sizes, acquisition and processing rates, and other characteristics of the overall system.

Developers of broad categories of algorithms, database management systems, expert/knowledge-based systems, and vendors providing packages illustrating general R&D or systems integration capability that did not focus on the specific surface comparison function were considered to be outside the scope of this study.

TECHNOLOGY COMPARISON

Data Sources

The primary source of data was a set of 74 vendor-provided information packages in response to the FBI's request published in the Commerce Business Daily. These are listed in Appendix B in three categories: (1) applicable, (2) possibly applicable, and (3) not applicable. This preliminary sorting was performed along the lines of the discussion in the previous section.

A second source of data was a set of papers, vendor information collected over a period of years, and other documentation provided by the FBI from their own reference files on the subject. These are numbered and listed in Appendix C.

The two-volume DRUGFIRE Computer System specification document was also provided by the FBI as a supplemental document; although given the philosophy described in the previous section regarding compatibility issues, this document primarily provided background and a context for the surface topography requirements.

A number of additional sources were used including PNL technical papers and documents, discussions with a number of PNL staff, and telephone contact with vendors who submitted relevant packages. These are included in the bibliography.

A summary of the data sources for each technology and the data used for scoring is included in Appendix D.

Method

Preliminary Sort

As mentioned above, the initial set of 74 vendor packages was first sorted relative to whether they were applicable, possibly applicable, or not applicable. This resulted in 32, 16, and 24 vendors in those categories, respectively, plus one other, Battelle (Columbus Division), which was not included in the evaluation. PNL is operated by Battelle Memorial Institute as a part of its Pacific Northwest Division. Battelle Columbus Division is a sister division. In spite of the fact that the scope of this study involves evaluating and ranking technologies, not vendors, including the information package from Battelle Columbus Division in the comparison could be viewed as inappropriate. It was anticipated that the technologies identified by Battelle Columbus Division would be well represented by others. If those technologies were ranked high enough to be included in an RFP, Battelle would not be excluded from an opportunity to propose its unique implementation of the technology.

Compilation of a Comprehensive List

Many technologies were identified by more than one vendor resulting in fewer technologies than the number of vendors having relevant technology to offer. In addition, technologies were added to the list as they were identified from literature searches, additional FBI or PNL documents, or from discussions with PNL staff. Many identified technologies were members of families of specific variations of a general technology category. These were grouped when it was possible to do so without losing viability of a technology. An example is that several variations of interferometry having similar characteristics and limitations, but differing in physical configuration, were grouped to simplify the evaluation matrix. As a result, a total of 38 technologies were compiled into a comprehensive list which would then be evaluated in greater detail.

First Cut Sort - Minimum Requirements

Collecting a completely equivalent, comparable set of data on an extensive set of criteria for 38 technologies was expected to be effectively impossible within the cost and schedule constraints. Therefore, the list of 38 technologies was reduced to a short list by a first cut sort which applied a set of minimum requirements on a pass/fail basis. These were described in a previous section. Applying these criteria reduced the candidate technology list to six.

Final Ranking

The final ranking was done by scoring each of the six technologies on the short list, plus an "ideal system," using each of the criteria described earlier and shown in Tables 1 and 2. Table 3 shows the entire, combined decision tree applied in the final ranking. The combined list of criteria and sub-criteria is also shown in Appendix A, with the weighing factor and scoring scale used for each criterion.

Each criterion was weighted to reflect its importance within the overall context. Weighing factors shown in Appendix A are relative to other sub-criteria within the same primary criterion. This means that a weight of 1.00 for a secondary criterion does not carry the same ultimate weight as a weight of 1.00 for a primary criterion. A software tool, to be described in the next section, was used to implement this ranking process.

CRITERIUM™ - A Software Tool for Evaluation

CRITERIUM™ is a software application published by Sygenex (Redmond, Washington) that provides an organized structure for comparing, evaluating, and ranking large sets of alternatives, using potentially large, varied and complex criteria. It was selected as a tool for this study because it allows scoring using numerical or verbal user-defined scoring scales, provides for user-defined rules which are used as pass-fail criteria, provides a comprehensive set of reporting formats, incorporates a capability for evaluating model result sensitivity to changes in criteria scoring, facilitates "what if" testing to allow varying weighing factors, and generally lends itself to the nature of this ranking task.

A model results from developing a hierarchy as shown in Table 3, consisting of a goal, followed by multiple levels of criteria. Every primary criterion is weighted relative to every other primary criterion. Every secondary criterion is weighted against every secondary criterion within its own primary criterion.

Finally, every alternative is scored using a user-definable scale, relative to every secondary criterion, or every primary criterion which has no secondary criteria under it. A scale could be numerical data like initial system cost, in which score increases linearly with decreasing cost. A scale

Goal	Primary Criteria	Secondary Criteria
3D TECHNOLOGY-	+MINIMUM LATERAL RESOLUTION	
	+MINIMUM VERTICAL RESOLUTION	
	+MAXIMUM DEPTH OF FIELD	
	+LIFE CYCLE COST	+MINIMUM PURCHASE PRICE +GENERAL EASE OF OPERATION
	+SPEED OF DATA EXTRACTION	
	+NON-DESTRUCTIVE ?	
	+ROBUSTNESS	+SENS. TO CHANGING ROOM LIGHT +SENS. TO AIR CURRENTS OR TEMPERATURE +SENS. TO HUMIDITY +SENS. TO VIBRATION
	+GOOD FOR SIDE OF CARTRIDGE	+150um STEP POSSIBLE +80mm F.O.V./SCAN POSSIBLE
	+GOOD FOR END OF CARTRIDGE	+2.5mm STEP POSSIBLE +ABILITY TO VIEW/SCAN +OCCLUSION ANGLE (FROM NORMAL) +SENSITIVITY TO MARKING ORIENTATION OR DISTRIBUTION
	+GOOD FOR CARTRIDGE MATERIAL	+SENS. TO CONDUCTIVITY +SENS. TO REFLECTIVITY +SENS. TO CHANGES IN CONDUCTIVITY OR REFLECTIVITY
	+INHERENT SOURCES OF ERROR	+2-PI DEPTH AMBIGUITY +CUMULATIVE ERRORS +REFERENCE SURFACE ERRORS +REPEATABILITY +ALIGNMENT/LEVELING/TRANSLATION ERRORS
	+EASE OF USE	+EASE OF CALIBRATION +FREQUENCY OF CALIBRATION +RELIABILITY +SENSOR RUGGEDNESS +STANDOFF
	+FLEXIBILITY	+SHAPE OF SCAN +ADJUSTABILITY OF PARAMETERS
	+ACCEPTABILITY	+COMMERCIAL AVAILABLE +CORRELATION WITH OTHER METHODS +ASPECT RATIO +BYTES PER 3D DATA POINT +CONTACT VS. NON-CONTACT +SIMPLICITY OF CONCEPT

TABLE 3. Final Ranking Decision Tree

could be a subjective scale like rating, on a scale of 1 to 5, ease of use or concept complexity. A scale could be a verbal rating like yes/maybe/no, or, low sensitivity/moderate sensitivity but compensated/high sensitivity relative to some environmental factor. Numerical values are assigned to verbal scales according to the number of possible choices for final integration of all scores. CRITERIUM™ maintains the records of individual scores and combines and weights them to provide final scores.

In this case, a set of rules (pass/fail criteria) were used, as described earlier, to reduce the 38 alternatives to six. The first cut was done using all 38 technologies, but scoring them on only the five minimum requirements. Following this process, the model was revised to include only the six technologies in the short list, plus the "ideal system," and these were scored on all criteria.

CRITERIUM™ was used to generate a variety of reports which were used in peer reviewing the findings and as a basis for drawing conclusions. The final results shown in this document are slightly modified from the actual CRITERIUM™ reports in that final scores were normalized to aid in interpretation, and a final ranking bar chart was generated using a graphic application rather than the character-based bar chart used by CRITERIUM™.

Peer Review

A peer review of the results was conducted at PNL, following a preliminary analysis using CRITERIUM™. The review consisted of PNL staff J. S. Hartman (Electro-Optical Systems Group Leader) and B. B. Brenden (Staff Scientist), in addition to C. R. Batishko (Staff Scientist). The reviewers are all senior scientific staff in a technical group which has developed and delivered unique, often automated electro-optical measurement systems to a wide variety of government and private clients for many years. Their cumulative, relevant experience is over 50 man-years.

Since Batishko directed work done by B. J. Hickman who developed the model and compiled the data and F. M. Cuta who assisted in collecting data, he was an appropriate, unbiased reviewer.

The reviewers agreed fully with the resulting ranking. Their primary suggestions for improving the study were limited to means of improving clarity in communicating results. The only significant change following the peer review was to eliminate the shotgun shell head diameter scan requirement. This was based on the FBI's feedback that the primary area of interest is the primer area, requiring a much smaller scan. This change resulted in the highest scoring technology, CONFOCAL MICROSCOPY, passing the minimum requirement tests, rather than failing.

RESULTS

The results of the ranking process are illustrated in Figure 1. The figure includes the top seven ranked technologies plus an "ideal" system to normalize scores. Among the six technologies which passed the minimum requirement tests, CONFOCAL MICROSCOPY received top scores by a wider margin (~10%) than that which separates the remaining five technologies (~6½%). CONTACT STYLUS was included as the highest ranking of the remaining technologies which failed the minimum requirement tests, primarily to expedite comparison to a well-known technology which is traditionally used for surface topology. The CONTACT STYLUS score is clearly below (~11%) the lowest scoring of the technologies which passed the minimum requirements test.

CONCLUSIONS

A comprehensive list of technologies was reduced to a short list of six, which were ranked using a set of 14 primary criteria, many having secondary criteria.

The ranked short list results (highest to lowest) are as follows:

(1) confocal microscopy

(2) laser dynamic focusing

(3) moire interferometry

(4) fringe field capacitance

(5) laser triangulation

(6) structured/sectioned light

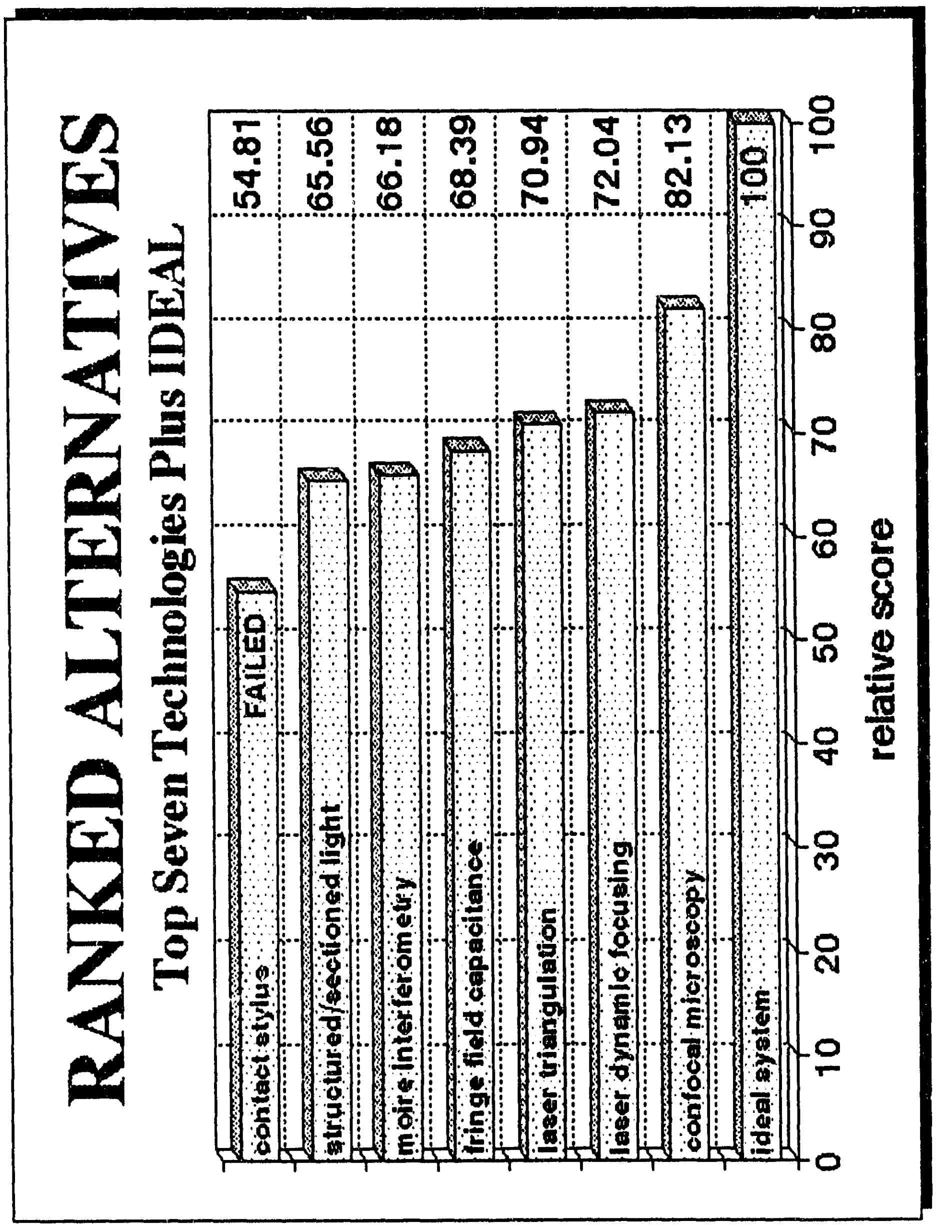

FIGURE 1. Summary of Ranking Results

Information used for the evaluation and ranking was not sufficiently detailed to evaluate specific implementations of the technologies. Each of the technologies listed in the short list was judged potentially capable of meeting the minimum requirements. Clever, novel engineering solutions resulting in a more cost effective system, or a closer fit to the "ideal system", could result in a reordering of the short list when actual proposed implementations are evaluated.

<u>BIBLIOGRAPHY</u>

See APPENDIX C - Supplemental Information Provided by the FBI

APPENDIX A

CRITERIA AND SUB-CRITERIA WITH RELATIVE WEIGHTS

APPENDIX A

CRITERIA AND SUB-CRITERIA WITH RELATIVE WEIGHTS

SAMPLE CRITERION **(weigh factor relative to others under the same primary criterion)**
[rating scale]

Minimum Lateral Resolution (1.00)
[1-5μm, <<1μm, >5μm]

Minimum Vertical Resolution (0.75)
[1-5μm, <<1μm, >5μm]

Maximum [Step] Depth-of-Field (0.75)
[>=150μm, <150μm]

Life Cycle Cost (1.00)
[critical, very important, important, unimportant, trivial]

- Minimum Purchase Price ((1.00)
  - [<=$10k, $10k-$50k, $50k-$100k, $100k-$150k, $150k-$200k, >$200k]
- General Ease of Operation (0.50)
  - [maximum, high, moderate, low, minimum]

Speed of Data Acquisition (0.75)
[>50k/s, 20k-50k/s, 10k-20k, 5k-10k, 1k-5k, 0.5k-1k, <0.5k]

Non-Destructive (1.00)
[yes, no, maybe]

Robustness (0.5)
[critical, very important, important, unimportant, trivial]

- Sensitivity to Changing Room Light (1.00)
  - [insensitive, sensitive but compensated, somewhat sensitive, very sensitive]
- Sensitivity to Air Currents or Temperature (0.67)
  - [insensitive, sensitive but compensated, somewhat sensitive, very sensitive]
- Sensitivity to Humidity (0.0)
  - [insensitive, sensitive but compensated, somewhat sensitive, very sensitive]
- Sensitivity to Vibration (1.0)
  - [insensitive, sensitive but compensated, somewhat sensitive, very sensitive]

Side of Cartridge Capability (0.75)
[critical, very important, important, unimportant, trivial]

150 μm step (1.00)
[yes, no, maybe]
80 mm Field-of View/Scan Possible (0.25)
[yes, no, maybe]

End (Head) of Cartridge Case Capability (1.00)
[critical, very important, important, unimportant, trivial]

2.5 mm Step Possible? (1.00)
[yes, no, maybe]
View/Scan 19 mm Circular Object (1.00)
[yes, no, maybe]
Occlusion Angle from Vertical (0.75)
[45° - 0° from zero]
Sensitivity to Markings/Orientation (0.75)
[insensitive, sensitive but compensated, somewhat sensitive, very sensitive]

Cartridge Material Compatibility (0.75)
[critical, very important, important, unimportant, trivial]

Sensitivity to Conductivity (0.75)
[insensitive, sensitive but compensated, somewhat sensitive, very sensitive]
Sensitivity to Reflectivity (1.00)
[insensitive, sensitive but compensated, somewhat sensitive, very sensitive]
Sensitivity to Changes in Conductivity/Reflectivity (0.75)
[insensitive, sensitive but compensated, somewhat sensitive, very sensitive]

Inherent Sources of Error (0.25)
[critical, very important, important, unimportant, trivial]

2π Depth Ambiguity (0.75)
[not applicable, possible]
Cumulative Errors (0.75)
[not applicable, possible]
Reference Surface Errors (0.50)
[not applicable, possible]
Repeatability (1.00)
[scale, 2% - 0%]
Alignment/Leveling/Translation Errors (0.5)
[insensitive, sensitive but compensated, somewhat sensitive, very sensitive]

Ease of Use (0.5)
[critical, very important, important, unimportant, trivial]

Ease of Calibration (0.50)
[maximum, high, moderate, low, minimum]
Frequency of Calibration (0.75)
[never,rarely,sometimes,often,very often]
Reliability (1.00)
[maximum, high, moderate, low, minimum]
Sensor Ruggedness (0.5)
[maximum, high, moderate, low, minimum]
Standoff (0.0)
[scale, 0-100 mm]

Flexibility (0.0)
[critical, very important, important, unimportant, trivial]

Shape of Scan (1.00)
[point, line, section, full field]
Adjustability of Parameters (0.67)
[maximum, high, moderate, low, minimum]

Acceptability (0.25)
[critical, very important, important, unimportant, trivial]

Commercial Availability (1.00)
[maximum, high, moderate, low, minimum]
Correlation with Other Methods (0.50)
[maximum, high, moderate, low, minimum]
Aspect Ratio (0.25)
[scale, 1-5000]
Bytes per 3-D Data Point (0.75)
[scale, 1-12]
Contact vs Non-Contact (1.00)
[none, non-damaging, possibly damaging]
Simplicity of Concept (0.0)
[maximum, high, moderate, low, minimum]

APPENDIX B

LISTINGS OF VENDOR PROPOSALS BY APPLICABILITY TO 3D IMAGING

APPENDIX B

LISTING OF VENDOR PROPOSALS BY APPLICABILITY TO 3D IMAGING

APPLICABLE		POSSIBLY APPLICABLE		NOT APPLICABLE	
Vendor	No.	Vendor	No.	Vendor	No.
BDM	1	TREC	4	HGO	2
Phoenix Technology, Inc.	7	Babcock & Wilcox, McDermott, Inc.	12	SAIC	3
Dynetics, Inc.	8	GTE	14	Diversified Technical Consultants, Ltd.	6
IITRI	9	Hughes Electro-Optical and Data Systems Group	33	Syscon Corp.	16
Hughes Aircraft Co.	10	Voyager Systems, Inc.	39	Technology Applications	21
TASC	11	Walsh Automation	43	Consultants for Mgmt. Decisions, Inc.	23
MSI Services, Inc.	13	Charles Stark Draper Laboratory	44	Digital	25
Westinghouse	15	Computer Science Innovations, Inc.	46	Fusion Systems	27
Hilton Systems, Inc.	18	Synetics Corp.	53	Phototelesis	28
ERIM	19	BDS Systems, Inc.	54	Dimensions Tech. Inc.	29
Gaylord, Morgan & Dunn	20	Mission Research Corp.	55	XImage Corp.	30
Wyco Corp.	22	Ektron Applied Imaging	62	University of Nevada	35
CyberOptics	24	Spectrum Management Group (SMG)	63	Becan Engineering	41

APPLICABLE		POSSIBLY APPLICABLE		NOT APPLICABLE	
Vendor	No.	Vendor	No.	Vendor	No.
Control Data	26	Corabi	66	Institute for Systems Analysis, Inc.	42
Century Computing	31	American Electronics, Inc.	73	Synetics	45
Riverside Research Inst.	32	LNK Corporation	74	Honeywell	48
Eugene Walushka	34			Intermetrics, Inc.	50
Mechanical Technology, Inc.	36			Xerox Advanced Information Technology	51
PAR Government Systems	37			S M Systems and Research Group	57
MegaVision	38			AI Corp.	58
Quest Integrated, Inc.	40			TAMSCO	61
Arvin Calspan	47			CSCI Communications	67
G.E. Aerospace	49			Lockheed Missiles & Space Co., Inc., Research & Development Division	68
ESL, Inc.	52			SBD Associates	72
Autometric, Inc.	56				
Southwest Research Institute	59				
TAU Corporation	61				
G.E. Advanced Technology Labs	64				
Lockheed Missiles & Space Co., Inc. Simple Image Processing Lab.	65				

APPLICABLE		POSSIBLY APPLICABLE		NOT APPLICABLE	
Vendor	No.	Vendor	No.	Vendor	No.
Chapman Instruments	69				
David Sarnoff Research Center	70				
Air Gage Company	71				

APPENDIX C

SUPPLEMENTAL INFORMATION PROVIDED BY THE FBI

APPENDIX C

SUPPLEMENTAL INFORMATION PROVIDED BY THE FBI

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APPENDIX D

TECHNOLOGY INFORMATION AND EVALUATION SUMMARY

APPENDIX D

TECHNOLOGY INFORMATION AND EVALUATION SUMMARY

[Vendor proposal numbers refer to Appendix B. Technical paper numbers refer to FBI-provided materials tabulated in Appendix C.]

AREAL CAPACITANCE

FBI References:
Vendor Proposal 36
Technical Papers 10, 55, 56

Vendors Contacted:
MTI (Vendor 36)
(518) 785-2505
Contact: Brian Fox

First Cut Criteria:
Minimum Lateral Resolution - 3mm
Minimum Vertical Resolution - 1-10nm
Depth of Field/Vertical Range - < 100μm
Life Cycle Cost -
1. Purchase Price - $10K
2. General Ease of Use - Very mature technology. Rating: high.

Speed of Data Extraction - 5000 points per second.
Destructiveness of Method - non-destructive.

CONCENTRIC BEAM INTERFEROMETRY

FBI References:
Technical Paper 55

Additional References:
Precision Engineering, Vol. 7, No. 4, Oct. 1985, p. 211

First Cut Criteria:
Minimum Lateral Resolution - 0.5μm
Minimum Vertical Resolution - 0.1nm
Depth of Field/Vertical Range - 16nm
Life Cycle Cost -
1. Purchase Price - Not commercial, unknown.
2. General Ease of Use - The advantages of this instrument is that it requires no reference surface and is very insensitive to vibration and reflectance, making it somewhat easier to use than other interferometers. Rating: moderate.

Speed of Data Extraction - Unknown. References use analog signal.
Destructiveness of Method - Non-destructive.

CONFOCAL MICROSCOPY

FBI References:
Vendor Proposals 64,70
Technical Papers 14, 15, 16, 17, 51, 73

Vendors Contacted:
Molecular Dynamics (formerly Sarastro)
1-800-333-5703
Contacts: Kathy Padgett, Steve Nelson
Tracor Northern
(608) 831-6511
Contact: Willie Hausner

Vendor References Contacted:
Dr. Duane Kreuger (for Molecular Dynamics)
Dow Chemical
(507) 636-6549
Rob Gutierrez (for Molecular Dynamics)
Eastman Kodak
(716) 722-3390

First Cut Criteria:
Minimum Lateral Resolution - Diffraction-limited by optics (1μm spot) for laser-based systems. Monochromatic light sources required for best quantitative measurements (Source: Paper #14).
Minimum Vertical Resolution - Adjustable step height. Minimum slice is approximately 0.5μm (Source: Technical papers #14 and #15).
Depth of Field/Vertical Range - 2mm is standard, but can extend to 9.2mm with special 10X objective (Source: Molecular Dynamics).
Life Cycle Cost -
1. Purchase Price - $135K with automated stage for laser-based system (Source: Molecular Dynamics). $70K for white light system (Source: Tracor Northern).
2. General Ease of Use - Not fully automated; have to manually set beginning of scan. Have to be somewhat familiar with microscopes, but easier than electron microscopes. Rating: moderate.

Speed of Data Extraction - 2.5 seconds for 16,000 points, 20 seconds for 1,000,000 points (One field of view, Source: Molecular Dynamics).
Destructiveness of Method - Non-destructive.

Second Cut Criteria:

Robustness -
1. Sensitivity to Changing Room Light - Can be laser or white light based, but neither is sensitive to room lighting because of limited field of view (Source: Molecular Dynamics, Tracor Northern).
2. Sensitivity to Air Currents - Insensitive (Source: Molecular Dynamics).
3. Sensitivity to Humidity - Insensitive (Source: Molecular Dynamics).
4. Sensitivity to Vibration - Sensitive, but vibration isolation provided (Source: Molecular Dynamics).

Suitability for Imaging Cartridge Side -
1. Ability to Achieve 150μm Vertical Step - Yes, can handle up to 9.2mm step with special lens (Source: Molecular Dynamics).
2. Ability to Achieve 80mm Field of View (or Scan Length) - No, field of view is limited by optics and CCD size to 2mm x 2mm, given 5μm lateral resolution. Instrument not set up to scan in horizontal direction (Source: Molecular Dynamics, Tracor Northern).

Suitability for Imaging Cartridge End -
1. Ability to Achieve 2.5mm Vertical Step - Yes, can handle up to 9.2mm step with special lens (Source: Molecular Dynamics).
2. Ability to View or Scan 19mm circular object - No, limited to 2mm field of view.
3. Minimum Occlusion Angle - 0° (Source: Molecular Dynamics).
4. Sensitivity to Marking Orientation or Distribution - Insensitive (Source: Molecular Dynamics).

Suitability for Cartridge Material -
1. Sensitivity to Sample Conductivity - Insensitive; optical method.
2. Sensitivity to Sample Reflectivity - Sensitive, but can be compensated (Source: Molecular Dynamics).
3. Sensitivity to Changes in Sample Conductivity or Reflectivity - Somewhat (Source: Molecular Dynamics).

Inherent Sources of Error (independent of environment) -
1. 2π Depth Ambiguities - Not applicable.
2. Cumulative Errors - Not applicable.
3. Reference Surface Errors - Not applicable.
4. Repeatability - 10-20% of a pixel (Source: Molecular Dynamics).
5. Alignment/Leveling Errors - Possible because have to manually set up beginning of scan (Source: Molecular Dynamics). Rating: Somewhat sensitive.

Ease of Use (second cut) -
1. Ease of calibration - Calibration not required (Source: Molecular Dynamics). Rating: Minimum.
2. Frequency of calibration - Never (both vendors).
3. Reliability - Assume high because customers never need to calibrate.
4. Sensor Ruggedness - Assume moderate since it is not a high- production instrument.
5. Standoff - Maximum of 9.2mm (Source: Molecular Dynamics).

Flexibility -
1. Shape of Scan - Section, 1024 x 1280 pixels (Source: Molecular Dynamics).
2. Adjustability of Measurement Parameters - Can easily adjust vertical step. Have to change out objective to change depth of field or lateral resolution. Rating: moderate.

Acceptability -
1. Commercial Availability - Available from at least 4 manufacturers. Rating: moderate.
2. Correlation with Other Profiling Methods - unknown.
3. Minimum Aspect Ratio - 2 (Minimum lateral resolution is 1μm; minimum vertical step is 0.5μm; both are adjustable).
4. Bytes per 3D Data Point - 8-bit grey scale used x number of pixels in field of view (Source: Molecular Dynamics). Thus, one byte per data point.
5. Contact vs. Non-contact - Non-contact.
6. Simplicity of Concept - Creates 3D image much like topographic map (lines of constant elevation). Rating: high.

CONTACT STYLUS

FBI References:
Vendor Proposal 9
Technical Papers 13, 51, 55, 56

Vendors Contacted:
Tokyo Seimitsu America
(313) 353-3888
Contact: Peter Akroyd

Customer References:
John Hughes
Canadian Energy Department
(wouldn't give phone number)

First Cut Criteria:

Minimum Lateral Resolution - 0.46μm (Source: Technical Paper #56). More common 1-2μm.
Minimum Vertical Resolution - 0.1nm (Source: Technical Paper #55).
Depth of Field/Vertical Range - 1mm standard, 2mm special order for 3D system (Source: Tokyo Seimitsu).

Life Cycle Cost -
1. Purchase Price - $100K for 3D system (Source: Tokyo Seimitsu).
2. General Ease of Use - Alignment and leveling important, fragile (Source: Technical Paper #55). Very mature

technology (50 years), standard to which everything is compared (Source: Technical Paper #56). Rating: High.

Speed of Data Extraction - 30 points per second (limited to slow scan speed to avoid flight, Source: Tokyo Seimitsu America).

Destructiveness of Method - Might be destructive, depending on stylus speed, force, stylus size, sample hardness, etc (Source: Technical Paper 56).

Second Cut Criteria:

Robustness -

1. Sensitivity to Changing Room Light - Insensitive.
2. Sensitivity to Air Currents - Insensitive.
3. Sensitivity to Humidity - Insensitive.
4. Sensitivity to Vibration - Sensitive, but vibration isolation provided.

Suitability for Imaging Cartridge Side -

1. Ability to Achieve 150μm Vertical Step - No, although depth of field might be enough (2mm special order), it is not suitable for abrupt changes in elevation (Source: Technical Paper #56).
2. Ability to Achieve 80mm Field of View (or Scan Length) - Yes, although vendor information is unclear, scan length is not usually a problem (Source: Technical Paper #56).

Suitability for Imaging Cartridge End -

1. Ability to Achieve 2.5mm Vertical Step - No (Source: Technical Paper #56).
2. Ability to View or Scan 19mm circular object - No, not suitable for making automatically varying scan lengths (Source: Tokyo Seimitsu America).
3. Minimum Occlusion Angle - 30° to 45° (Source: Technical Paper #56).
4. Sensitivity to Marking Orientation or Distribution - very sensitive (Source: Tokyo Seimitsu America).

Suitability for Cartridge Material -

1. Sensitivity to Sample Conductivity - Insensitive.
2. Sensitivity to Sample Reflectivity - Insensitive.
3. Sensitivity to Changes in Sample Conductivity or Reflectivity - Insensitive.

Inherent Sources of Error (independent of environment) -

1. 2π Depth Ambiguities - Not applicable.
2. Cumulative Errors - Not applicable.
3. Reference Surface Errors - Skid errors possible (Source: Technical Paper #55).
4. Repeatability - 1% for required lateral and vertical resolution (Source: Tokyo Seimitsu).
5. Alignment/Leveling Errors - Leveling errors cited as weakness (Source: Technical Paper #55). Rating: very sensitive.

Ease of Use (second cut) -

1. Ease of calibration - Use calibration standard with steps for lateral, use interferometer for vertical (Source: Technical Paper #56). Using steps can be fully automated, but very slow (Source: Tokyo Seimitsu). Rating: high.
2. Frequency of calibration - Rarely (Source: John Hughes).
3. Reliability - Maximum reliability (Sources: John Hughes, Vendor Proposal #9)
4. Sensor Ruggedness - Can be fragile (Source: Technical Paper #55). Rating: low.
5. Standoff - None; contact method.

Flexibility -

1. Shape of Scan - series of points.
2. Adjustability of Measurement Parameters - Can adjust sensitivity of vertical measurement with filters. Can adjust lateral resolution with software. Cannot adjust depth of field. Not much adjustment of speed. Can adjust scan length but not continuously (Source: Tokyo Seimitsu America). Rating: high.

Acceptability -

1. Commercial Availability - Very mature technology, but not as prevalent as coordinate measuring machines. Rating: high.
2. Correlation with Other Profiling Methods - Maximum, this is the standard to which everything else is measured.
3. Aspect Ratio - 4600 (Minimum lateral resolution is 0.46μm; minimum vertical resolution is 0.1nm; both are adjustable).
4. Bytes per 3D Data Point - assume at least 6.
5. Contact vs. Non-contact - Can braze surface and change appearance (Source: Tokyo Seimitsu). Rating: Possibly damaging.
6. Simplicity of Concept - Output is directly proportional to undulations in surface. Rating: maximum.

COORDINATE MEASURING MACHINE (CMM) - CONTACT

FBI References:
None.

Vendors Contacted:
Brown and Sharpe
(206) 431-8203
Contact: Dave Tackes

References Contacted:
Art Deyo
Datum, Inc.
(602) 437-5760

First Cut Criteria:

Minimum Lateral Resolution - 2-3μm (Source: Brown and Sharpe).

Minimum Vertical Resolution - 2-3μm (Source: Brown and Sharpe).

Depth of Field/Vertical Range - Unlimited (Source: Brown and Sharpe).
Life Cycle Cost -
1. Purchase Price - $60K for automated 3D system (Source: Brown and Sharpe).
2. General Ease of Use - Fully automated and programmable. Very developed technology. Rating: maximum.

Speed of Data Extraction - 80 points per minute (1.33 points per second).
Destructiveness of Method - Only touches sample, and raises between each sample point (stitch mode); does not "drag" across surface like stylus.

COORDINATE MEASURING MACHINE (CMM) - (VIDEO)

FBI References:
None.

Vendors Contacted:
Fred V. Fowler Co., Inc.
(617) 332-7004
Contact: Monticello Abrams

Note: The vendor indicated that this product was not really suitable for detecting of small flaws, despite the specifications. It is highly dependent on lighting conditions, and is more suitable for imaging printed circuit boards, etc. The reference for Touch-type CMM's said that he would always use a contact type over a video type because video was so unreliable due to lighting problems.

First Cut Criteria:
Minimum Lateral Resolution - 2μm
Minimum Vertical Resolution - 2μm
Depth of Field/Vertical Range - 100mm
Life Cycle Cost -
1. Purchase Price - $60K for automated 3D system.
2. General Ease of Use - Fully automated and programmable. Very developed technology. Rating: maximum.

Speed of Data Extraction - 60 points per minute (1 point per second).
Destructiveness of Method - Non-destructive.

DIFFRACTIVE RANGING

FBI Reference:
None.

Additional References:
SPIE Vol. 754, Optical and Digital Pattern Recognition, 1987, p. 55

First Cut Criteria:
Minimum Lateral Resolution - Depends on beam spread; probably greater than 5μm.
Minimum Vertical Resolution - Limited to 1mm by grating spacing.
Depth of Field/Vertical Range - Unknown, but probably greater than 150μm.
Life Cycle Cost -
1. Purchase Price - Not commercial, unknown.
2. General Ease of Use - If technology was mature, would be similar to LIDAR. Rating: High.

Speed of Data Extraction - Unknown.
Destructiveness of Method - Non-destructive.

FRINGE-FIELD CAPACITANCE

FBI References:
Technical Paper 55

Vendors Contacted:
Extrude Hone
(412) 863-5900
Contact: Ralph Resnick

Vendor References Contacted:
Dr. J. L. Garbini (inventor)
University of Washington
(206) 543-5399
Dr. Robert Hocken
University of North Carolina
(704) 547-4863
Tim Tuttle
Carrier Corporation
(315) 432-6090

First Cut Criteria:
Minimum Lateral Resolution - 0.1μm theoretical, 6μm presently (Source: Extrude Hone). Garbini says that this resolution is only good in the scan direction, which limits its use to samples with predominantly one- dimensional surface markings.
Minimum Vertical Resolution - 0.1μm (Source: Extrude Hone)
Depth of Field/Vertical Range - Vertical range is quite large (500-600μm), but since the sensor rides inside ruby ball, and ruby ball is 1/8" in diameter, the ball acts as a skid and cannot go down into narrow cracks. If the skid cannot enter the depression, the deepest crack that it can sense is 2mm (Source: Extrude Hone).
Life Cycle Cost -
1. Purchase Price - $50K for turnkey system (Source: Extrude Hone).
2. General Ease of Use - Much like stylus, but faster. Rating: High.

Speed of Data Extraction - Garbini says that speed of data acquisition could be 40,000 points per second, but Extrude Hone says electronics are limiting to 2000 points per second.

Destructiveness of Method - Extrude Hone says that diameter of ruby ball is 1" on bottom, so it is almost flat. Thus, it cannot scratch the surface. Rating: Maybe.

Second Cut Criteria:

Robustness -

1. Sensitivity to Changing Room Light - Insensitive.
2. Sensitivity to Air Currents - Sensitive to air temperature changes, but is compensated with temperature sensor and software.
3. Sensitivity to Humidity - Extrude Hone says they have done testing and found that there is no detectable effect.
4. Sensitivity to Vibration - Insensitive; ruby ball acts as damping device.

Suitability for Imaging Cartridge Side -

1. Ability to Achieve 150μm Vertical Step - Yes (Source: Extrude Hone).
2. Ability to Achieve 80mm Field of View (or Scan Length) - Yes (Source: Extrude Hone).

Suitability for Imaging Cartridge End -

1. Ability to Achieve 2.5mm Vertical Step - No, can make step but can't resolve bottom of crack (Source: Extrude Hone).
2. Ability to View or Scan 19mm circular object - Yes, scan length is adjustable and programmable (Source: Extrude Hone).
3. Minimum Occlusion Angle - 0°
4. Sensitivity to Marking Orientation or Distribution - Very sensitive. Has much greater sensitivity in direction of scan.

Suitability for Cartridge Material -

1. Sensitivity to Sample Conductivity - very sensitive (Source: Extrude Hone)
2. Sensitivity to Sample Reflectivity - insensitive.
3. Sensitivity to Changes in Sample Conductivity or Reflectivity - very sensitive (Source: Extrude Hone)

Inherent Sources of Error (independent of environment) -

1. 2π Depth Ambiguities - not applicable.
2. Cumulative Errors - not applicable.
3. Reference Surface Errors - possible, but compensated in software (Source: Extrude Hone).
4. Repeatability - 1.32% (Source: Extrude Hone).
5. Alignment/Leveling Errors - very sensitive.

Ease of Use (second cut) -

1. Ease of calibration - Fully automated using calibrated step. Rating: high.
2. Frequency of calibration - not required between samples as long as there is no film on sample. Only sensitive to capacitance of air between sample and probe. (Source: Tim Tuttle). Rating: sometimes.
3. Reliability - doesn't give reliable readings sometimes because of vibrations experienced in probe (too long and slender). (Source: Tim Tuttle). Rating: moderate.
4. Sensor Ruggedness - probe fragile (Source: Tim Tuttle). Rating: minimum.
5. Standoff - contact method.

Flexibility -

1. Shape of Scan - series of points.
2. Adjustability of Measurement Parameters - Can adjust vertical and horizontal resolution with software. Cannot adjust vertical range. Can adjust scan length. Rating: moderate.

Acceptability -

1. Commercial Availability - only one manufacturer in the world (Source: Extrude Hone).
2. Correlation with Other Profiling Methods - Garbini says that there is some attenuation of higher frequencies. Rating: moderate.
3. Aspect Ratio - 60 (Minimum lateral resolution is 6μm, minimum vertical resolution is 0.1μm; both are adjustable).
4. Bytes per 3D Data Point - 1-32 bit word per axis plus 1-16 bit word for sensor reading = 14 bytes total.
5. Contact vs. Non-contact - contact, but non-damaging.
6. Simplicity of Concept - Fairly simple to visualize. Rating: High.

GRADIENT FILTER PROFILING

FBI References:
None.

Additional References:
Tim Peters
Pacific Northwest Laboratory
(509) 375-2101

First Cut Criteria:

Minimum Lateral Resolution - 50μm
Minimum Vertical Resolution - 200μm
Depth of Field/Vertical Range - 6mm
Life Cycle Cost -

1. Purchase Price - Not commercial, unknown.
2. General Ease of Use - Concept somewhat similar to light sectioning. Rating: high.

Speed of Data Extraction - 200,000 points per second.
Destructiveness of Method - Non-destructive.

HOLOGRAPHIC/SPECKLE INTERFEROMETRY

FBI References:
None.

Additional References:
Automated Visual Inspection (Battelle Frankfort document)

Vendors Contacted:
Ealing Electro-Optics
(508) 429-8370

First Cut Criteria:
Minimum Lateral Resolution - 1μm
Minimum Vertical Resolution - nanometer-range.
Depth of Field/Vertical Range - 2-4 cm., but not as a step. Limited to 0.7μm step.
Life Cycle Cost -
1. Purchase Price - $75K
2. General Ease of Use - Similar to other commercial interferometers. Rating: moderate.
Speed of Data Extraction - 2913 points per second.
Destructiveness of Method - Non-destructive.

HOLOGRAPHY

FBI References:
Vendor Proposal 8

Vendors Contacted:
Newport
1-800-222-6440
Contact: Warren Booth

First Cut Criteria:
Minimum Lateral Resolution - 3μm.
Minimum Vertical Resolution - 3μm.
Depth of Field/Vertical Range - 6 feet (1.83m).
Life Cycle Cost -
1. Purchase Price - $47K
2. General Ease of Use - Some alignment and vibration isolation required, but otherwise easy to use. Rating: High.
Speed of Data Extraction - 0 points per second. Unable to find any sources doing 3D data extraction from holography.
Destructiveness of Method - Non-destructive.

IR PHASE SHIFTING INTERFEROMETRY (TWYMAN-GREEN)

FBI References:
Phase Shifting Interferometry - Vendor Proposal 22, Technical Paper 6
Twyman-Green Interferometry - Technical Papers 55, 56

Vendors Contacted:
Wyko
(602) 741-1044
Contact: Lisa Merrill

First Cut Criteria:
Minimum Lateral Resolution - 10.6μm (due to IR wavelength).
Minimum Vertical Resolution - 10.6 nm.
Depth of Field/Vertical Range - limited to step of 2.65 μm.
Life Cycle Cost -
1. Purchase Price - $127K
2. General Ease of Use - Similar to other commercial interferometers. Rating: moderate.
Speed of Data Extraction - 4923 points per second.
Destructiveness of Method - Non-destructive.

LASER DYNAMIC FOCUSING

FBI References:
Vendor Proposals 9, 19, 36
Technical Papers 1, 2, 3, 7, 9, 10, 51, 55

Vendors Contacted:
Rodenstock Precision Optics
(815) 874-6374
Contact: Dan Nagle
UBM Corporation
(908) 241-8652
Contact: Leigh Mummery

Vendor References Contacted:
Dan Cotter (Rodenstock)
GTE Labs
(617) 890-8460
Primo Gugnoni (Rodenstock)
Torrington Co.
(203) 482-9511
Matt Pennings (Rodenstock)
Semitech
(408) 732-9697
Dino Ciarlo
Lawrence Livermore Laboratory
(510) 422-8872
Russ Ziebel
Cray Research
(715) 726-1291

First Cut Criteria:
Minimum Lateral Resolution - 1μm spot (both vendors).
Minimum Vertical Resolution - 0.1μm for Rodenstock, 0.06μm for UBM (for greatest vertical range).
Depth of Field/Vertical Range - $\pm$500μm for UBM, $\pm$300μm for Rodenstock.
Life Cycle Cost -
1. Purchase Price - $100K for Rodenstock, $55K for UBM (probably not as inclusive of options as Rodenstock price).
2. General Ease of Use - Based on simplicity of principle and commercial availability, assume ease of use is high.
Speed of Data Extraction - Both vendors say it varies, depending on vertical range, from 120 points per second (height changes > 300μm) to 2000 points per second (height changes < 10μm). Assuming that

most impressions won't be very deep, speed should be around 1200 points per second (Source: UBM).
Destructiveness of Method - non-contact.

Second Cut Criteria:

Robustness -

1. Sensitivity to Changing Room Light - Both vendors say that it is insensitive to room lighting.
2. Sensitivity to Air Currents - Insensitive.
3. Sensitivity to Humidity - Insensitive.
4. Sensitivity to Vibration - Vibration isolation provided.

Suitability for Imaging Cartridge Side -

1. Ability to Achieve 150μm Vertical Step - Yes (both vendors).
2. Ability to Achieve 80mm Field of View (or Scan Length) - Yes (both vendors). Rodenstock can do 100mm, UBM can do 300mm.

Suitability for Imaging Cartridge End -

1. Ability to Achieve 2.5mm Vertical Step - No (both vendors).
2. Ability to View or Scan 19mm circular object - Yes (both vendors).
3. Minimum Occlusion Angle - 0°, but limit on slope of object itself is 13°.
4. Sensitivity to Marking Orientation or Distribution - Rodenstock says no, UBM say slightly. Rating: sensitive, but compensated.

Suitability for Cartridge Material -

1. Sensitivity to Sample Conductivity - insensitive.
2. Sensitivity to Sample Reflectivity - Can handle from 2% to 95% reflectivity (both vendors). Cotter said that tolerance for reflectivity is the reason that he selected this technology over others (he images ceramics and metals with high degrees of reflectivity). Ciarlo says that he has trouble with steep slopes and edges because of the reflectivity issue. He has had to manually adjust the laser power to get around these problems. Rating: Somewhat sensitive.
3. Sensitivity to Changes in Sample Conductivity or Reflectivity - Rodenstock says that a step of 2% to 95% would cause the instrument to lose its focus. UBM says that they have an algorithm to compensate for this problem. Rating: somewhat sensitive.

Inherent Sources of Error (independent of environment) -

1. 2π Depth Ambiguities - Not applicable.
2. Cumulative Errors - Not applicable.
3. Reference Surface Errors - Not applicable.
4. Repeatability - 0.3% (Source: Rodenstock).
5. Alignment/Leveling Errors - Possible stage translation errors (UBM). Rodenstock requires coarse alignment. Somewhat sensitive.

Ease of Use (second cut) -

1. Ease of calibration - Only takes 5 minutes and is fully automated (Source: UBM). Have to send back to factory for Rodenstock for 8 weeks (Source: Rodenstock). Rating: moderate.
2. Frequency of calibration - Never (all references).
3. Reliability - Over all, very reliable (all references), some limit- switch bugs at first (Source: Pennings). Some software bugs at first (Source: Ciarlo). Rating: high.
4. Sensor Ruggedness - None of the references have had to replace any components yet; some have had their systems for 2 years. Rating: high.
5. Standoff - standard is 2mm for UBM, 10mm for Rodenstock.

Flexibility -

1. Shape of Scan - series of points.
2. Adjustability of Measurement Parameters - scan length, scan width, resolutions in all dimensions (Source: both vendors). Standoff not adjustable.

Acceptability -

1. Commercial Availability - Only three vendors known (Rodenstock, UBM, and Olympus). Rating: low.
2. Correlation with Other Profiling Methods - Gugnoni says that he has very poor luck getting his readings to correlate with stylus readings, primarily with large amounts of surface roughness. He says that he feels that he has not had the system long enough to learn it adequately yet or interpret the results (he has had the system under a year), but he still like the system very much. Other sources indicate good correlation (Ciarlo). Rating: moderate.
3. Aspect Ratio - 17 (minimum lateral resolution 1μm; minimum vertical resolution 0.06μm; both adjustable)
4. Bytes per 3D Data Point - 6 bytes for UBM, 4 bytes for Rodenstock.
5. Contact vs. Non-contact - non-contact.
6. Simplicity of Concept - Fairly simple concept. Rating: high.

LASER RADAR/SAR/ISAR

FBI References:
Vendor Proposals 8, 32, 56

Vendors Contacted:
Azimuth Corp.
(508) 692-8500
Contact: Ron Roth

First Cut Criteria:

Minimum Lateral Resolution - 0.5 to 2 milliradians beam width (at required range, this is much greater than 1μm).

Minimum Vertical Resolution - 5 cm.

Depth of Field/Vertical Range - few meters to 3 kilometers. Obviously more applicable to long range measurements.

Life Cycle Cost -

1. Purchase Price - $160K - $210K.
2. General Ease of Use - Based on maturity of technology and simplicity of concept, rate as High.

Speed of Data Extraction - 2000 points per second.

Destructiveness of Method - Non-destructive.

LASER TRIANGULATION

FBI References:

Vendor Proposals 1, 20, 24, 40, 59

Vendors Contacted:

Chesapeake Laser Systems
(301) 459-7977
Contact: Bill Shade
CyberOptics
(612) 331-5702
Contact: Martha (no last name given)

References Contacted:

Clark Fortney (for CyberOptics)
Battelle Columbus
(614) 424-3706
Richard Long (for CyberOptics)
Digital Equipment Corp.
(508) 493-4330
Boyd Eldridge (for Chesapeake)
Adolph Coors
(303) 277-3901
Dr. Brian Lang (for Chesapeake)
Michigan School of Dentistry
(313) 763-5280

First Cut Criteria:

Minimum Lateral Resolution - 3μm (Source: CyberOptics). This number is suspect because of allusions to 10μm spot size.

Minimum Vertical Resolution - 1μm (Source: CyberOptics).

Depth of Field/Vertical Range - at least 150μm (Source: CyberOptics).

Life Cycle Cost -

1. Purchase Price - $37.5K (Source: Chesapeake).
2. General Ease of Use - High, based of maturity of technology and commercial availability.

Speed of Data Extraction - 1000 points per second.

Destructiveness of Method - Non-destructive.

Second Cut Criteria:

Robustness -

1. Sensitivity to Changing Room Light - Insensitive (both vendors).
2. Sensitivity to Air Currents - Insensitive (both vendors).
3. Sensitivity to Humidity - Insensitive (both vendors).
4. Sensitivity to Vibration - Vibration isolation provided (both vendors).

Suitability for Imaging Cartridge Side -

1. Ability to Achieve 150μm Vertical Step - Yes (both vendors).
2. Ability to Achieve 80mm Field of View (or Scan Length) Yes (both vendors).

Suitability for Imaging Cartridge End -

1. Ability to Achieve 2.5mm Vertical Step - Maybe; CyberOptics say they can not, and Chesapeake says they can without a sacrifice in resolution.
2. Ability to View or Scan 19mm circular object - Yes (both vendors).
3. Minimum Occlusion Angle - Sensor is normal to surface, receiver is at 30° for Chesapeake and 45° for CyberOptics.
4. Sensitivity to Marking Orientation or Distribution - yes (both vendors).

Suitability for Cartridge Material -

1. Sensitivity to Sample Conductivity - Insensitive.
2. Sensitivity to Sample Reflectivity - very sensitive, works better with diffuse samples (both vendors). Another reference (see Laser Dynamic Focusing references) said that triangulation was very bad for shiny metals and ceramics.
3. Sensitivity to Changes in Sample Conductivity or Reflectivity - sensitive, but compensated (both vendors). Fortney says that changes in surface reflectivity really slow the system down; he has had the system actually slow down to 10 points per second!

Inherent Sources of Error (independent of environment) -

1. 2π Depth Ambiguities - not applicable.
2. Cumulative Errors - not applicable.
3. Reference Surface Errors - not applicable.
4. Repeatability - ±2 times the resolution for CyberOptics, ±1 times the resolution for Chesapeake. Equal to a 512 unit with 0.78% repeatability.
5. Alignment/Leveling Errors - somewhat sensitive.

Ease of Use (second cut) -

1. Ease of calibration - User cannot calibrate sensor, just table (both vendors).
2. Frequency of calibration - should never need it unless dropped (Source: CyberOptics).
3. Reliability - References all say very reliable for several years; one vendor of touch-type

coordinate measuring machines said that he had many problems with using triangulation probes on his machines because of sensor fragility. Rating: high.

4. Sensor Ruggedness - some disagreement (see above). Rating: low.
5. Standoff - CyberOptics says 18.9mm for required resolution, Chesapeake says 4.5" (highly suspect number).

Flexibility -

1. Shape of Scan - series of points.
2. Adjustability of Measurement Parameters - lateral resolution controlled by translation and adjustable. Vertical resolution and standoff are interrelated and cannot be independently adjusted.

Acceptability -

1. Commercial Availability - Very common, but not quite as common as coordinate measuring machines. Rating: high.
2. Correlation with Other Profiling Methods - Fortney has checked it against a power microscope and found it to correlate well. Rating: high.
3. Aspect Ratio - 3 (minimum lateral resolution 3μm; minimum vertical resolution 1μm) '
4. Bytes per 3D Data Point - 16 bits for z, 24 bits for x and y (Source: CyberOptics). Array of 25-character ASCII words for Chesapeake (equates to a minimum of 7 bits per character).
5. Contact vs. Non-contact - non-contact.
6. Simplicity of Concept - somewhat difficult to understand for the layperson. Rating: low.

LIGHT SCATTERING

FBI References:
Vendor Proposals 32, 36
Technical Papers 1, 10, 13, 22, 23, 25, 51, 56

Vendors Contacted:
MTI (Vendor 36)
(518) 785-2505
Contact: Brian Fox

First Cut Criteria:
Minimum Lateral Resolution - 10μm (paper 22) to 500μm (MTI).
Minimum Vertical Resolution - 0.1μm (paper 22) to 25μm (MTI).
Depth of Field/Vertical Range - 500μm (paper 23).
Life Cycle Cost -

1. Purchase Price - $3K to $10K
2. General Ease of Use - Very mature technology and simple. Rating: maximum.

Speed of Data Extraction - 200,000 points per second.
Destructiveness of Method - Non-destructive.

MASK CAMERA

FBI References:
None.

Additional References:
Optics and Lasers in Engineering, Vol. 10, 1989, P. 227
Tim Peters
Pacific Northwest Laboratory
(509) 375-2101

First Cut Criteria:
Minimum Lateral Resolution - 1-2μm
Minimum Vertical Resolution - 100μm
Depth of Field/Vertical Range - Very large; much greater than 150μm.
Life Cycle Cost -

1. Purchase Price - Not commercial, unknown.
2. General Ease of Use - Similar to using video. Rating: maximum.

Speed of Data Extraction - 13,400 points per second.
Destructiveness of Method - Non-destructive.

MOIRE (PROJECTION) INTERFEROMETRY

FBI References:
Vendor Proposal 71
Technical Paper 20

Vendors Contacted:
Wyko (Note: they dropped the Moire instrument from their line of products because of lack of sales)
Air Gage
(313) 591-0434
Contact: Leonard Bieman
EOIS
(213) 451-8566
Contact: John Fitts

Vendor References Contacted:
Bill Maurey (for EOIS)
Chem-Tronics
(619) 258-5113
Kevin Harding (for Air Gage)
Industrial Technology Institute
(313) 769-4195

First Cut Criteria:
Minimum Lateral Resolution - 1.78μm (Source: Air Gage).
Minimum Vertical Resolution - 1.02μm (Source: Air Gage).
Depth of Field/Vertical Range - 127mm (Source: Air Gage), 100mm (Source: EOIS).
Life Cycle Cost -

1. Purchase Price - $80K-$100K for Air Gage. $150K-$200K for EOIS.
2. General Ease of Use - Seems cumbersome, especially as sensitive as it is to air currents,

vibration, etc. Still easier to use than development items. Rating: moderate.

Speed of Data Extraction - 13,000 points per second for EOIS system. 50,000 points per second for Air Gage.

Destructiveness of Method - Non-destructive.

Second Cut Criteria:

Robustness -

1. Sensitivity to Changing Room Light - EOIS system is laser-based and is not as sensitive to room lighting. Air Gage system is white-light based and sensitive. Rating: very sensitive.
2. Sensitivity to Air Currents - yes (both vendors).
3. Sensitivity to Humidity - no (Source: Air Gage).
4. Sensitivity to Vibration - yes, vibration isolation provided (both vendors).

Suitability for Imaging Cartridge Side -

1. Ability to Achieve 150μm Vertical Step - yes (both vendors).
2. Ability to Achieve 80mm Field of View (or Scan Length) - maybe, largest field of view is 2.5mm for 5μm lateral resolution, but could use scanning techniques (Source: EOIS). Rating: maybe.

Suitability for Imaging Cartridge End -

1. Ability to Achieve 2.5mm Vertical Step - yes (both vendors).
2. Ability to View or Scan 19mm circular object - maybe, limited to 2.5mm field of view, but could use scanning techniques (both vendors).
3. Minimum Occlusion Angle - 20° standard for Air Gage, 30° standard for EOIS.
4. Sensitivity to Marking Orientation or Distribution - somewhat sensitive, but can manually adjust gratings to compensate (Source: Air Gage).

Suitability for Cartridge Material -

1. Sensitivity to Sample Conductivity - Insensitive.
2. Sensitivity to Sample Reflectivity - Yes; not good for highly reflective surfaces (both vendors). EOIS actually has two systems; one for diffuse and one for specular surfaces. Bill Maurey said that his system gave him some trouble with reflectivity; he uses it to image titanium fan blades.
3. Sensitivity to Changes in Sample Conductivity or Reflectivity - Somewhat (Source: Air Gage).

Inherent Sources of Error (independent of environment) -

1. 2π Depth Ambiguities - Possible, but well compensated with software. One system can handle as many as 24 fringes in a single step (Air Gage).
2. Cumulative Errors - Not applicable.
3. Reference Surface Errors - possible.
4. Repeatability - 2% (Source: EOIS).
5. Alignment/Leveling Errors - Very sensitive (Source: EOIS).

Ease of Use (second cut) -

1. Ease of calibration - Totally automated (both vendors). Rating: maximum.
2. Frequency of calibration - Very often. Both vendors said once a day. Maurey calibrates once every two hours!
3. Reliability - Technology too new to determine. Both references had some setup problems, both hardware and software. Rating: moderate.
4. Sensor Ruggedness - Maurey says system is appropriate for use on factory floor. Rating: high.
5. Standoff - 100mm (Source: EOIS).

Flexibility -

1. Shape of Scan - full field.
2. Adjustability of Measurement Parameters - can adjust depth resolution, field of view, standoff, and illumination angle (Source: EOIS). Rating: maximum.

Acceptability -

1. Commercial Availability - At least two vendors; used to be three (Wyko discontinued product). Rating: low.
2. Correlation with Other Profiling Methods - unknown, but is calibrated with NBS step standard. Rating: moderate.
3. Aspect Ratio - 1.75 (lateral resolution 1.78μm; vertical resolution 1.02μm; Source: Air Gage)
4. Bytes per 3D Data Point - 2 bytes x 512 x 512 pixels (Source: Air Gage). 6 bytes (2 bytes per dimension, floating point data) for EOIS.
5. Contact vs. Non-contact - non-contact.
6. Simplicity of Concept - Not very simple to the layman.

MULTIPLE BEAM (>2) INTERFEROMETRY

FBI References:

Tolansky Interferometry - Technical Paper 55

Additional References:

Tolansky Interferometry - SPIE Vol. 342, Integrated Circuit Metrology, 1982, p. 92

FECO Interferometry - Applied Optics, Vol. 15, No. 11, Nov. 1976

First Cut Criteria:

Minimum Lateral Resolution - 2μm.

Minimum Vertical Resolution - 0.8nm.

Depth of Field/Vertical Range - Slopes given in Å per μm, so very limited depth of field. Assume less than 150μm. Use primarily for measuring flatness of hard disks.

Life Cycle Cost -
1. Purchase Price - Unable to find commercial source.
2. General Ease of Use - Similar to other interferometers. Rating: moderate.

Speed of Data Extraction - 15,000 points per second.
Destructiveness of Method -

NEAR FIELD OPTICAL SCANNING MICROSCOPY

FBI References:
Technical Paper 14

Additional References:
Applied Physics Letters, Vol. 44, No. 7, April 1984, p. 651
Applied Optics, Vol. 25, No. 12, June 1986, p. 1890

First Cut Criteria:
Minimum Lateral Resolution - Designed to achieve resolution below the diffraction limit (much less than 1 μm).
Minimum Vertical Resolution - Much less than 1μm.
Depth of Field/Vertical Range - 0.2μm.
Life Cycle Cost -
1. Purchase Price - Not commercial; unknown.
2. General Ease of Use - Similar to other developmental microscopes. Rating: minimum.

Speed of Data Extraction - Unknown.
Destructiveness of Method - Non-destructive.

NEAR FIELD THERMOCOUPLE MICROSCOPY

FBI References:
Technical Paper 14

Additional References:
Applied Physics Letters, Vol. 49, No. 23, Dec. 1986, p. 1587

First Cut Criteria:
Minimum Lateral Resolution - 0.1μm.
Minimum Vertical Resolution - 3nm.
Depth of Field/Vertical Range - 100μm.
Life Cycle Cost -
1. Purchase Price - Not commercial; unknown.
2. General Ease of Use - Similar to other developmental microscopes. Rating: minimum.

Speed of Data Extraction - Scanning signal modulated at 1000 Hz, thus sampling speed would probably be less than 500 Hz.
Destructiveness of Method - Non-destructive.

NOMARSKI DIFFERENTIAL INTERFEROMETRY

FBI References:
Vendor Proposal 69

Additional References:
Journal of the Optical Society of America, Vol 69, No. 2, Feb 1979, p. 357
Applied Optics, Vol. 19, No. 17, Sep. 1980, p. 2998

Vendors Contacted:
Chapman Instruments (Vendor 69)
(716) 461-1950
Tom Bristow

First Cut Criteria:
Minimum Lateral Resolution - 1μm.
Minimum Vertical Resolution - 0.1nm.
Depth of Field/Vertical Range - Slope limitations of less than 20°; instrument designed to use on smooth surfaces. Could not handle step of 150μm.
Life Cycle Cost -
1. Purchase Price - $85K-$100K
2. General Ease of Use - Similar to other interferometers. Rating: moderate.

Speed of Data Extraction - 740 points per second.
Destructiveness of Method - Non-destructive.

OPTICAL HETERODYNE INTERFEROMETRY

FBI References:
Technical Papers 55, 56

Additional References:
Applied Optics, Vol. 20, No. 4, Feb. 1981, p. 610

Vendors Contacted:
Zygo
(203) 347-8506
Contact: Peter Fluke

First Cut Criteria:
Minimum Lateral Resolution - 0.5-2μm.
Minimum Vertical Resolution - 0.1nm.
Depth of Field/Vertical Range - Instrument designed for very smooth surfaces. 22μm depth of field maximum.
Life Cycle Cost -
1. Purchase Price - $100K
2. General Ease of Use - Similar to other interferometers. Rating: moderate.

Speed of Data Extraction - Less than one sample per second (15 seconds per sample).
Destructiveness of Method - Non-destructive.

PHOTON TUNNELING MICROSCOPY

FBI References:
Technical Paper 24

First Cut Criteria:
Minimum Lateral Resolution - 0.4μm.
Minimum Vertical Resolution - 1nm.
Depth of Field/Vertical Range - 10nm - 1μm.
Life Cycle Cost -
1. Purchase Price - Not commercial; unknown.
2. General Ease of Use - Very sensitive and tedious. Rating: minimal.

Speed of Data Extraction - Unknown.
Destructiveness of Method - Requires that metal surfaces be replicated with a dielectric medium. Might damage sample in the process.

PNEUMATIC/HYDRAULIC SENSORS

FBI References:
Technical Paper 56
Vendor 36 (technology not included in proposal)

Additional References:
Journal of Physics E: Scientific Instruments, Vol. 13, 1980, p. 593

Vendors Contacted:
Air Gage (Vendor 36)
(313) 591-0434
Contact: Wayne Bending

First Cut Criteria:
Minimum Lateral Resolution - Very poor. This instrument is exclusively designed to do gaging in one dimension only.
Minimum Vertical Resolution - 0.16-5.69μm. Commercial instrument is not used for profiling because the relationship between back pressure and vertical distance is not linear, and thus geometry must be known ahead of time.
Depth of Field/Vertical Range - 100μm
Life Cycle Cost -
1. Purchase Price - unknown.
2. General Ease of Use - Mature technology. Rating: moderate for intended use.

Speed of Data Extraction - Does not do data extraction, only gages.
Destructiveness of Method - Gaging with other than water can result in altering the sample.

REFLECTION ELECTRON MICROSCOPY

FBI References:
Technical Paper 56

First Cut Criteria:
Minimum Lateral Resolution - Atomic scale, much less than 1μm.
Minimum Vertical Resolution - Atomic scale, much less than 1μm.
Depth of Field/Vertical Range - Very limited. Instrument designed for ultra-smooth surfaces. Much less than 150μm.
Life Cycle Cost -
1. Purchase Price - Not commercial, unknown.
2. General Ease of Use - Very sensitive and tedious. Rating: minimum.

Speed of Data Extraction - Unknown.
Destructiveness of Method - Non-destructive.

SCANNING ACOUSTIC MICROSCOPY

FBI References:
Technical Paper 14, 51

Additional References:
Physics Today, August 1985, p. 34

Vendors Contacted:
Olympus
(516) 488-3880
Michael Testa

First Cut Criteria:
Minimum Lateral Resolution - 1.3μm at 800 MHz
Minimum Vertical Resolution - 1.3μm at 800 MHz
Depth of Field/Vertical Range - 1/10 wavelength (in water), which is less than 150μm.
Life Cycle Cost -
1. Purchase Price - $150K to $330K
2. General Ease of Use - Similar to other commercial microscopes. Rating: low.

Speed of Data Extraction - unknown.
Destructiveness of Method - Water or some other fluid would have to be used. Could alter the appearance of sample.

SCANNING ELECTRON MICROSCOPY

FBI References:
Technical Papers 8, 10, 11, 14, 19, 42, 43, 51, 56

Vendors Contacted:
Carl Zeiss
(914) 747-1800

First Cut Criteria:
Minimum Lateral Resolution - 0.1μm
Minimum Vertical Resolution - 50nm
Depth of Field/Vertical Range - 1μm
Life Cycle Cost -
1. Purchase Price - $180K

2. General Ease of Use - Similar to other commercial microscopes. Rating: low.

Speed of Data Extraction - 5-10 minutes per field of view (28,000 points per second).

Destructiveness of Method - Some disagreement among references, but Paper 14 says that sample preparation is destructive.

SCANNING FORCE MICROSCOPY

FBI References:
Technical Papers 14, 55

Vendors Contacted:
Wyko
(602) 741-1044
Contact: Lisa Merrill

First Cut Criteria:

Minimum Lateral Resolution - few Å
Minimum Vertical Resolution - few Å
Depth of Field/Vertical Range - 12μm
Life Cycle Cost -

1. Purchase Price - $85K
2. General Ease of Use - Similar to other commercial microscopes. Rating: low.

Speed of Data Extraction - 10μm square field of view in 1 minute; approximately 16,000 points per second.

Destructiveness of Method - Probe touches surface, but very lightly. Non-destructive.

SCANNING TUNNELING MICROSCOPY

FBI References:
Technical Papers 14, 26, 27, 55, 56

Vendors Contacted:
Wyko
(602) 741-1044
Contact: Lisa Merrill

First Cut Criteria:

Minimum Lateral Resolution - few Å
Minimum Vertical Resolution - few Å
Depth of Field/Vertical Range - 12μm
Life Cycle Cost -

1. Purchase Price - $85K
2. General Ease of Use - Similar to other commercial microscopes. Rating: low.

Speed of Data Extraction - 16,000 (Commercial instrument is virtually the same as the Scanning Force Microscope; only a change in probe is needed).

Destructiveness of Method - Non-destructive.

SCHLIEREN MICROSCOPY

FBI References:
Technical Paper 10

Additional References:
Applied Optics, Vol 24, No. 6, Mar. 1985, p. 816
Optical Engineering, Vol. 27, No. 10, Oct. 1988, p. 878

First Cut Criteria:

Minimum Lateral Resolution - 1mm
Minimum Vertical Resolution - 0.1μm
Depth of Field/Vertical Range - Very sensitive to slope; depth of field is much less than 150μm.
Life Cycle Cost -

1. Purchase Price - Unable to find commercial source.
2. General Ease of Use - Should be somewhat easier than commercial microscopes. Rating: moderate.

Speed of Data Extraction - Unknown.

Destructiveness of Method - Non-destructive.

SPECKLE

FBI References:
Technical Papers 13, 56

Additional References:
Optical Engineering, Vol. 24, No. 3, June 1985, p. 423

First Cut Criteria:

Minimum Lateral Resolution - 100 μm
Minimum Vertical Resolution - 0.06-10μm
Depth of Field/Vertical Range - Only good for very even, Gaussian surfaces. Cannot handle 150μm steps.
Life Cycle Cost -

1. Purchase Price - Not commercial, unknown.
2. General Ease of Use - Similar to other light scattering methods. Rating: high.

Speed of Data Extraction - Scan speed of 0.5m per second. At 100μm resolution, that equates to 5000 points per second.

Destructiveness of Method - Non-destructive.

SPUTTERING (ION MICROSCOPY)

FBI References:
Technical Paper 5

First Cut Criteria:

Minimum Lateral Resolution - Less than 1μm.
Minimum Vertical Resolution - 10nm
Depth of Field/Vertical Range - Less than 150μm.
Life Cycle Cost -

1. Purchase Price - Not commercial, unknown.

2. General Ease of Use - Most tedious and slow. Rating: minimum.

Speed of Data Extraction - Unknown.

Destructiveness of Method - Destructive; have to cross-section sample.

STEREO MICRO-PHOTOGRAMMETRY

FBI References:
Vendor Proposals 7, 10, 11, 13, 18, 26, 31, 37, 52, 59, 64, 65
Technical Papers 51, 57

Vendors Contacted:
Geo Spectra
(313) 994-3450
Contact: Bob Vincent
JFK, Inc. (consultant)
(407) 725-2715
Contact: John Kenniffic
Galileo Syscam
(914) 669-8405
Contact: John Heshcock
3M Comtol
(213) 726-6439
Contact: Ben Wooldridge
Dimensional Technology
(716) 442-7450

First Cut Criteria:
Note: Although 1μm resolution is well within the abilities of stereophotogrammetry, the only manufacturer who was actually automating 3D data extraction (Geo Spectra) could only provide 12.5μm resolution. The information below is based on that system, with the understanding that the resolution could possibly be improved with some development.

Minimum Lateral Resolution - 12.5μm

Minimum Vertical Resolution - 20μm

Depth of Field/Vertical Range - Greater than 150μm.

Life Cycle Cost -

1. Purchase Price - $200K
2. General Ease of Use - Very simple, some scanning involved to increase field of view. Rating: maximum.

Speed of Data Extraction - The system does not run on a standard PC because it is too computationally expensive. It runs on a SPARC station at 9000 points per second, but this would not be an appropriate comparison to the other technologies in this study. If it is too slow to run on a PC, then its speed must be below 500 points per second.

Destructiveness of Method - Non-destructive.

STRUCTURED/SECTIONED LIGHT

FBI References:
Vendor Proposals 15, 36, 64
Technical Paper 55

Additional References:
Applied Optics, Vol. 27, No. 24, Dec. 1988, p. 5165

Vendors Contacted:
MVS Modular Vision Systems
(514) 333-0140
Contact: Peter Walker
Gardner Mfg. Services
(206) 892-0136
Contact: Frank Gardner
Hymarc, Ltd.
(613) 727-1584
Contact: Forrest Livingstone
MTI
(518) 785-2800
Contact: John Wagoner

Vendor References Contacted:
Alaine Coulombe (for MVS)
IBM
(514) 534-6329

First Cut Criteria:
Minimum Lateral Resolution - MVS commercial system was 20μm, Gardner commercial system was 10μm (he said that 5μm would be pushing the limit of the technology), Hymarc commercial system was 25μm, MTI semi-custom system was 1 part in 2000 of field of view (quoted 6μm for 20mm x 15mm field of view). Theoretically possible to go lower (see above Additional Reference), but doesn't seem to be commercially available.

Minimum Vertical Resolution - At an angle of 45°, lateral and depth resolution are equal. See above.

Depth of Field/Vertical Range - 5mm for MVS system, 6mm for MTI system.

Life Cycle Cost -

1. Purchase Price - MTI says $500K for fully automated system.
2. General Ease of Use - Similar to triangulation. Rating: high.

Speed of Data Extraction - 10,000 points per second for Hymarc.

Destructiveness of Method - Non-destructive.

Second Cut Criteria:
Robustness -

1. Sensitivity to Changing Room Light - Sensitive, but compensated (Source: MVS).
2. Sensitivity to Air Currents - Requires temperature regulation (Source: MTI).
3. Sensitivity to Humidity - Insensitive.
4. Sensitivity to Vibration - Vibration isolation provided (Sources: MTI, MVS).

Suitability for Imaging Cartridge Side -

1. Ability to Achieve 150μm Vertical Step - Yes, can handle full range of depth of field in one step (Source: MTI, MVS).
2. Ability to Achieve 80mm Field of View (or Scan Length) - Since scan is a line rather than a point, it has a variable field of view in

one dimension. Scan length is unlimited; scan width is 5-8mm (Source: MTI, MVS).

Suitability for Imaging Cartridge End -

1. Ability to Achieve 2.5mm Vertical Step - Yes, can handle full range of depth of field in one step (Source: MTI, MVS).
2. Ability to View or Scan 19mm circular object - Maybe, by making multiple scans.
3. Minimum Occlusion Angle - 45° (can get lower, but makes vertical resolution worse, Source: Additional Reference cited above).
4. Sensitivity to Marking Orientation or Distribution - Very sensitive (Source: MVS, MTI).

Suitability for Cartridge Material -

1. Sensitivity to Sample Conductivity - Insensitive.
2. Sensitivity to Sample Reflectivity - Very sensitive (Sources: MTI, MVS).
3. Sensitivity to Changes in Sample Conductivity or Reflectivity - As long as reflectivity is within range, no problem (Source: MVS).

Inherent Sources of Error (independent of environment) -

1. 2π Depth Ambiguities - Not applicable.
2. Cumulative Errors - Not applicable.
3. Reference Surface Errors - Not applicable.
4. Repeatability - Can be as good as 1 part in 25,000 for a field of view if surface is not shiny (less than 0.01%). Assume 1% because of cartridge material.
5. Alignment/Leveling Errors - stage translation errors possible. Rating: somewhat sensitive.

Ease of Use (second cut) -

1. Ease of calibration - Rating: moderate.
2. Frequency of calibration - If temperature varies widely, need to recalibrate often (Source: MTI).
3. Reliability - Coulombe has not had system long enough to assess. Should be roughly the same as triangulation. Rating: high.
4. Sensor Ruggedness - Should be similar to triangulation. Rating: low.
5. Standoff - 100mm (Source: MTI).

Flexibility -

1. Shape of Scan - line.
2. Adjustability of Measurement Parameters - Similar to triangulation. Rating: low.

Acceptability -

1. Commercial Availability - Although several manufacturers were contacted, very few dealt with high resolution applications. Rating: low.
2. Correlation with Other Profiling Methods - unknown, similar to triangulation, except that MTI says that there are many non-linearities to watch out for. Rating: Moderate.
3. Aspect Ratio - 1 (at 45°, lateral and vertical resolution are the same).
4. Bytes per 3D Data Point - 16 bit grey scale for depth, 8 bits apiece for x and y. Total 4 bits (Source: MVS).
5. Contact vs. Non-contact - Non-contact.
6. Simplicity of Concept - Similar to triangulation. Rating: low.

TRANSMISSION ELECTRON MICROSCOPY

FBI References:
Technical Papers 55, 56

Vendors Contacted:
Carl Zeiss
(914) 747-1800

First Cut Criteria:

Minimum Lateral Resolution - Atomic, much less than $1\mu m$

Minimum Vertical Resolution - Atomic, much less than $1\mu m$

Depth of Field/Vertical Range - $1\mu m$

Life Cycle Cost -

1. Purchase Price - \$250K- \$275K
2. General Ease of Use - Similar to other commercial microscopes. Rating: low.

Speed of Data Extraction - 5-10 minutes for field of view; 28,000 points per second.

Destructiveness of Method - Has potential to be destructive.

ULTRASOUND

FBI Sources:
Vendor Proposals 32, 49
Technical Paper 55

Vendors Contacted:
Ultrasonic Arrays
(206) 481-6611

First Cut Criteria:

Minimum Lateral Resolution - 21.6mm

Minimum Vertical Resolution - 21.6mm

Depth of Field/Vertical Range - Greater than $150\mu m$.

Life Cycle Cost -

1. Purchase Price - \$7K
2. General Ease of Use - Relatively simple. Rating: moderate.

Speed of Data Extraction - 125 points per second.

Destructiveness of Method - Must put sample in water. Could alter appearance of sample.

VISIBLE PHASE SHIFTING INTERFEROMETRY

(Includes Mirau, Michelson and Linnik interferometers as commercial instruments)

FBI References:

Vendor Proposal 22
Technical Papers 6, 55, 56

Vendors Contacted:

Wyko
(602) 741-1044
Contact: Lisa Merrill

First Cut Criteria:

Minimum Lateral Resolution - Ranges from 0.6μm
Minimum Vertical Resolution - Ranges from 0.3nm
Depth of Field/Vertical Range - Ranges to 42.3μm
Life Cycle Cost -

1. Purchase Price - $100K - $110K
2. General Ease of Use - Similar to other interferometers. Rating: moderate.

Speed of Data Extraction - 4923 points per second.
Destructiveness of Method - Non-destructive.

APPENDIX E

RATINGS DESCRIPTION

APPENDIX E

RATINGS DESCRIPTION

Ratings for 3D TECHNOLOGY on a scale measuring Importance, using direct verbal ratings and ranging from Trivial to Critical

Rating	Block
Critical	MINIMUM LATERAL RESOLUTION
Very Important	MINIMUM VERTICAL RESOLUTION
Very Important	MAXIMUM DEPTH OF FIELD (STEP)
Critical	LIFE CYCLE COST
Very Important	SPEED OF DATA EXTR.
Critical	NON-DESTRUCTIVE ?
Important	ROBUSTNESS
Very Important	GOOD FOR SIDE OF CARTRIDGE?
Critical	GOOD FOR END OF CARTRIDGE?
Very Important	GOOD FOR CARTRIDGE MATERIAL?
Unimportant	INHERENT SOURCES OF ERROR
Important	EASE OF USE
Trivial	FLEXIBILITY
Unimportant	ACCEPTABILITY

Ratings for MINIMUM LATERAL RESOLUTION on a scale measuring CLOSEST TO OPTIMUM, using direct verbal ratings and ranging from > 5.0 um to about 1.0-5.0 um

Rating	Block
about 1.0-5.0 um	IDEAL SYSTEM
about 1.0-5.0 um	Contact Stylus
about 1.0-5.0 um	Laser Triangulation
about 1.0-5.0 um	Laser Dynamic Focusing
about 1.0-5.0 um	Structured/Sectioned Light
about 1.0-5.0 um	Moire (Projection) Interferometry
about 1.0-5.0 um	Fringe Field Capacitance
about 1.0-5.0 um	Confocal Microscopy

Ratings for MINIMUM VERTICAL RESOLUTION on a scale measuring CLOSEST TO OPTIMUM, using direct verbal ratings and ranging from > 5.0 um to about 1.0-5.0 um

Rating	Block
<< 1 um	Contact Stylus
about 1.0-5.0 um	Laser Triangulation
<< 1 um	Laser Dynamic Focusing
about 1.0-5.0 um	Structured/Sectioned Light
about 1.0-5.0 um	Moire (Projection) Interferometry
about 1.0-5.0 um	Fringe Field Capacitance
about 1.0-5.0 um	Confocal Microscopy
about 1.0-5.0 um	IDEAL SYSTEM

Ratings for MAXIMUM DEPTH OF FIELD (STEP) on a scale measuring DEPTH OF FIELD, using direct verbal ratings and ranging from < 150 um to >= 150 um

Rating	Block
>= 150 um	Contact Stylus
>= 150 um	Laser Triangulation
>= 150 um	Laser Dynamic Focusing
>= 150 um	Structured/Sectioned Light
>= 150 um	Moire (Projection) Interferometry
>= 150 um	Fringe Field Capacitance
>= 150 um	Confocal Microscopy
>= 150 um	IDEAL SYSTEM

Ratings for LIFE CYCLE COST on a scale measuring Importance, using direct verbal ratings and ranging from Trivial to Critical

Rating	Block
Critical	MINIMUM PURCHASE PRICE
Important	GENERAL EASE OF OPERATION (1st cut)

Ratings for MINIMUM PURCHASE PRICE on a scale measuring Cost, using direct verbal ratings and ranging from cost > $200K to <= $10K

Rating	Block
$50K < cost <= $100K	Contact Stylus
$10K < cost <= $50K	Laser Triangulation
$50K < cost <= $100K	Laser Dynamic Focusing
cost > $200K	Structured/Sectioned Light
$50K < cost <= $100K	Moire (Projection) Interferometry
$10K < cost <= $50K	Fringe Field Capacitance
$50K < cost <= $100K	Confocal Microscopy
<= $10K	IDEAL SYSTEM

Ratings for GENERAL EASE OF OPERATION (1st cut) on a scale measuring Degree, using direct verbal ratings and ranging from Minimum to Maximum

Rating	Block
High	Contact Stylus
High	Laser Triangulation
High	Laser Dynamic Focusing
High	Structured/Sectioned Light
Moderate	Moire (Projection) Interferometry
High	Fringe Field Capacitance
Moderate	Confocal Microscopy
Maximum	IDEAL SYSTEM

Ratings for SPEED OF DATA EXTR. on a scale measuring POINTS PER SECOND, using direct verbal ratings and ranging from less than 500 to greater than 50,000

Rating	Block
less than 500	Contact Stylus
500 to 1000	Laser Triangulation
1000 to 5000	Laser Dynamic Focusing
10,000 to 20,000	Structured/Sectioned Light
20,000 to 50,000	Moire (Projection) Interferometry
1000 to 5000	Fringe Field Capacitance
20,000 to 50,000	Confocal Microscopy
greater than 50,000	IDEAL SYSTEM

Ratings for NON-DESTRUCTIVE? on a scale measuring Yes/No, using direct verbal ratings and ranging from No to Yes

Rating	Block
Maybe	Contact Stylus
Yes	Laser Triangulation
Yes	Laser Dynamic Focusing
Yes	Structured/Sectioned Light
Yes	Moire (Projection) Interferometry
Maybe	Fringe Field Capacitance
Yes	Confocal Microscopy
Yes	IDEAL SYSTEM

Ratings for ROBUSTNESS on a scale measuring Importance, using direct verbal ratings and ranging from Trivial to Critical

Rating	Block
Very Important	SENS. TO CHANGING ROOM LIGHT
Important	SENS. TO AIR CURRENTS OR TEMPERATURE
Trivial	SENS. TO HUMIDITY
Very Important	SENS. TO VIBRATION

Ratings for SENS. TO CHANGING ROOM LIGHT on a scale measuring SENSITIVITY, using direct verbal ratings and ranging from VERY SENSITIVE to INSENSITIVE

Rating	Block
INSENSITIVE	Contact Stylus
INSENSITIVE	Confocal Microscopy
INSENSITIVE	Fringe Field Capacitance
VERY SENSITIVE	Moire (Projection) Interferometry
SENSITIVE BUT COMPEN	Structured/Sectioned Light
INSENSITIVE	Laser Dynamic Focusing
INSENSITIVE	Laser Triangulation
INSENSITIVE	IDEAL SYSTEM

Ratings for SENS. TO AIR CURRENTS OR TEMPERATURE on a scale measuring SENSITIVITY, using direct verbal ratings and ranging from VERY SENSITIVE to INSENSITIVE

Rating	Block
INSENSITIVE	Contact Stylus
INSENSITIVE	Confocal Microscopy
SENSITIVE BUT COMPEN	Fringe Field Capacitance
VERY SENSITIVE	Moire (Projection) Interferometry
SENSITIVE BUT COMPEN	Structured/Sectioned Light
INSENSITIVE	Laser Dynamic Focusing
INSENSITIVE	Laser Triangulation
INSENSITIVE	IDEAL SYSTEM

Ratings for SENS. TO HUMIDITY on a scale measuring SENSITIVITY, using direct verbal ratings and ranging from VERY SENSITIVE to INSENSITIVE

Rating	Block
INSENSITIVE	Contact Stylus
INSENSITIVE	Confocal Microscopy
INSENSITIVE	Fringe Field Capacitance
INSENSITIVE	Moire (Projection) Interferometry
INSENSITIVE	Structured/Sectioned Light
INSENSITIVE	Laser Dynamic Focusing
INSENSITIVE	Laser Triangulation
INSENSITIVE	IDEAL SYSTEM

Ratings for SENS. TO VIBRATION on a scale measuring SENSITIVITY, using direct verbal ratings and ranging from VERY SENSITIVE to INSENSITIVE

Rating	Block
SENSITIVE BUT COMPEN	Contact Stylus
SENSITIVE BUT COMPEN	Confocal Microscopy
INSENSITIVE	Fringe Field Capacitance
SENSITIVE BUT COMPEN	Moire (Projection) Interferometry
SENSITIVE BUT COMPEN	Structured/Sectioned Light
SENSITIVE BUT COMPEN	Laser Dynamic Focusing
SENSITIVE BUT COMPEN	Laser Triangulation
INSENSITIVE	IDEAL SYSTEM

Ratings for GOOD FOR SIDE OF CARTRIDGE? on a scale measuring Importance, using direct verbal ratings and ranging from Trivial to Critical

Rating	Block
Critical	150um STEP POSSIBLE?
Unimportant	80mm F.O.V./SCAN POSSIBLE?

Ratings for 150um STEP POSSIBLE? on a scale measuring Yes/No, using direct verbal ratings and ranging from No to Yes

Rating	Block
No	Contact Stylus
Yes	Confocal Microscopy
Yes	Fringe Field Capacitance
Yes	Moire (Projection) Interferometry
Yes	Structured/Sectioned Light
Yes	Laser Dynamic Focusing
Yes	Laser Triangulation
Yes	IDEAL SYSTEM

Ratings for 80mm F.O.V./SCAN POSSIBLE? on a scale measuring Yes/No, using direct verbal ratings and ranging from No to
Yes

Rating	Block
Yes	Contact Stylus
No	Confocal Microscopy
Yes	Fringe Field Capacitance
Maybe	Moire (Projection) Interferometry
Yes	Structured/Sectioned Light
Yes	Laser Dynamic Focusing
Yes	Laser Triangulation
Yes	IDEAL SYSTEM

Ratings for GOOD FOR END OF CARTRIDGE? on a scale measuring Importance, using direct verbal ratings and ranging from Trivial to Critical

Rating	Block
Critical	2.5mm STEP POSSIBLE?
Critical	ABILITY TO VIEW/SCAN 19mm CIRC. OBJECT
Very Important	OCCLUSION ANGLE (meas. from vertical)
Very Important	SENSITIVITY TO MARKING ORIENT/DISTRIB

Ratings for 2.5mm STEP POSSIBLE? on a scale measuring Yes/No, using direct verbal ratings and ranging from No to Yes

Rating	Block
No	Contact Stylus
Yes	Confocal Microscopy
No	Fringe Field Capacitance
Yes	Moire (Projection) Interferometry
Yes	Structured/Sectioned Light
No	Laser Dynamic Focusing
Maybe	Laser Triangulation
Yes	IDEAL SYSTEM

Ratings for ABILITY TO VIEW/SCAN 19mm CIRC. OBJECT? on a scale measuring Yes/No, using direct verbal ratings and ranging from No to Yes

Rating	Block
No	Contact Stylus
No	Confocal Microscopy
Yes	Fringe Field Capacitance
Maybe	Moire (Projection) Interferometry
Maybe	Structured/Sectioned Light
Yes	Laser Dynamic Focusing
Yes	Laser Triangulation
Yes	IDEAL SYSTEM

Ratings for OCCLUSION ANGLE (meas. from vertical) on a scale measuring degrees, using direct numeric ratings and ranging from 45.00 to 0.00

Rating	Block
30.00	Contact Stylus
0.00	Confocal Microscopy
0.00	Fringe Field Capacitance
20.00	Moire (Projection) Interferometry
45.00	Structured/Sectioned Light
0.00	Laser Dynamic Focusing
30.00	Laser Triangulation
45.00	IDEAL SYSTEM

Ratings for SENSITIVITY TO MARKING ORIENT/DISTRIB. on a scale measuring SENSITIVITY, using direct verbal ratings and ranging from VERY SENSITIVE to INSENSITIVE

Rating	Block
VERY SENSITIVE	Contact Stylus
INSENSITIVE	Confocal Microscopy
VERY SENSITIVE	Fringe Field Capacitance
SOMEWHAT SENSITIVE	Moire (Projection) Interferometry
VERY SENSITIVE	Structured/Sectioned Light
SENSITIVE BUT COMPEN	Laser Dynamic Focusing
VERY SENSITIVE	Laser Triangulation
INSENSITIVE	IDEAL SYSTEM

Ratings for GOOD FOR CARTRIDGE MATERIAL? on a scale measuring Importance, using direct verbal ratings and ranging from Trivial to Critical

Rating	Block
Very Important	SENS. TO CONDUCTIVITY
Critical	SENS. TO REFLECTIVITY
Very Important	SENS. TO CHANGES IN REFLECT./CONDUCT.

Ratings for SENS. TO CONDUCTIVITY on a scale measuring SENSITIVITY, using direct verbal ratings and ranging from VERY SENSITIVE to INSENSITIVE

Rating	Block
INSENSITIVE	Contact Stylus
INSENSITIVE	Confocal Microscopy
VERY SENSITIVE	Fringe Field Capacitance
INSENSITIVE	Moire (Projection) Interferometry
INSENSITIVE	Structured/Sectioned Light
INSENSITIVE	Laser Dynamic Focusing
INSENSITIVE	Laser Triangulation
INSENSITIVE	IDEAL SYSTEM

Ratings for SENS. TO REFLECTIVITY on a scale measuring SENSITIVITY, using direct verbal ratings and ranging from VERY SENSITIVE to INSENSITIVE

Rating	Block
INSENSITIVE	Contact Stylus
SENSITIVE BUT COMPEN	Confocal Microscopy
INSENSITIVE	Fringe Field Capacitance
VERY SENSITIVE	Moire (Projection) Interferometry
VERY SENSITIVE	Structured/Sectioned Light
SOMEWHAT SENSITIVE	Laser Dynamic Focusing
VERY SENSITIVE	Laser Triangulation
INSENSITIVE	IDEAL SYSTEM

Ratings for SENS. TO CHANGES IN REFLECT./CONDUCT. on a scale measuring SENSITIVITY, using direct verbal ratings and ranging from VERY SENSITIVE to INSENSITIVE

Rating	Block
INSENSITIVE	Contact Stylus
SOMEWHAT SENSITIVE	Confocal Microscopy
VERY SENSITIVE	Fringe Field Capacitance
SOMEWHAT SENSITIVE	Moire (Projection) Interferometry
SOMEWHAT SENSITIVE	Structured/Sectioned Light
SOMEWHAT SENSITIVE	Laser Dynamic Focusing
VERY SENSITIVE	Laser Triangulation
INSENSITIVE	IDEAL SYSTEM

Ratings for INHERENT SOURCES OF ERROR on a scale measuring Importance, using direct verbal ratings and ranging from Trivial to Critical

Rating	Block
Very Important	2-PI DEPTH AMBIGUITIES
Very Important	CUMULATIVE ERRORS
Important	REFERENCE SURFACE ERRORS
Critical	REPEATABILITY
Important	ALIGNMENT/LEVELING/TRANSLATI ON ERRORS

Ratings for 2-PI DEPTH AMBIGUITIES on a scale measuring POSSIBILITY, using direct verbal ratings and ranging from POSSIBLE to NOT APPLICABLE

Rating	Block
NOT APPLICABLE	Contact Stylus
NOT APPLICABLE	Confocal Microscopy
NOT APPLICABLE	Fringe Field Capacitance
POSSIBLE	Moire (Projection) Interferometry
NOT APPLICABLE	Structured/Sectioned Light
NOT APPLICABLE	Laser Dynamic Focusing
NOT APPLICABLE	Laser Triangulation
NOT APPLICABLE	IDEAL SYSTEM

Ratings for CUMULATIVE ERRORS on a scale measuring POSSIBILITY, using direct verbal ratings and ranging from POSSIBLE to NOT APPLICABLE

Rating	Block
NOT APPLICABLE	Contact Stylus
NOT APPLICABLE	Confocal Microscopy
NOT APPLICABLE	Fringe Field Capacitance
NOT APPLICABLE	Moire (Projection) Interferometry
NOT APPLICABLE	Structured/Sectioned Light
NOT APPLICABLE	Laser Dynamic Focusing
NOT APPLICABLE	Laser Triangulation
NOT APPLICABLE	IDEAL SYSTEM

Ratings for REFERENCE SURFACE ERRORS on a scale measuring POSSIBILITY, using direct verbal ratings and ranging from POSSIBLE to NOT APPLICABLE

Rating	Block
POSSIBLE	Contact Stylus
NOT APPLICABLE	Confocal Microscopy
POSSIBLE	Fringe Field Capacitance
POSSIBLE	Moire (Projection) Interferometry
NOT APPLICABLE	Structured/Sectioned Light
NOT APPLICABLE	Laser Dynamic Focusing
NOT APPLICABLE	Laser Triangulation
NOT APPLICABLE	IDEAL SYSTEM

Ratings for REPEATABILITY on a scale measuring max % error, using direct numeric ratings and ranging from 2.00 to 0.00

Rating	Block
1.00	Contact Stylus
0.02	Confocal Microscopy
1.32	Fringe Field Capacitance
2.00	Moire (Projection) Interferometry
1.00	Structured/Sectioned Light
0.30	Laser Dynamic Focusing
0.78	Laser Triangulation
0.00	IDEAL SYSTEM

Ratings for ALIGNMENT/LEVELING/TRANSLATION ERRORS on a scale measuring SENSITIVITY, using direct verbal ratings and ranging from VERY SENSITIVE to INSENSITIVE

Rating	Block
VERY SENSITIVE	Contact Stylus
SOMEWHAT SENSITIVE	Confocal Microscopy
VERY SENSITIVE	Fringe Field Capacitance
VERY SENSITIVE	Moire (Projection) Interferometry
SOMEWHAT SENSITIVE	Structured/Sectioned Light
SOMEWHAT SENSITIVE	Laser Dynamic Focusing
SOMEWHAT SENSITIVE	Laser Triangulation
INSENSITIVE	IDEAL SYSTEM

Ratings for EASE OF USE on a scale measuring Importance, using direct verbal ratings and ranging from Trivial to Critical

Rating	Block
Important	EASE OF CALIBRATION
Very Important	FREQUENCY OF CALIBRATION
Critical	RELIABILITY
Important	SENSOR RUGGEDNESS
Trivial	STANDOFF

Ratings for EASE OF CALIBRATION on a scale measuring Degree, using direct verbal ratings and ranging from Minimum to Maximum

Rating	Block
High	Contact Stylus
Minimum	Confocal Microscopy
High	Fringe Field Capacitance
Maximum	Moire (Projection) Interferometry
Moderate	Structured/Sectioned Light
Moderate	Laser Dynamic Focusing
Minimum	Laser Triangulation
Maximum	IDEAL SYSTEM

Ratings for FREQUENCY OF CALIBRATION on a scale measuring Frequency, using direct verbal ratings and ranging from Very Often to Never

Rating	Block
Rarely	Contact Stylus
Never	Confocal Microscopy
Sometimes	Fringe Field Capacitance
Very Often	Moire (Projection) Interferometry
Sometimes	Structured/Sectioned Light
Rarely	Laser Dynamic Focusing
Never	Laser Triangulation
Never	IDEAL SYSTEM

Ratings for RELIABILITY on a scale measuring Degree, using direct verbal ratings and ranging from Minimum to Maximum

Rating	Block
Maximum	Contact Stylus
High	Confocal Microscopy
Moderate	Fringe Field Capacitance
Moderate	Moire (Projection) Interferometry
High	Structured/Sectioned Light
High	Laser Dynamic Focusing
High	Laser Triangulation
Maximum	IDEAL SYSTEM

Ratings for SENSOR RUGGEDNESS on a scale measuring Degree, using direct verbal ratings and ranging from Minimum to Maximum

Rating	Block
Moderate	Contact Stylus
Moderate	Confocal Microscopy
Minimum	Fringe Field Capacitance
High	Moire (Projection) Interferometry
Low	Structured/Sectioned Light
High	Laser Dynamic Focusing
Low	Laser Triangulation
Maximum	IDEAL SYSTEM

Ratings for STANDOFF on a scale measuring millimeters, using direct numeric ratings and ranging from 0.00 to 100.00

Rating	Block
0.00	Contact Stylus
9.20	Confocal Microscopy
0.00	Fringe Field Capacitance
100.00	Moire (Projection) Interferometry
100.00	Structured/Sectioned Light
10.00	Laser Dynamic Focusing
18.90	Laser Triangulation
100.00	IDEAL SYSTEM

Ratings for FLEXIBILITY on a scale measuring Importance, using direct verbal ratings and ranging from Trivial to Critical

Rating	Block
Very Important	SHAPE OF SCAN
Important	ADJUSTABILITY OF PARAMETERS

Ratings for SHAPE OF SCAN on a scale measuring TYPE OF SCAN, using direct verbal ratings and ranging from FULL FIELD to POINT

Rating	Block
POINT	Contact Stylus
SECTION	Confocal Microscopy
POINT	Fringe Field Capacitance
FULL FIELD	Moire (Projection) Interferometry
LINE	Structured/Sectioned Light
POINT	Laser Dynamic Focusing
POINT	Laser Triangulation
POINT	IDEAL SYSTEM

Ratings for ADJUSTABILITY OF PARAMETERS on a scale measuring Degree, using direct verbal ratings and ranging from Minimum to Maximum

Rating	Block
High	Contact Stylus
Moderate	Confocal Microscopy
Moderate	Fringe Field Capacitance
Maximum	Moire (Projection) Interferometry
Low	Structured/Sectioned Light
High	Laser Dynamic Focusing
Low	Laser Triangulation
Maximum	IDEAL SYSTEM

Ratings for ACCEPTABILITY on a scale measuring Importance, using direct verbal ratings and ranging from Trivial to Critical

Rating	Block
Critical	COMMERCIAL AVAILABILITY
Important	CORRELLATION WITH OTHER METHODS
Unimportant	ASPECT RATIO
Very Important	BYTES PER 3D DATA POINT
Critical	CONTACT VS. NON-CONTACT
Trivial	SIMPLICITY OF CONCEPT

Ratings for COMMERCIAL AVAILABILITY on a scale measuring Degree, using direct verbal ratings and ranging from Minimum to Maximum

Rating	Block
High	Contact Stylus
Moderate	Confocal Microscopy
Minimum	Fringe Field Capacitance
Low	Moire (Projection) Interferometry
Low	Structured/Sectioned Light
Low	Laser Dynamic Focusing
High	Laser Triangulation
Maximum	IDEAL SYSTEM

Ratings for CORRELLATION WITH OTHER METHODS on a scale measuring Degree, using direct verbal ratings and ranging from Minimum to Maximum

Rating	Block
Maximum	Contact Stylus
Moderate	Confocal Microscopy
Moderate	Fringe Field Capacitance
Moderate	Moire (Projection) Interferometry
Moderate	Structured/Sectioned Light
Moderate	Laser Dynamic Focusing
High	Laser Triangulation
Maximum	IDEAL SYSTEM

Ratings for ASPECT RATIO on a scale measuring lat. res./vert. res., using direct numeric ratings and ranging from 5000.00 to 1.00

Rating	Block
4600.00	Contact Stylus
2.00	Confocal Microscopy
60.00	Fringe Field Capacitance
1.75	Moire (Projection) Interferometry
1.00	Structured/Sectioned Light
17.00	Laser Dynamic Focusing
3.00	Laser Triangulation
1.00	IDEAL SYSTEM

Ratings for BYTES PER 3D DATA POINT on a scale measuring bytes per data point, using direct numeric ratings an ranging from 12.00 to 1.00

Rating	Block
?	Contact Stylus
1.00	Confocal Microscopy
12.00	Fringe Field Capacitance
6.00	Moire (Projection) Interferometry
4.00	Structured/Sectioned Light
4.00	Laser Dynamic Focusing
8.00	Laser Triangulation
1.00	IDEAL SYSTEM

Ratings for CONTACT VS. NON-CONTACT on a scale measuring DEGREE OF CONTACT, using direct verbal ratings and ranging from POSSIBLY DAMAGING to NONE

Rating	Block
POSSIBLY DAMAGING	Contact Stylus
NONE	Confocal Microscopy
NON-DAMAGING	Fringe Field Capacitance
NONE	Moire (Projection) Interferometry
NONE	Structured/Sectioned Light
NONE	Laser Dynamic Focusing
NONE	Laser Triangulation
NONE	IDEAL SYSTEM

Ratings for SIMPLICITY OF CONCEPT on a scale measuring Degree, using direct verbal ratings and ranging from Minimum to Maximum

Rating	Block
Maximum	Contact Stylus
High	Confocal Microscopy
High	Fringe Field Capacitance
Minimum	Moire (Projection) Interferometry
Low	Structured/Sectioned Light
High	Laser Dynamic Focusing
Low	Laser Triangulation
Maximum	IDEAL SYSTEM

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