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Development of a Mobile, Automated Tool Mark Characterization / Comparison System

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L.S. Chumbley, S. Zhang, M. Morris

Abstract

The purpose of this research was to develop a portable prototype instrument designed to provide forensic examiners with the ability to characterize a tool marked surface, compare the data from that surface to data files obtained from any other surface, and evaluate the likelihood that the two surfaces were made using the same tool. While the areas selected for characterization are at the discretion of the examiner, acquisition of the data is carried out using a system based on a portable 3-D optical profilometer manufactured by Alicona, GmbH. Comparison of resulting data files is done in an objective manner using software algorithms developed and tested by researchers at Ames Laboratory / Iowa State University (AL/ISU). Due to the relatively small size of the instrument the actual device is portable; all the microscope components can be packed into a hard-shell suitcase allowing it to be taken directly to crime scenes if need be. The software package used for analysis, called "Mantis," standing for Mark and Tool Inspection Suite, is resident on a laptop computer. Mantis is designed to be user friendly and easy to operate and employs open source software code to allow for continued research and expansion. Currently, using the system an examiner can 1) compare all types of tool marked surfaces in a manner similar to a comparison microscope; 2) obtain objective statistical evaluation of data files; 3) elucidate factors that existed when certain types of tool marks were made, e.g., angle of the tool. The design of the system is such that it provides an open source platform that other researchers can write algorithms for and test, while offering data-files that can be used by any system or researcher. Finally, all these benefits are resident in a portable system available at a greatly reduced hardware cost as compared to current systems in use. At this time the system has been tested on data sets consisting of i) fully striated marks created from 50 sequentially manufactured screwdrivers, ii) quasi striated markings produced by 50 sequentially manufactured shear-cut pliers, and iii) impression marks produced by 50 sequentially manufactured cold chisels. In all cases the system was able to analyze the markings and separate true matches from nonmatches to a high level of success. Exploratory studies on rifling marks left on fired bullets and cut marks produced by knives present a greater challenge, due to both the size of the files and their intrinsic nature. These initial results suggest that further development of statistical algorithms to address more complex markings is required.

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Executive Summary

1. Problem

In recent years the field of tool mark examination has faced unprecedented (and unrelenting) challenges from legal professionals, research academics, and the popular press charging that the entire field is unscientific and tainted by subjective bias [1-5]. These charges come despite numerous objective research studies aimed at establishing the applicability and science of comparative examination [8, 9, 12, 15, 36] systems. Such studies have resulted in the development of objective methods of analysis [15, 16] and systems [18, 19, 22] that enable comparisons to be made based on sound scientific principles in support of the expert testimony of forensic examiners.

While advances have been made there is still considerable room for improvement when it comes to the objective analysis of toolmarks. Studies in recent years have confirmed that objective analyses based on computer algorithms can perform to a high level of success [15, 26-32], however, it has also been noted that 1) objective automated systems do not perform to the same level of accuracy as human examiners and 2) algorithms developed and optimized for analysis of one type of toolmark do not perform equally well when employed on other types of toolmarks [25, 26, 30-31]. Current systems for objective analysis are restricted to either the research laboratory or limited in distribution to centrally located law enforcement agencies due to either the size of the system, the cost, or both. Development by commercial concerns of suitable systems is often hindered by market economics; companies see little profit in expending capital and human resources in developing a system that most likely will be too expensive to generate large numbers of sales or too narrowly focused to attract wide-spread acceptance.

2. Purpose

The purpose of this project was development of an instrument for toolmark analysis, the goal being to create a working prototype that might serve as a model for future research in the area of low-cost, portable, objective analysis of toolmarks. The prototype instrument has been designed to provide forensic examiners with the ability to characterize a tool marked surface, compare the data from that surface to data files obtained from other surfaces, and evaluate the likelihood that the two surfaces match using a statistical algorithm that evaluates the degree of surface roughness measured. Acquisition of the data is carried out using a system based on a portable 3-D optical profilometer manufactured by Alicona, GmbH. This device was selected as it allows non-contact acquisition of data from both flat and curved surfaces but also provides excellent data from steep sided samples such as, for example, the end of a screwdriver.

Comparison of resulting data files is done in an objective manner using developed software algorithms. While efforts continue to further develop and refine statistical algorithms suitable for the comparison of a wide range of toolmarks, at the current time samples that can be characterized and evaluated with a high degree of success include fully striated marks such as those produced by screwdrivers and quasi striated shear-cut markings produced by by-pass pliers. Initial testing on rifling marks left on fired bullets and cut marks produced by knives has also been carried out and research on these types of marks is continuing.

The purpose of this Executive Summary is to describe the current status of the system and outline it's operation and current capabilities.

3. Research Design

Hardware: The equipment around which the prototype is based was obtained from Alicona, GmbH. and is shown in Figure ES1. The system consists of an optical profilometer and a laptop computer (Fig. ES1a) and is small, portable, lightweight (80 lbs), and can be packed into a hard-shell traveling case (Fig. ES1b). Despite the size the optical head still offers outstanding performance, typical parameters used producing a complete scan in 1-2 minutes that contains a lateral resolution in the x and y directions of 4 μm and a vertical resolution in the z direction of 1 μm. While the current system is only used to examine fixed samples a stage for holding and rotating cylindrical samples does exist and can be adapted to the system.

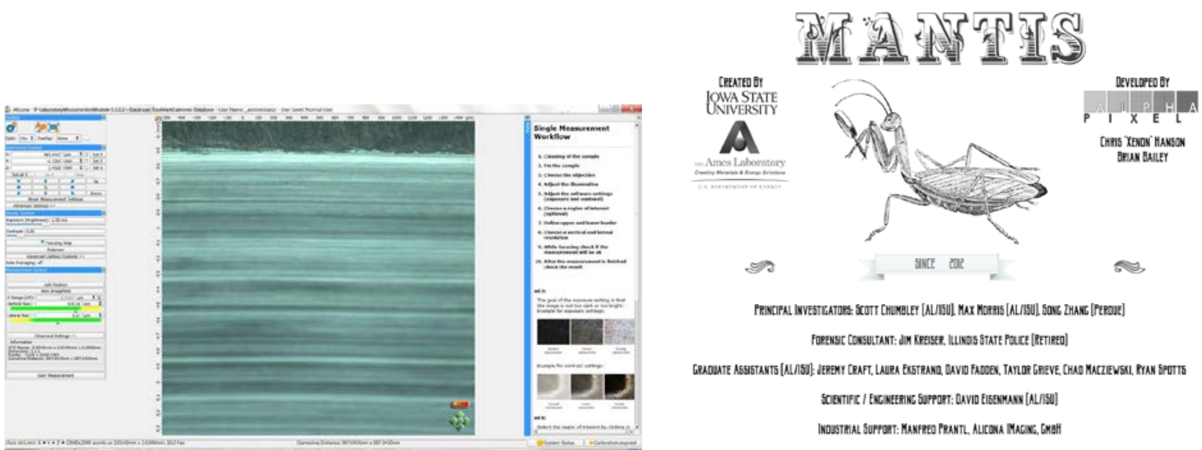
a. b.

Figure ES1: (a) Prototype hardware (b) System packed in traveling case.

Control of the hardware is accomplished using a modified version of Alicona's system software, Figure ES2. Working with AL/ISU the standard acquisition software was simplified and unnecessary functions eliminated or hidden to ease training. The window used for data acquisition has included a simplified tutorial that can be referred to when setting up the initial scan of the data. Tests have shown that high quality, high resolution data can be obtained routinely in well under ten minutes.

Software: The software suite developed at AL/ISU is termed Mantis for Manipulative Toolmark Inspection Suite. The software suite mainly uses C++ for the majority of the code; OpenGL and Graphics processing unit (GPU) is used to produce virtual marks of tools at any given angle and resolution and to visualize geometric data on the screen; Qt is used to create the graphical user interface (GUI); and Java script is used to interact with computers through command lines. The basic development of the software, consisting of the cleaning and data analysis routines, was carried out at AL/ISU. The project was then greatly aided in transforming the initial code into a more user-friendly interface by Chris Hanson and Brian Bailey of Alphapixel, Evergreen, CO. An image of the splash screen is shown in Figure ES2b.

The software provides various options to the examiner, starting from a simple visual comparison of the data to more advanced analyses using the embedded statistical algorithm. The development of the basic algorithm has been detailed in a number of papers [15, 27, 30], including how well it performs on different types of toolmarks [30, 31]. Currently, using the software an examiner can 1) clean raw data files obtained using the Alicona hardware 2) compare data files from the cleaned tool marked surfaces in a manner similar to a comparison microscope 3) obtain objective statistical evaluation of comparisons made between those data files and 4) elucidate factors that existed when certain types of tool marks were made, e.g., angle of the tool.



(a) (b)

Figure ES2: (a) Screen shot of Mantis startup; (b) Mantis initial startup screen.

Mantis is really the core of the prototype development project as it contains all the necessary code developed at AL/ISU, allowing the user to clean the raw data, mask off unwanted, irrelevant portions of the acquired file, display the data for visual comparisons or conduct statistical analyses.

4. Findings

In operation, an examiner first acquires the data then import the raw data files into Mantis for characterization. At this time Mantis is written only to accept data files from the Alicona system. The PIs recognize that this currently limits use of the Mantis software. If additional funding can be obtained the ability to read data files from all types of instruments will be introduced. The PIs have already contacted Alicona and examined means by which the conversions can be made.

The complete procedure consists of three steps, Data Cleaning, Masking, and Data Analysis.

<u>Data Cleaning:</u>

Once the raw data is acquired it must be cleaned to remove aberrations or areas of the scan that will not be used in a subsequent analysis. Elimination of these irregularities is done using a series of routines. Firstly, minor imperfections due to random scattering from the surface (which appears as either holes or spikes in the data when viewed at high magnification / high resolution) are pre-processed before entering the statistical analysis. Spikes are removed based on a filtering routine and the holes are filled by analyzing the surface of the regions surrounding the holes. Secondly, all measured surfaces tend to have a slope or "trend" associated with them, i.e., they are not perfectly flat. A de-trending routine removes this slight slope, rendering the data flat.

Masking:

Since the acquisition parameters are routinely set to overlap the actual mark in question, the raw data will often have information from irrelevant regions contained at the edges of the file that must be removed using a masking routine. For example, suppose the examiner acquires an image of an impression mark left by a chisel, but only wants to examine one side of the chisel point at a time at a time since the opposite sides are quite different. Options provided in the script allow the examiner to mask data from further analysis while at the same time preserving the original raw data. The software contains a number of options to give maximum flexibility when using the masking tool.

Data Analysis :

The analysis available in Mantis consists of a number of options that includes:

- ☐ Simple visual comparison
- ☐ Observation coupled with graphical information of the surfaces
- ☐ Observation, graphing, and statistical analysis of the surface
- ☐ Generation of virtual toolmarks from measured tool surfaces
- ☐ Automatic determination of angle of incidence for a tool that created a given toolmark using virtual marking and an optimization routine.

Examples of all of these capabilities are described in turn.

Simple Visual Examination: Figure ES3 shows an example of the simple visual comparison. The examiner can view the data gathered by the InfiniteFocus SL and compare the image files in the same way they currently view actual images using a comparison microscope. The images can be linked so they can be moved and magnified together or unlinked for individual translations. A slider bar at the bottom of the image allows the examiner to move back and forth across the samples, analogous to the comparison microscope.

Statistical Analysis: Note that although the files appear as optical images, due to the method of acquisition the images contain quantitative information produced through use of the system. Thus, in addition to looking at the images the examiner, if they choose, can look at graphs displaying quantitative measurements of the surface roughness of the samples by simply hitting the "Show Graphs" radio button below the images. This is illustrated in Figure ES4, which shows two toolmarks created by a specific screwdriver. The visual comparison is still available only now the graphical results are included and shown on the left. The linear plots are not an average obtained from the entire scan; they display the raw data (after the cleaning and masking step) obtained from a single column of pixels that spans the sample, corresponding to the hairline position. As such the plots changes as the slider is moved back and forth between the images.

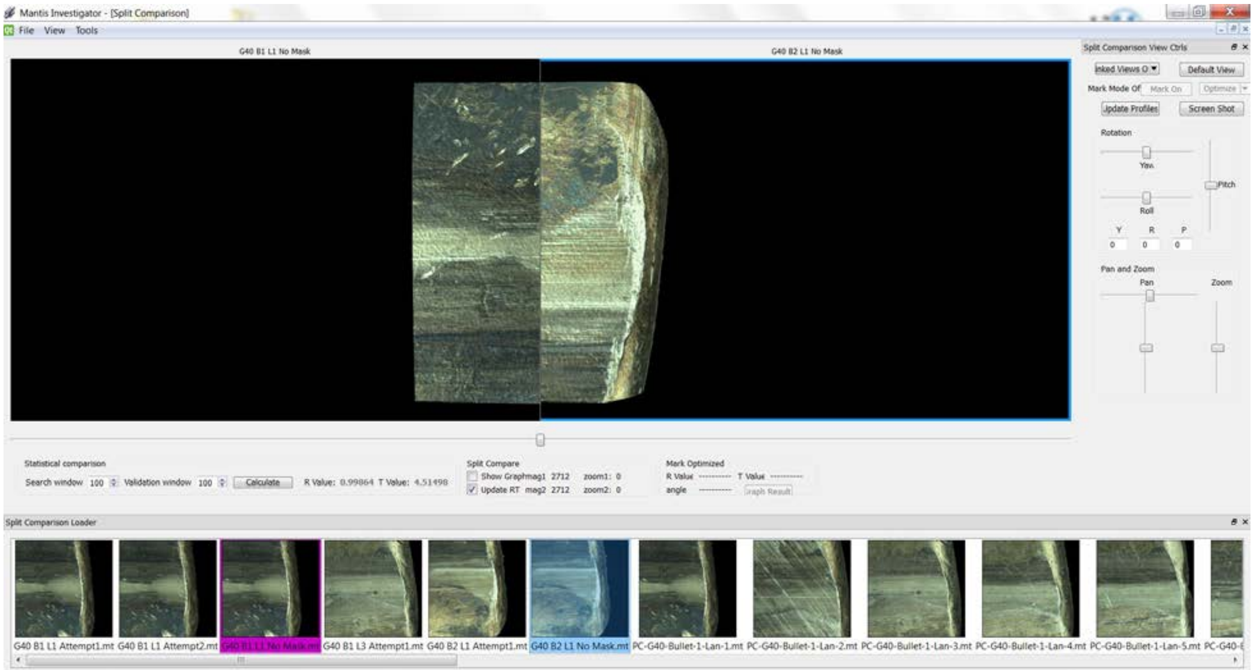


Figure ES3: Simple visual comparison of two bullets.

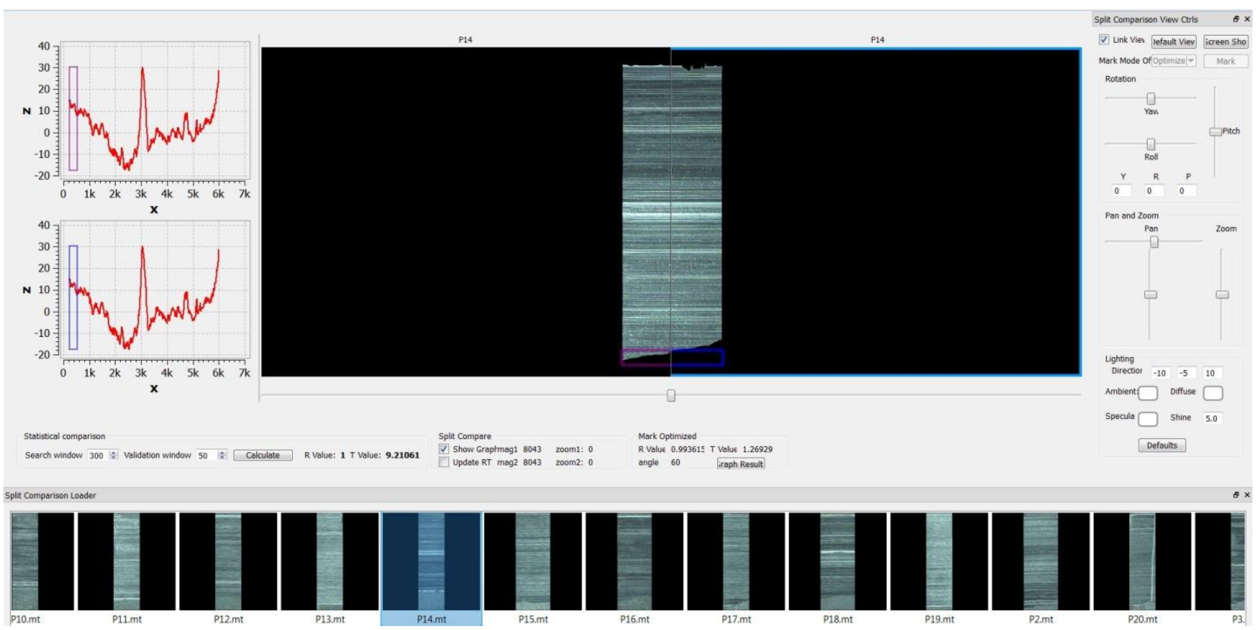


Figure ES4: Comparison screen of prototype under development showing matching comparison with graphs and statistics displayed.

By hitting the “calculate” button the operator can see information related to the objective analysis of the two samples under comparison. The region of “best fit” for the window size specified by the operator is marked on the graphs and on the images by rectangles that correspond to the size of the search window used. The size of the search and validation windows can be varied if desired and the statistical information can be selected to continually update as the slider bar below the pictures is moved back and forth, allowing the examiner to check the quality of the objective comparison at numerous locations.

Toolmark vs Tool Analysis: The prototype has the ability to acquire data from surfaces that vary greatly in surface profile and roughness. This allows the examiner to directly compare one tool to another or, perhaps more importantly, a tool to the toolmark it created. An example of this is shown in Figure ES5. When a tool file is opened for comparison to a toolmark file, Mantis takes the raw tool tip data and uses it to generate a virtual surface that, in turn, can be used to generate a "virtual toolmark" [34, 35], which is calculated on the basis of the highest points measured from the tool tip, under the assumption that these points would be creating the mark when in use.

In Figure ES5 the graphs compare the actual data obtained from <u>measuring</u> the toolmarked surface to the <u>generated</u> surface obtained from the actual tool by calculating a "virtual toolmark". In the example selected there is an obvious visual relationship between the graphical data obtained from both the toolmark and the "virtual toolmark". The objective statistical routine can be used to compare the toolmark to the "virtual toolmark" (once again by hitting the calculate button) in the same manner discussed above when comparing two real toolmarks to each other. A pseudo-image of the "virtual toolmark" can also be created and displayed if desired.

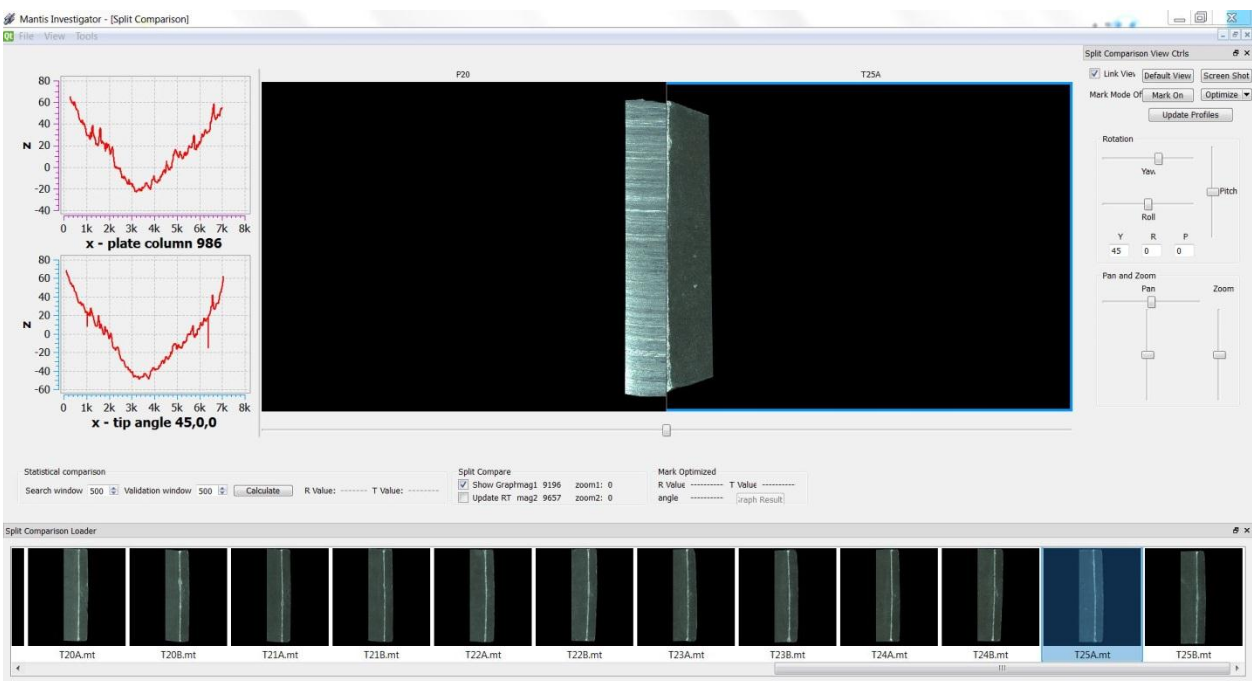


Figure ES5: Comparison of a plate to a tool tip. Note that the quantitative measured surfaces match well (as evidenced by the graphical information on the left).

Automated Angle Prediction: Note that the match shown in Figure ES5 is only valid because the angle at which the tooltip is viewed and the angle at which the toolmark was created are the same. Examiners have long known and studies have shown [15] that toolmarks must be made within approximately 10 degrees of each other in order to have a reasonable chance of determining identification. It is for this reason the software has incorporated within it an “optimization” routine for toolmarks of this nature. This function allows the angle at which a toolmark was created to be predicted for replication by an examiner if desired. The optimization process is based on the fact that as the angle of the tool changes new regions on the tool tip will be presented as the highest points that contact a surface and create a toolmark. This, in turn, means that with the creation of a virtual tool, the resulting virtual toolmark will change continually as the angle is changed.

The process, then, involves first acquiring data from the tooltip. For this project, a select number of screwdriver tips were selected from the database of 50 sequentially made tips available and data was obtained from both sides of the tip at an angle of 45 degrees.   This angle allows the entire edge of the screwdriver tip responsible for creating a toolmark to be acquired in one scan. The raw data is saved using a file designation that Mantis recognizes as coming from an actual tool. When the tool file is opened in Mantis the program take the raw data and automatically calculates the “virtual tool” that can then be used to generate virtual toolmarks.

In operation, the examiner needs selects “Optimize” from the comparison screen (upper right in Figure ES6) and inputs the starting and ending angular range they wish to explore into the optimization routine, along with the angular spacing between marks they want examined. The routine then starts at one end of the angular range, computes the virtual toolmark, compares it to the actual mark using the statistical algorithm to determine the T1 value, records this value in a data file, then moves on. Upon completion the parameters pertaining to the virtual mark that best match the actual mark are displayed, along with the ability to graph all of the results.

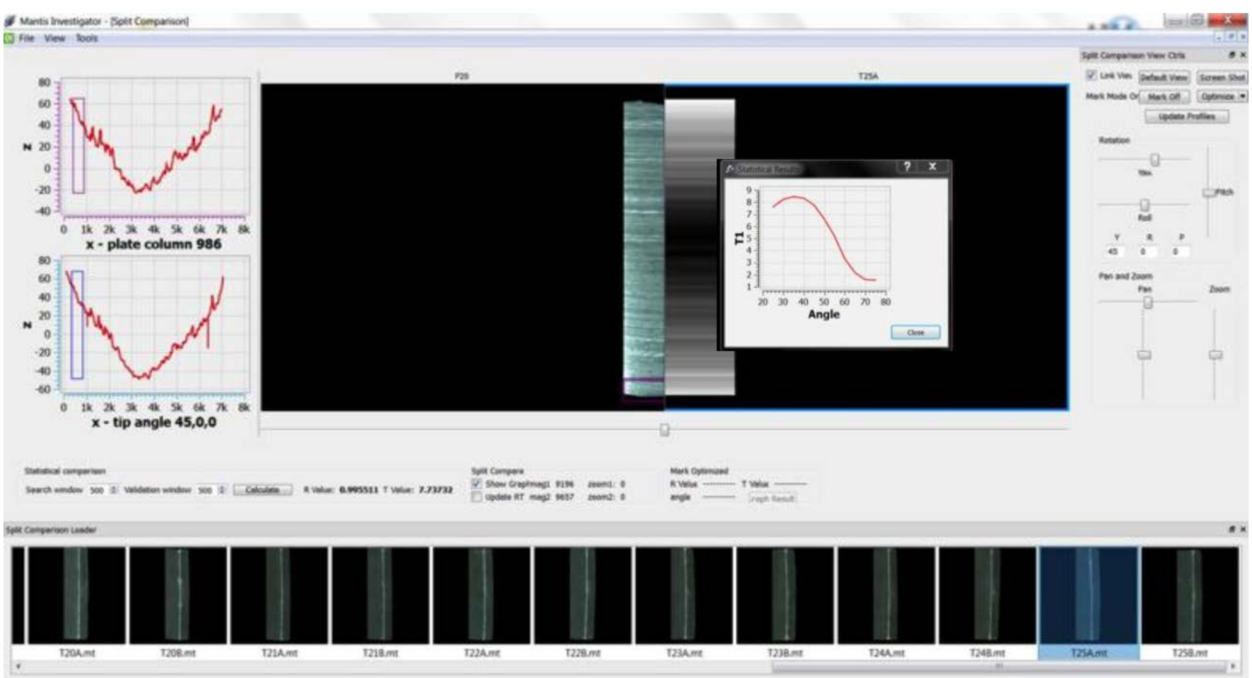


Figure ES6: Comparison of a real toolmark to a virtual toolmark created from data obtained from the actual tool surface. Results of the optimization process are displayed in a popup window.

A blind study conducted to test the efficiency of the optimization process was able to correctly identify 20 out of 20 toolmarks to the tips that created them and the angle was predicted to within 10 degrees for all comparisons and within 5 degrees in 16 of 20 comparisons [32]. It is noteworthy that the routine was able to detect a tip that had been added (without the knowledge of the testers) by the examiner who made the marks since those marks could not be matched to any of the tips in the researchers possession.

Complex Toolmarks: While the initial work regarding development of the prototype was based on fully striated marks various other data sets have been analyzed. Screen shots illustrating the varying nature of the images produced by the system are displayed in Figures ES7-ES10.

Figure ES7 shows a comparison of surfaces from wires that had been severed using by-pass pliers. The shear cut surfaces are quite different from the fully striated markings seen in screwdriver drag marks. The prototype was able to effectively acquire the data and carry out the same type of analyses on these markings, although the images appear quite different and the data spread is larger, as detailed in [30].

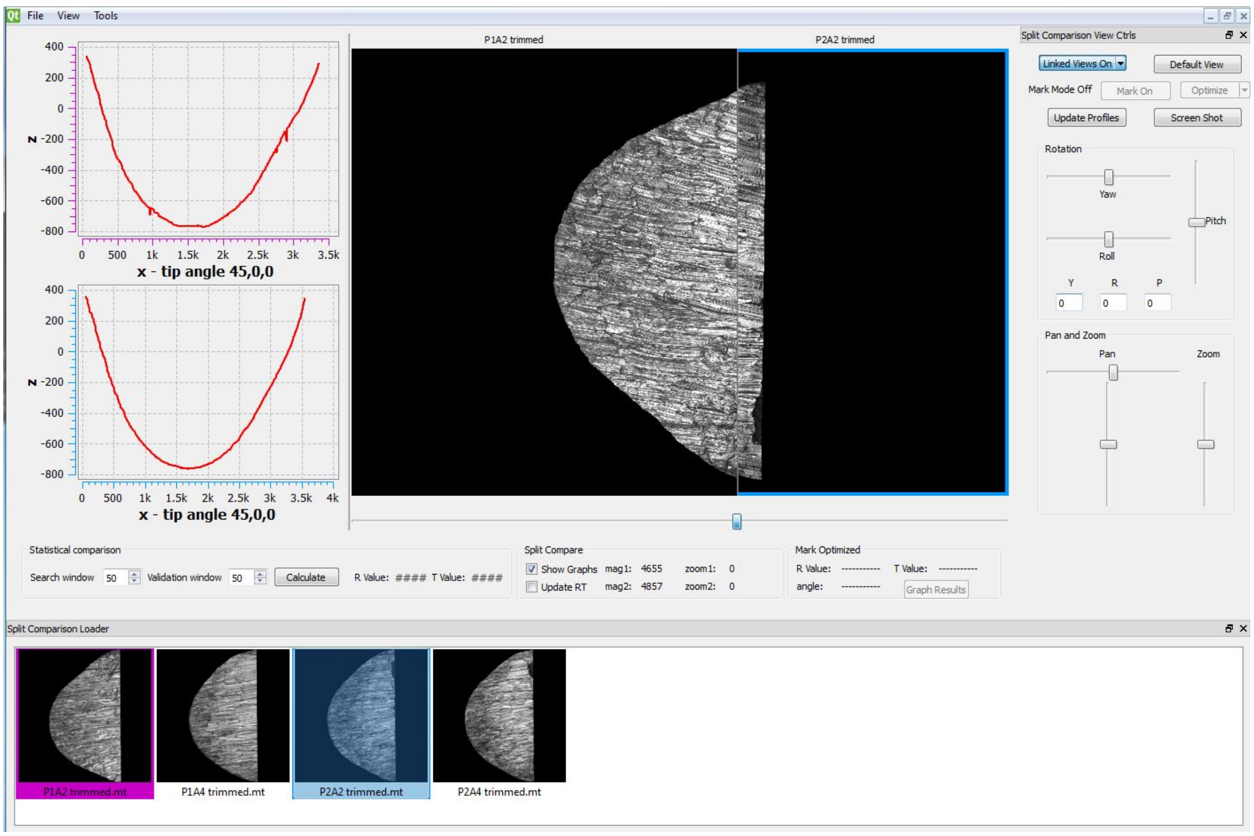


Figure ES7: Comparison of plier data.

Figure ES8 shows a comparison of images obtained from the impression marks of cold chisels. Analysis of data of this type has been detailed in [31]. As for the shear-cut marks the algorithm embedded within the Mantis software was able to compare and identify matches in the data set, although as mark complexity has increased from the fully striated marks performance declines slightly, with wider data spread and more outliers appearing as for the plier data.

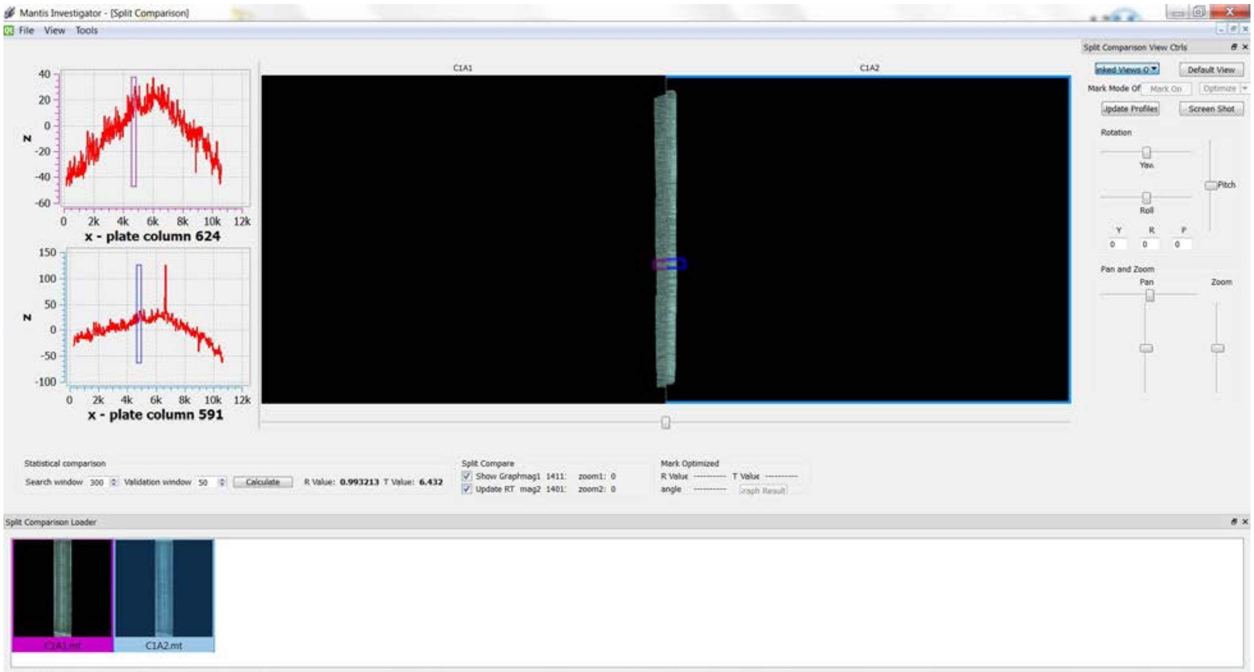
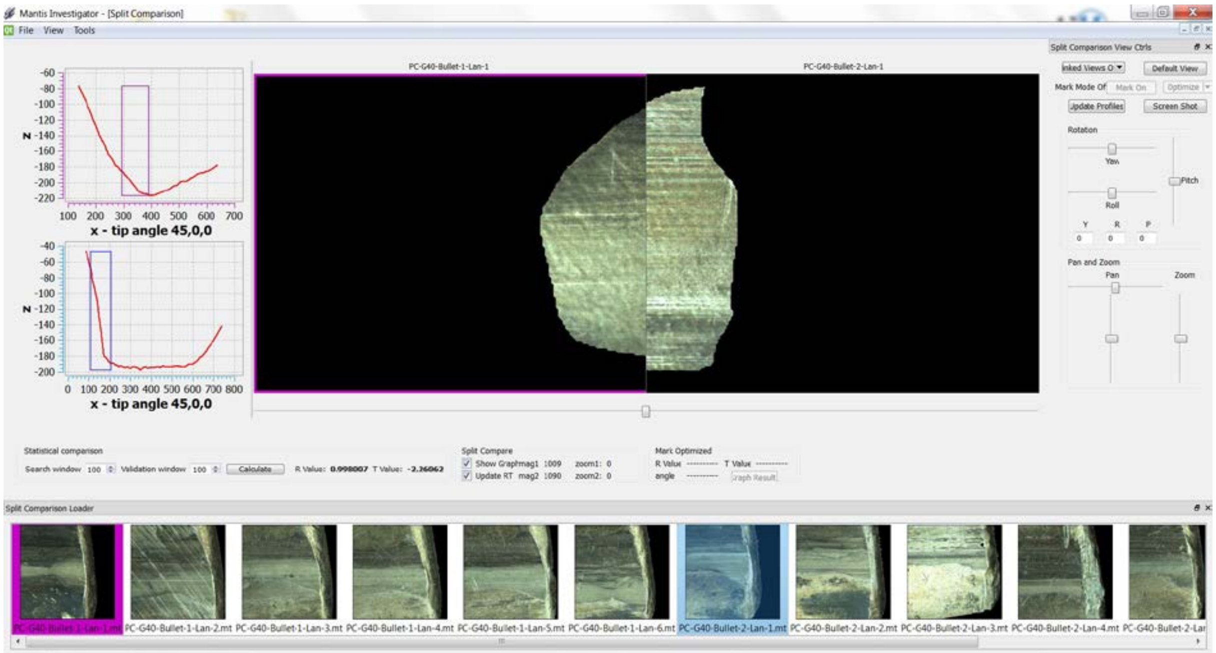


Figure ES8: Comparison of chisel impression marks.

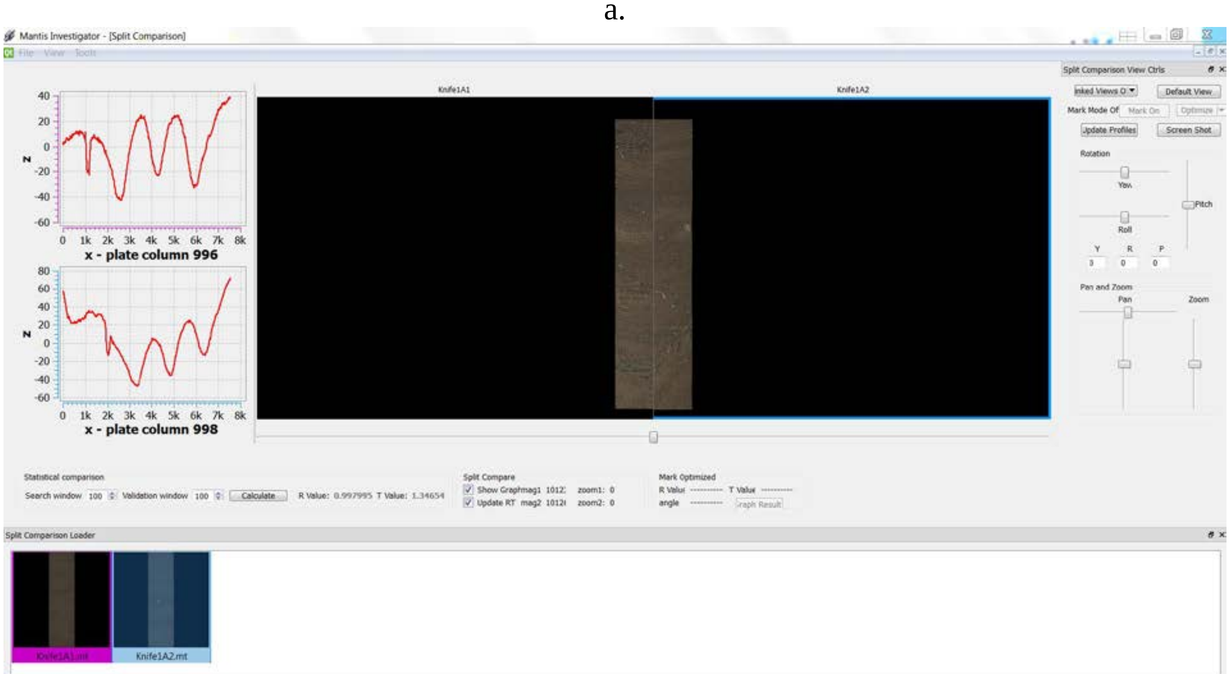
Limited data has also been obtained on two different types of advanced marks, those produced from knife blades and from bullets. Samples for data collection were provided by Mr. Aaron Brudenell, who was asked to come and evaluate the system. Neither type of toolmark had been examined previous to Mr. Brudenell's visit. Figure ES3 showed the overall scan obtained from the bullets. During the course of the examination it was discovered that the prototype has two issues that need to be addressed, both concerning the acquisition of data at what might be considered as the two extremes of data file size.

For our initial attempts on quantitative analysis of the bullets, in order to obtain a data file that consisted primarily of parallel striations it was necessary to mask off a large amount of the data acquired from the bullet surface, leaving a fairly small data file. The result is shown in Figure ES9a. The amount of data left to actually characterize using the algorithm embedded in Mantis was really small – too small for any meaningful results to be obtained.

On the other end of the data file size range are the toolmarks left by knife cuts (Fig. ES9b). These markings were created by pushing the knife through a polymeric material, leaving both class characteristics as well as unique markings. Because of the size of the knife these data files are large in comparison to those left by screwdrivers or on wire when it is cut. A complete scan of the mark results in a huge data file, requiring considerable computing power to handle. Initial attempts on these markings reveal that a better way to discriminate class characteristics is needed, and a proposal to further develop algorithms to extend application of Mantis to other types of complex toolmarks such as knife marks was submitted [rejected].



a.



b.

Figure ES9. Data obtained from a) two bullets fired from a Glock 40 pistol. b) knife cuts made in a polymeric material. (Both samples courtesy of A. Brudenell)

5. Conclusions

The goal of this study was to determine the feasibility of developing a portable, semi-automated system for characterizing and analyzing toolmarks that could be used for conducting objective, quantitative studies. The PI's feel the data and results outlined in this report and the papers published using the system developed support our contention that this goal has been achieved to a large extent. The results obtained through various studies also lend credence to the primary assumption made in many forensic investigations, namely, that all tools leave unique marks. From the studies conducted the following conclusions can be drawn:

1. The small, portable, optical system obtained from Alicona GmbH and used for the prototype can obtain excellent data from extremely variable surfaces in a fraction of the time of previous optical systems. The optical system has been shown to be flexible enough to obtained data from individual bullet lans even though the sample surface is curved substantially. The microscope and the laptop computer used for control can be packed, ready for transport within 20-30 minutes and deployed in as little as 15 minutes.

2. Mantis, the application suite of software developed for the prototype, offers a high degree of functionality, allowing the examiner to obtain objective data from samples and then conduct simple comparisons, statistical comparisons, and automated comparisons that involve the creation of a "virtual tool" from acquired data.

3. Application of the statistical algorithm to a variety of striated and quasi-striated toolmarks has produced good results. However, as toolmark complexity has increased data scatter is seen to increase, as well as the number of outliers. Application of the algorithm to complex markings such as bullet marks and knife cuts has resulted in the identification of new problems and challenges that must be addressed.

4. Given the above results it is apparent that additional algorithms will need to be developed to handle specific toolmark types. Extremely small toolmarked regions may need higher resolution scanning to produce data files with enough information for discrimination. Extremely large data files will need additional routines incorporated to remove class characteristics and data compression routines to provide files manageable in size. The open source-code nature of the prototype as developed should allow new algorithms to be easily incorporated into Mantis.

6. Implications for Policy and Practice

This project is an excellent first-step in showing that objective, non-partisan systems as called for by the recent NAS study [1] are not only possible but practical. Further developments of the software and the creation of additional statistical routines will only increase performance

Automation of the comparison and analysis of the comparison methodology will certainly speed this process. However, it is clear to the PIs that the role of a forensic examiner will become even more important. In addition to being conversant with the various types of toolmarks and the manner by which replicates are made for comparison, examiners should also be aware of the instrument itself and the factors that are crucial for obtaining reliable data. This points to increased training for examiners.

Implementation of the proposed project might also lead to a requirement for additional forensic examiners. An increased emphasis on the value of objective comparative evidence may result in increased workload in the same manner that the success of DNA evidence has in many cases caused an expansion of those sections of forensic laboratories.

I. Introduction

1. Statement of the Problem

In recent years the field of tool mark examination has faced unprecedented (and unrelenting) challenges from legal professionals, research academics, and the popular press charging that the entire field is unscientific and tainted by subjective bias. While numerous objective research studies exist as to the applicability and science of comparative examination, and others are underway, a system that provides objective measurements based on sound scientific principles in support of expert testimony is crucially needed.

Such a system, consisting of an automated measuring device and analysis software should be easy to use, flexible enough to apply to a wide range of possible forensic examinations, improve analysis throughput via the use of automation, and reliably and reproducibly provide objective data to the forensic examiner by means of computer analysis. In addition, the entire system should be economically priced in order for it to be accepted and implemented at a time where the nation is facing an ever-growing national debt that threatens to jeopardize the future. Finally, if such a system could be made small enough so as to be portable, it should find application in areas where a more traditional forensic examination is difficult to perform.

2. Literature Citations and Review

A recent National Research Council (NRC) report <u>Strengthening Forensic Science: A Path Forward</u> [1] stated in the Executive Summary of the report, "*A body of research is required to establish the limits and measures of performance and to address the impact of sources of variability and potential bias. Such research is sorely needed, but it seems to be lacking in most of the forensic disciplines that rely on subjective assessments of matching characteristics. These disciplines need to develop rigorous protocols to guide these subjective interpretations and pursue equally rigorous research and evaluation programs.*" This report, containing statements such as this, along with several well-publicized errors concerning comparative examinations [2, 3] has caused a furor in the popular press when it comes to the reliability and quality of forensic investigations [4, 5]. The entire field has come under attack as having no basis in science and of being totally lacking in any scientific evidence to support the assumptions upon which the field is based. Comparison methods are painted as being overtly subjective, with little or no attempt made to introduce objective measurements into the system.

Open forums have pointed out that the NRC committee either missed or neglected to mention [6] the large body of work that does exist in the forensic community exactly related to the perceived deficiencies they discuss, especially in the area of firearms and toolmarks. As early as 1958 Davis discussed a method that would make objective, quantitative measurements from a tool marked surface [7] and in 1959 Biasotti [8] applied statistical methods to the objective characterization of bullets. Biasotti continued his work over the intervening years and along with Murdock [9] in 1984 discussed the topic of establishing criteria for identification. Numerous studies concerning individuality and the problems associated with establishing identification criteria can be found in the literature, many of which are summarized well by Nichols [10, 11]. Nichols specifically addressed charges concerning the scientific foundations of firearms and toolmark examinations and discussed many of these same issues in detail [12]. It also is of note that the forensic community was already addressing these issues of subjectivity and establishing criteria before the 1993 Daubert vs. State of Florida decision [13], and long before the NRC committee issued it's report. Thus, examiners have been proactive in trying to better define and codify their craft for a number of years. However, despite these efforts it is also true that no systematic, objective protocol has been identified that can consistently provide the same level of identification as a trained examiner [14, 15].

The development of such protocols is difficult at best, given the complex nature of the problem. The earliest and perhaps best-known attempt is that involving Consecutive Matching Striae [16]. This technique, originally proposed by Biasotti [8] involves a direct observation of the samples and quantitative measurements being taken and compared. Although relatively simple in concept and execution, the fundamental idea that a mathematical comparison of striae can be made between two images is an important one. Although Biasotti's original work concentrated on bullets, the idea is equally applicable to any tool mark that results in striations and serves as the basis upon which current efforts to develop comparison protocols are constructed.

Early efforts aimed at utilizing the speed of modern computerized systems to conduct automated comparisons were built on an analysis of two-dimensional images, similar to those presented to an examiner using a comparison microscope. For example, in the DRUGFIRE system [17] simple optical images of fired cartridges could be compared and evaluated quickly by an examiner for possible matches. DRUGFIRE has since been supplanted by the Integrated Ballistics Imaging System (IBIS) [18] as part of the National Integrated Ballistics Imaging Network (NIBIN), and other studies employing optical systems have been conducted [19]. While DRUGFIRE and IBIS / NIBIN have enjoyed considerable success as a means of sharing images and information between law enforcement agencies, they really have done very little to address the central concern, which is providing objective, statistical evidence as to the validity of the comparisons they are making. Instead, IBIS / NIBIN serves more in the manner of a web page, maintaining a database of possible cartridges and bullets and providing a search engine that allows comparisons to the database. Possible matches are provided, and it is true that the matches are based upon statistical comparisons of the digital data files being examined. However, currently there is little or no statistical significance given to the numbers generated by each "hit", as pointed out by an NRC study [20] as being a deficiency.

DRUGFIRE and IBIS (at least all the early versions) were based on the analysis of 2D images taken of the surface to be analyzed. Measurements based upon 2D optical images are inherently limited by the quality of the acquired image. As such they do not measure the true nature of the surface but only the depiction of that surface, which is subject to differences in lighting, reflectivity, etc. True characterization for analysis should involve measurement of the 3D nature of the surface, and studies in recent years have focused on this using a variety of systems and approaches. These include laser profilometry [21], confocal laser sensors [22, 23], and surface contact profilometry [24]. The study by Bachrach [22] not only used the acquired data to compare data sets but also evaluated different 3D systems as to their ability to examine different types of samples. Updated versions of IBIS are now available that use the method identified by Bachrach, i.e. laser confocal microscopy, to obtain 3D characterizations for comparison. Although all these studies and improvements have added materially to the analysis of toolmarked surfaces, they have been limited in scope when it comes to testing the scientific validity of the basic assumption that all tools possess unique identifying marks.

The 2008 NRC study also pointed out the troubling fact that the data generated by the current IBIS / NIBIN system is not generally available for examination by researchers desiring to study the problem of individuality, but is proprietary to the Canadian company that markets the system. This shortcoming seriously hinders researchers not only in testing the validity of the basic assumption, i.e. individuality, but also in testing new algorithms they seek to develop for analysis. For example, it is becoming increasingly clear through the recent work of Petraco [25] and others [26] that different algorithms will most likely be needed to effectively analyze different types of tool marks. Petraco showed that a combination of principal component analysis (PCA), canonical variate analysis (CVA) and support vector machines (SVM) proved effective for analyzing relatively complete striated toolmarks but was inadequate for incomplete striations (such as produced by chisel marks) or impression marks. Work by investigators at AL/ISU has shown that the analysis of machining markings is also a more complicated process than striated marks [26]. If suitable analytical algorithms are to be developed and tested quickly and efficiently that are targeted toward specific types of markings, open source systems and data files need to be made available, eliminating the necessity of regenerating copious amounts of data for each study. In this aspect the Petraco study should serve as a model for all future projects in that access to their data files is freely given.

Work by the PIs at AL/ISU has been directed at providing scientific evidence and objective, statistical analysis of the relationship between toolmarked surfaces in order to examine the basic assumptions for several years now [26-29]. Statistic studies have shown that results from an objective computer-based algorithm supported long-held assumptions concerning the matching of surfaces marked by a screwdriver [15, 27]. This algorithm employed data obtained using a surface profilometer to characterize marks made by 50 sequentially manufactured screwdrivers. A survey of instruments conducted to see which offered the best prospect for the characterization of surfaces at high angles with respect to each other found that many of the systems commonly associated with surface profilometry were unsuitable for such difficult specimens [28]. However, a non-contact optical profilometry technique was identified as having the potential to measure steep sided samples such, for example, the end of a screwdriver. Subsequent experiments with an instrument of this type have shown that the data is comparable to that of the best surface profilometers, without being hampered by having a nearly flat surface [29].

On-going efforts at AL/ISU are centered on further refining the algorithm developed in [15, 27] to provide greater statistical relevance to the comparison numbers generated, and to expand the analysis beyond screwdrivers. At this time surfaces marked when pliers are used to cut copper wire [30] and impression marks left by cold chisels [31] have been studied. Concurrent with this effort has been an attempt to characterize screwdriver tips so completely as to allow a "virtual tool" to be constructed, enabling a toolmark to be completely characterized as to the conditions that existed when the mark was made regarding applied force, angle of attack, and tool twist [32, 33].

Given the success of previous and current research at AL/ISU the PIs felt the next logical step was to combine these results into an integrated package that can be tested for possible use in the field of forensics. Such a package would involve not only the developed algorithms but also integration into a data acquisition system that is easy to use and employ. Thus, what this report describes is the development of a prototype model system that allows comparisons to be made while providing statistical relevance to the comparisons. In doing this the ultimate goal is two-fold: 1) Provide data and experience that will guide future development of an effective, semi-automated method for carrying out impression evidence comparisons; 2) Develop as a prototype a working research platform for others to use to both acquire different types of impression evidence and test their own developed algorithms. Recent developments in the area of optical profilometry by Alicona, a partner in this project, have resulted in equipment being now available at substantially reduced costs that have never before been possible.

3. Statement of the Hypotheses and Rational for the Research

The project sought to develop a prototype analytical system that integrated current research software algorithms into the operating software of that system, involving both company representatives and university research personnel. Prototype development often has many unforeseen problems that arise, which cannot be predicted. However, recent developments in the area of profilometry helped to mitigate most of the concerns typically associated with prototype development.

The research question we sought to answer was: Can a computer-based, objective, comparative system be designed and assembled that will **improve both the "front end" of the forensic process** by being transportable to the crime scene for direct collection of evidence, if necessary, AND **improve analysis and throughput** by incorporating the latest statistical algorithms? We believe the answer to this question has been decidedly YES.

The hypothesis we held was that such a system was possible by incorporating the latest advances in optical profilometry to a laptop computer running objective, statistics-based, comparison software. Such a system has been created and if development should continue we anticipate eventually a marketable system be available at a significantly reduced cost from anything previously attempted. The fact that the system was designed to be "open source" from the beginning will allow researchers to continue to write and test various algorithms for data analysis, ensuring that the latest, most advanced analytical methods are employed.

II. Methods

1. Experimental Design

As this project was focused on the development of a prototype hardware system it involved less experimental design and more system design, primarily centered on software development. The approach taken when designing the software interface was to develop interface between the user and the objective data that would seem familiar to an examiner experienced in using a comparison microscope while at the same time giving them access to statistical analysis capabilities available through the acquisition of objective, quantifiable data. The software suite developed has been named Mantis, for Mark and Tool Inspection Suite. As the name implies both toolmarks and the tools that created them can be analyzed with the system, compared to one another, and statistically evaluated.

2. Experimental Methods

The experimental method followed when developing the prototype consisted of a series of steps aimed at both acquiring data and then ensuring he data can be analyzed in a manner as familiar to forensic examiners as possible. Most of the experimental method involved the development of software to interface with the hardware acquired as part of this project. Software development centered on the following objectives:

1. Acquisition of Data: Data acquisition involves use of a non-contact optical profilometer. Data acquisition is accomplished simply by employing a simplified version of the software provided by the profilometer manufacturer.

2. Data Cleaning: Data cleaning involves a visual examination of the acquired data file. Irrelevant data (e.g. regions lacking interest, low quality areas, etc.) is removed and the data detrended to make it ready for further comparison.

3. Data Comparison: Data comparison is where the user has a wide range of features from which to use. These will all be illustrated in the Results section but include:

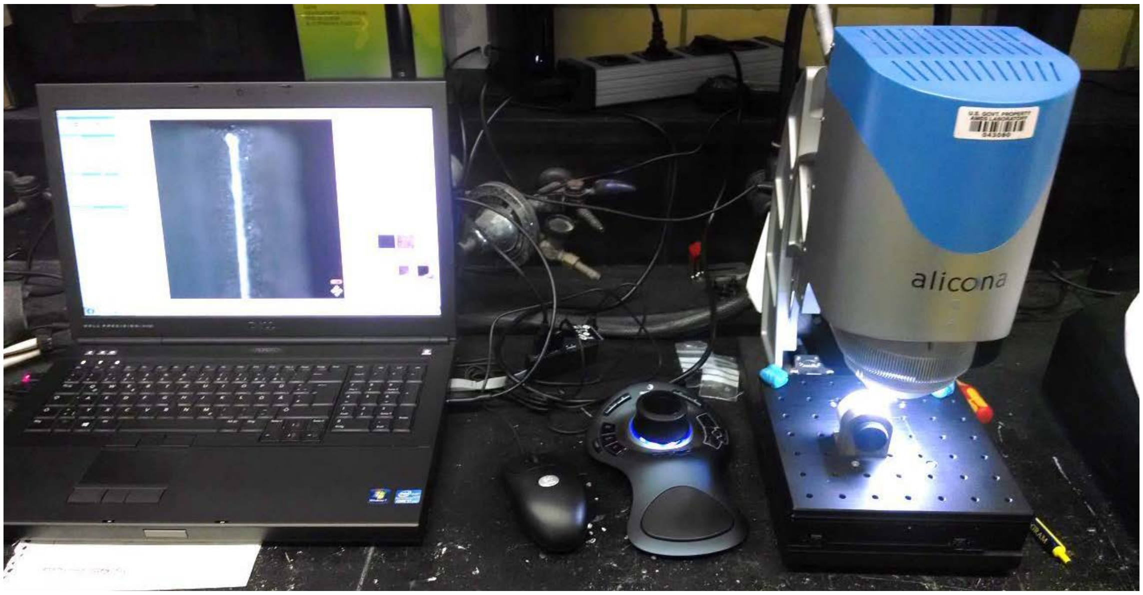
- Simple visual comparison with the ability to move, tilt, pan, and zoom the image.
- Updated Statistical comparison data as you examine the sample.
- Graphical comparison of surface roughness
- Prediction of tool angle used when a mark was created.

3. Materials Used

The prototype developed is based on the InfiniteFocus SL optical system available from Alicona, GmbH. The InfiniteFocusSL can measure with high accuracy (~1 µm vertical resolution, 4 µm spacial) a 50 mm x 50 mm x 26 mm sample in one scan in about 1-2 minutes; this can be decreased if the resolution desired is decreased as well. Conversely, higher resolutions can be obtained with increased scanning times. One advantage of this system is that it is capable of scanning surfaces at high angles with respect to horizontal (approaching 90 degrees). Alicona is a leading manufacturer of optical profilometers that operate on the principle of focus optimization rather than interferometry, and for this proof-of-concept prototype the InfiniteFocus SL was purchased attached to a lightweight, portable framework. The weight of the entire system (microscope, laptop, cables, transport case, etc.) is 80 lbs. The list price in 2016 for the system is $157, 275.00.

A laptop computer is employed to control the hardware and carry out the subsequent data cleaning and analysis. The laptop was also provided by Alicona and is a Dell Precision M6700, operating Windows 7 and running an i7 vpro core.

The complete prototype system, consisting of the InfiniteFocusSL unit and the laptop, is shown in Figure 1. The small size of the unit is evident in comparison to the laptop. The mouse and controls for moving the stage connected to the optical head are located between the microscope and the laptop. The system can be broken down and packed away for transport in a hard-shell rolling suitcase in as little as 30 minutes (Fig. 1b). Once at its destination the system can be set up and in operation again in as little as 15-20 minutes.



a.

b.

Figure 1: Portable prototype developed at AL/ISU. a) As assembled, b) packed and ready for transport. The transport case is 11” x 21” x 32” and equipped with wheels. Total weight ≈ 80 lbs.

Standard blocks exist to calibrate the system after set-up if desired. Calibration can take up to 20 minutes depending upon the absolute accuracy necessary. Tests have shown that due to the simplicity of the measurement system the instrument is extremely rugged and holds calibration extremely well. Calibrations checks conducted after an operation span of many months have shown almost no differences in measured results. In addition, the basis of the comparison program used and described in detail in [15] operates on different measured relative distances rather than absolute ones, so a steady decline in absolute accuracy with time will have little effect on the results. Thus, the system is extremely robust and valid comparisons can be obtained immediately upon set-up without requiring a calibration to be run, athough of course regular checks of the equipment are still recommended.

While the work detailed in this report was conducted primarily on flat samples, since the initial purchase Alicona has continued development of a sample stage that allows cylindrical samples to be examined and a proposal has been submitted that, if funded, would seek to incorporate this feature into the prototype for the analysis of bullets.

4. Procedures

The procedures followed in development of the prototype followed the following discrete steps:

1. Acquisition of Components: As stated above, an InfiniteFocus SL system was purchased from Alicona. At the time of purchase this item was not offered commercially. Alicona delivered it with a stage already attached for simple measurements and a travel case for transport, eliminating the need to design and built a stage.

2. Testing of Components: Once the new hardware was on-site it was used to re-characterize samples already examined using the previous optical system employed by AL/ISU to see if the quality of data was comparable. This was accomplished by carrying out abbreviated studies similar to those detailed in [15, 27]. It was quickly determined that the data obtained was in most cases better than the previous data and could be acquired in a fraction of the time. This allowed the next phase of the project to get underway, Software Modification.

3. Software Modification: Modification of the Alicona acquisition software was carried out in conjunction with Alicona. This step basically involved simplifying the standard company as-delivered software to make it somewhat more forensic-examiner user-friendly. The as-delivered system contained many features and options that give it wide applicability to industrial processes, but also tend to complicate the simple acquisition of data. Therefore, working with AL/ISU Alicona agreed to hide / delete functions that were considered irrelevant or of limited value by AL/ISU personnel to unclutter the user interface.

4. Software Development: Much of the project time was spent in software development to render the algorithms and comparison methods used in the research environment of AL/ISU into a user-friendly interface suitable for forensic examinations. This step was greatly hindered when the student who had been working on the project and was detailed with developing the software decided suddenly and without warning to leave the project. The timing of the announcement was such that no other students were immediately available to replace this individual. The problem was exacerbated by the high starting salaries being paid by companies to attract computer programmers. These facts, when coupled with the unique combination of skill sets required for the position (i.e. conversant in C++, Open GL, GPU, QT, etc.) meant that over a year went by before a source could be found to complete the work that had started involving software development. Finally, Chris Hanson of Alphapixel was contracted to assist in the continued development of the software. Major programming was carried out by Brian Bailey of Code-Hammer Technologies working with Alphapixel. In this joint venture Alphapixel and AL/ISU have developed a beta version of the software interface suitable for testing.

5. Testing of the Complete System: At the time of writing the system has been tested and reviewed by James Kreiser, former forensic examiner for the state of Illinois and Aaron Brudenell, consultant, forensic examiner, and instructor for Bureau of Alcohol Tobacco and Firearms National Firearm Examiner Academy. We plan to continue testing of the system by making it available to interested parties and we have also contacted the Iowa State Crime Laboratory and have plans to demonstrate the system to them.

5. Samples Studied

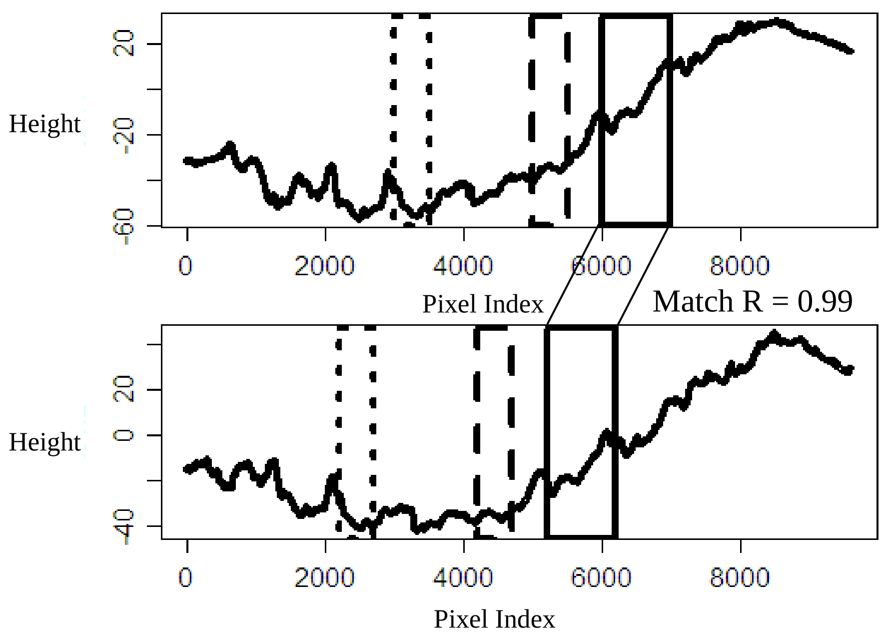
The majority of early testing of the system was carried out using the same set of 50 sequentially made screwdriver tips studied in [27]. However, as the software interface matured and greater flexibility was added additional samples and distinct sample sets have been analyzed. This includes a set of 50 sequentially manufactured shear-cut pliers as described in [30]; a set of fifty sequentially manufactured cold chisels [31]; a subset of screwdriver marks selected from the larger set of 50 tips that were used to make random marks at different angles as detailed in [32]; and in recent efforts the prototype system has been used to conduct exploratory studies involving bullets and knife cuts. The latter two types of toolmarks were provided by Mr. Aaron Brudenell as part of his inspection and testing of the system, and access to these unique samples has already provided valuable information concerning expanding the capabilities of the system and in methodologies necessary to address these types of toolmarks.

6. Statistical Methods

The statistical methods employed by the Mantis software have been described in detail in [15] with slight changes and improvements summarized in numerous papers by the authors [30]. For the sake of completeness the algorithm is described briefly here, using the same illustrations provided in [15].

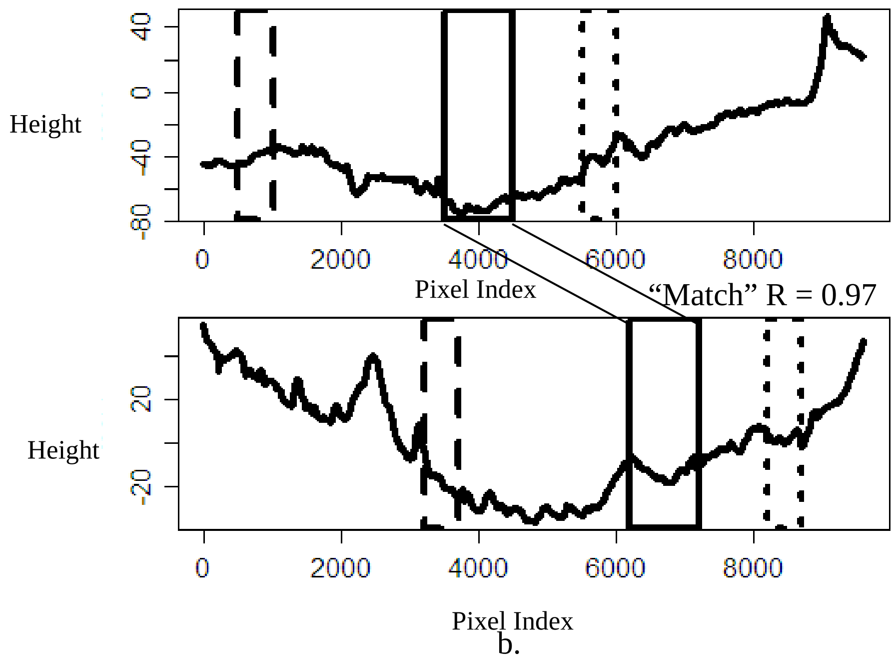
The algorithm begins by first identifying a region of best agreement in each of the two data sets for the specified size of the (user-defined) search window. This is determined by the maximum correlation statistic (i.e. the “R-value”). By way of illustration, two different possibilities are shown in Figure 2, namely, a true match comparison (Fig. 2a) and a true nonmatch (Fig. 2b). In each case, the matched regions are marked with solid rectangles. Note that in both cases the R-value returned is very close to 1, the largest numerical value a correlation coefficient can take. In the first instance this is so because a match does in fact exist; in the second case a large R-value is found simply by chance. This is not unreasonable to expect, given the very large number of correlations calculated and the probability that for the short segments compared it is inevitable that at least one pair of segments will have a large R-value. For this reason the R-values cannot be interpreted in the same way that simple correlations are generally evaluated in most statistical settings. For reference this first step is referred to as the Optimization step.

The algorithm now conducts a second step called Validation. In this step corresponding validation windows of equal size are specified by the user. Typically validation window sizes are selected to be smaller than search windows. Once specified, validation windows are selected at randomly chosen, but common, distances from the previously identified regions of highest R values. This is best illustrated by a simple example. In Figure 2a two randomly chosen shifts (say, of 1012 and 2976 pixels) to the left of the best matching search window regions might correspond to the dashed rectangles. The correlation for this pair of corresponding regions is now determined. Note that this correlation <u>must</u> be lower than the already found highest R-value determined in the Optimization step. The assumption behind the Validation step is that if a match truly does exist, correlations between these rigidly-shifted window pairs will also be reasonably large because they will correspond to common sections of the tool surface. In other words, if a match truly exists fairly good matches should exist along the <u>entire</u> scan length. However, if a high R-value is found between the search windows of two nonmatch samples simply by accident, there is no reason to believe that the accidental match will hold up at other points along the scan length. In other words, while the likelihood of one accidental match may be high, the probability of a large number of high R values is low.



a.

Figure 2: a) Comparison pair showing a true match. Best region of fit shown in solid rectangle with corresponding R value. Note the similarity of the regions within the two possible sets of validation windows (dashed and dotted rectangles). Figure taken from [15].

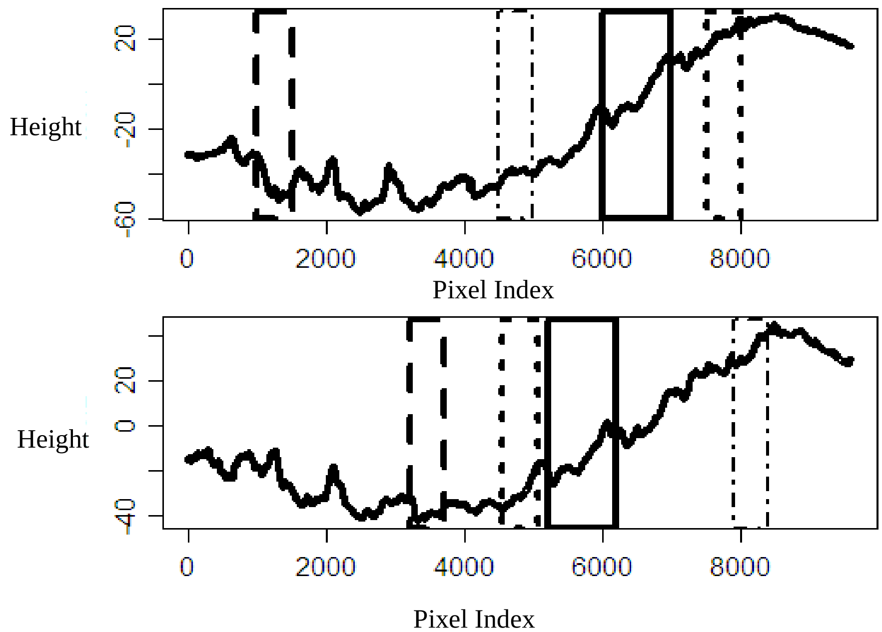


b.

Figure 2: b) Comparison pair showing a true nonmatch. While a high R value is still found between "Match" segments, the validation windows are distinctly different from one another. (Figure taken from [15]).

Continuing with the example shown reproduced in Figure 2a, the regions in the dashed rectangles for the true match do appear somewhat similar, and can be expected to return fairly large correlation values. However, consider the results seen for the nonmatching pair, Figure 2b. In this case the two randomly chosen rigid shifts (one 1752 pixels to the right and the second 3219 pixels to the left) fall over areas that visually have almost no relationship to each other. Lower correlation values will be obtained in this case.

While we have been referring to the correlations between the validation windows as being high for the true match and low for the true nonmatch, in reality the correlation values can be judged to be "high" or "low" only if a baseline can be established for each of the sample comparisons. This is achieved by identifying a second set of paired validation windows of the same size as the previous windows for comparison. The location of these windows along the data trace is again randomly selected, except with one very important difference. For this new series of comparisons there is no constraint that the windows be shifted an equal number of pixels from their respective regions of best fit. In other words, for this second set of comparisons the shifts are selected at random and independently from each other – any segment of the selected length from one specimen has an equal probability of being compared to any segment from the other. This is illustrated in Figure 3 for three pairs of windows, denoted by the dashed rectangles, the dotted rectangles, and the dot-and-dash rectangles. It is evident that even on this true matching pair visually there is no correlation between these randomly selected windows. Thus, this step establishes a baseline for comparison of the rigid shifts previously conducted in the Validation step.



c.

Figure 3: Validation windows (dashed, dotted, and dot-and-dash rectangles) selected at random for the comparison pair shown in a) to establish a baseline value. (Figure taken from [15]).

The Validation step concludes with a comparison of the two sets of correlation values just described, one set from windows of common random rigid-shifts from their respective regions of best agreement, and one set from the independently selected windows. If the assumption of similarity between corresponding points for a match is true the correlation values of the first set of windows should be larger than those in the second. In other words, the rigid-shift window pairs should result in higher correlation values than the baseline established by the independently selected, totally random pairs. In the case of a nonmatch, since the identification of a region of best agreement is simply a random event and there really is no similarity between corresponding points along the trace, the correlations in the two comparison sets should be very similar.

A nonparametric Mann-Whitney U-statistic (referred to as T1), is generated for the comparison. Where the correlation values of the two comparison sets are similar, T1 takes values near zero, supporting a null hypothesis of "no match". If the correlations from the first rigid-shift sample are systematically larger than the independently selected shifts, the resulting values of T1 are larger, supporting an alternative hypothesis of "match"."

The above basic algorithm has been used to analyze various data sets [15, 30-33], and minor improvements / changes have been made to increase performance. For example, it was commonly noted that outlier data points were observed to stem from the algorithm misidentifying the opposite ends of marks as a positive match. This occurred because in the earliest version the algorithm moved back and forth comparing search windows independently of how the samples for comparison were aligned. Through random chance opposite ends of a mark occasionally have the regions of highest correlation between marks for the given search window size selected. For example, samples where the shape of the toolmark was very distinctive, such as for cut wires, or where the left and right edges of the marks were known, occasionally would match at the opposite ends of the data traces [30]. Clearly, it is physically impossible for this to occur. In investigating the cause for the false match it was discovered that in cases where the region of highest correlation between two marks occurs at the end of the scan profile, the validation routine used by the algorithm to ascertain the quality of the comparison cannot function properly. When a "match" is found near the end of a scan profile the space needed to successfully accomplish the rigid shifts and complete the Validation step does not exist. This results in an incorrect validation, and a "match" being declared when in fact a non-match may exist.

To address this problem a "leash" was applied to the search window of the algorithm during the initial Optimization step, the purpose being to limit the comparison distance between profiles. In this case the comparative correlation is no longer calculated over the entirety of a trace for each iteration of the search window but only to a certain percentage of the entire distance. The leash limits the search range for the region of highest correlation. Leashing the search window makes it impossible for the algorithm to identify regions far from each other on the real surface as matching by taking advantage of the contextual information available to forensic examiners when creating marks for comparison.

III. Results

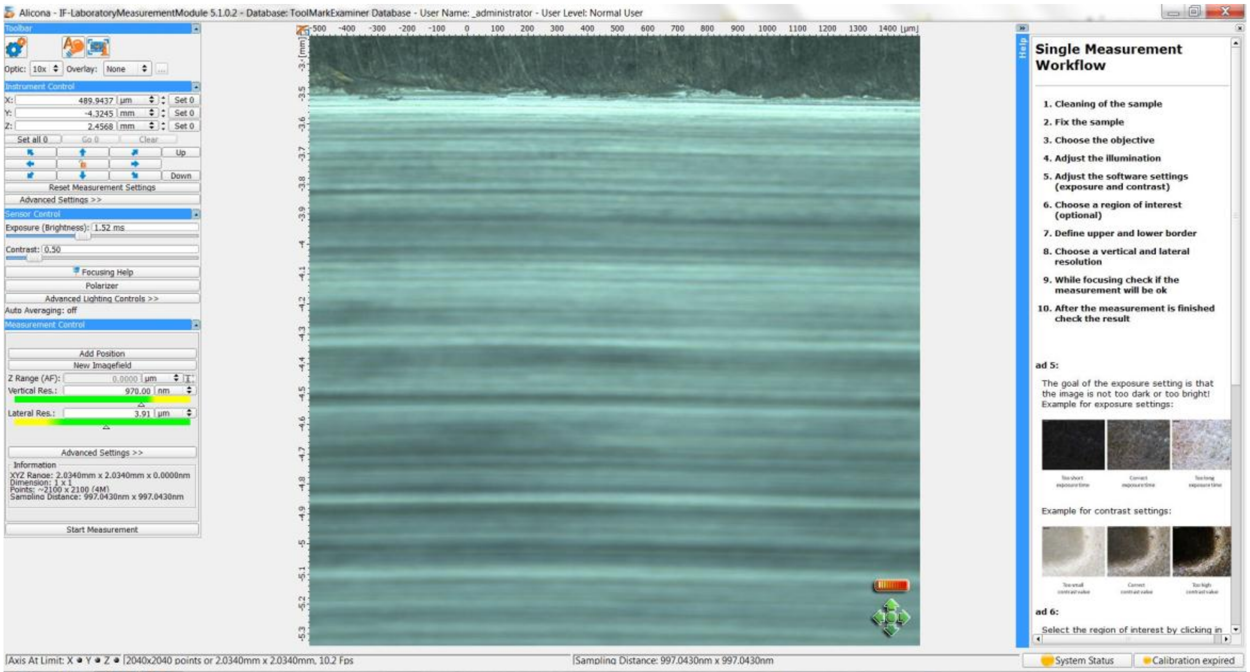
1. System Hardware

The system hardware components were discussed in Section II.3. Since the as-delivered hardware was suitable for the needs of the prototype development no modification was done to them.

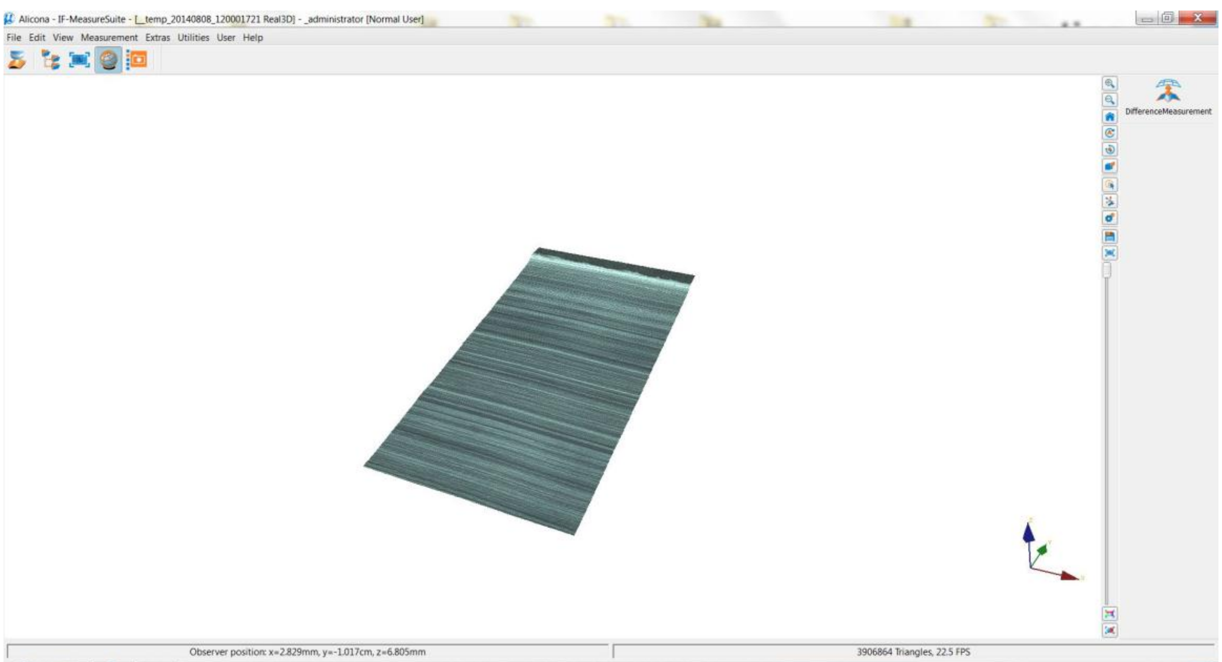
The majority of results to report concerns development of the software used to collect the data and especially to analyze the data acquired by the system. These efforts are discussed in the following sections.

2. Data Acquisition

Data for comparison is acquired using software provided by Alicona. Working with Alicona, a simplified interface for use in the prototype was developed and a screen shot of the interface is shown in Figure 4a. This interface removes much of the features Alicona provides to industrial customers since they are not needed in forensic applications. While the features are still present in the software if eventually needed, access to them is simply hidden from the user interface screen. A flow chart is provided on the right side of the screen to assist in obtaining the best data possible. Figure 4b shows an example of acquired data as viewed using the Alicona software.



a.



b.

Figure 4: Simplified Alicona interface for data acquisition. a) Acquisition screen. b) Digitized data acquired.

Alicona offers ways to link their acquisition software to company equipment and incorporation of the data acquisition step into the operating software of the prototype was one objective of a proposal submitted to the National Institute of Justice [37], along with expanding the capabilities of the system by adding the ability to import and analyze data from any number of other instruments and data storage formats. The proposed idea was that the prototype would offer a one click, one software package interface to the examiner, with the acquisition of the data being fully integrated into software developed at AL/ISU (as described in the next section) or the ability to import any data into the system and carry out the same type of analysis. Unfortunately this proposal was not funded.

3. MANTIS: Mark And Tool Inspection Suite

Once acquired the raw data files are opened using Mantis. Mantis is really the core of the prototype development project as it contains all the necessary code allowing the user to clean the raw data, mask off unwanted, irrelevant portions of the acquired file, then display the data for visual comparisons or statistical analyses. The software contains the functions and routines developed at AL/ISU including the statistical analysis developed by PI Morris' group (Section II.6), and data cleaning and virtual mark generation routines developed by PI Zhang's group all embedded in what the PIs hope is a fairly intuitive, user-friendly interface. As described in Section II.4, development of the interface has been in cooperation with Chris Hanson and Brian Bailey of Alphapixel. The working relationship between AL/ISU and Alphapixel has been one of the real successes of the project, allowing development to proceed rapidly while preserving the open-source, non-proprietary nature of the project.

The software suite mainly uses C++ for the majority of the code; OpenGL and a graphics processing unit (GPU) is used to produce virtual marks of tools at any given angle and resolution and to visualize geometric data on the screen; Qt is used to create the graphical user interface (GUI); and Java script is used to interact with computers through command lines. The basic development of the software, consisting of the cleaning and data analysis routines, was carried out at AL/ISU. An image of the splash screen is shown in Figure 5.

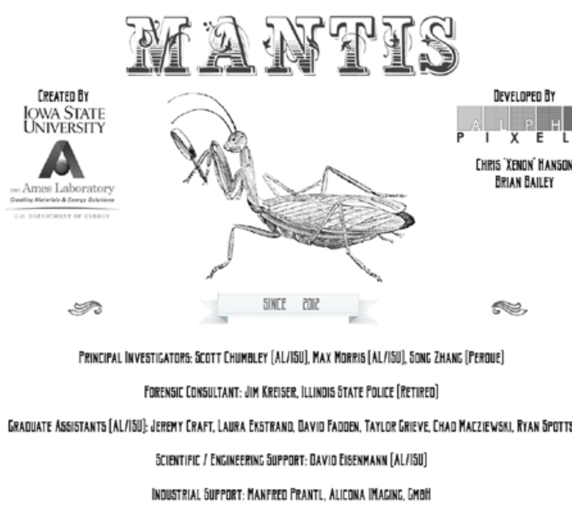


Figure 5: Splash screen shown upon start-up of Mantis.

The various steps available in Mantis, namely, data-cleaning, masking, and data analysis will now be described.

Data Cleaning:

Once the raw data is acquired in certain instances the data must be cleaned to remove aberrations or areas of the scan that will not be used in a subsequent analysis. These regions arise due to imperfections or irregularities on the surface that scatter the light, resulting in either a high glare or lack of imaging capabilities. Elimination of these irregularities is done using a series of routines. Firstly, minor imperfections due to random scattering from the surface (which appears as either holes or spikes in the data when viewed at high magnification / high resolution) are pre-processed before entering the statistical analysis. Spikes are removed based on a filtering routine and holes are filled by analyzing the surface regions surrounding the holes. Generally the data from the InfiniteFocus SL is so good that few adjustments of this nature are required.

Secondly, all measured surfaces tend to have a slope or "trend" associated with them, i.e., they are not perfectly flat. A de-trending routine removes this slight slope, rendering the data flat.

Masking:

Since the acquisition parameters of the InfiniteFocus SL are routinely set to overlap the actual mark in question to ensure that no data is omitted, the raw data will often have information from irrelevant regions contained at the edges of the file that must be removed using a masking routine. This is illustrated in Figure 6, which shows data obtained from a chisel impression. In this example while data is acquired over the entire impact surface for analysis only one side of the impression mark at a time was selected. The masking routine allows the undesired parts of the data to be marked and then a simple script removes these regions form the data file. In the example shown in Figure 6 the rectangular box at the bottom of the image is the desired region for comparison. The top part of the file is excluded simply by using a drawing tool to draw an "X" through it and the edge at the right is excluded with a simple line. Only the region contained within the box will now be analyzed. In all cases the raw data remains untouched, with the cleaned files requiring a new designation to distinguish them from the raw data files as being cleaned data.

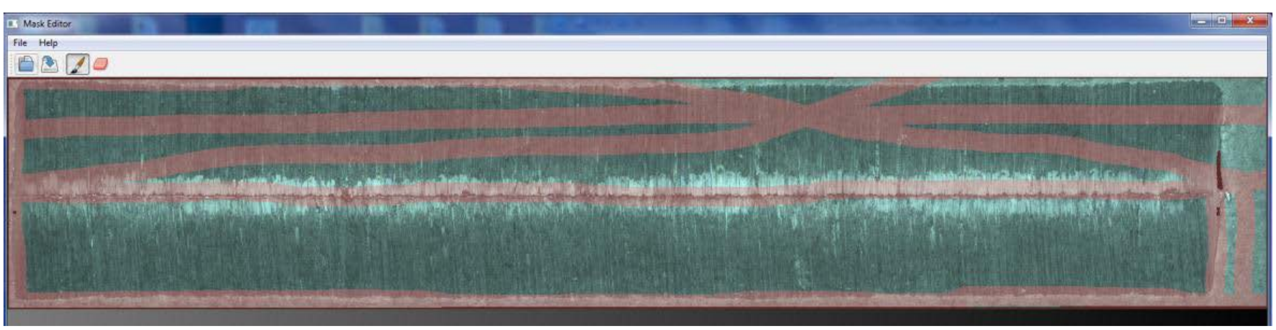


Figure 6: Masking of undesired data. The bottom half of the chisel mark will be analyzed, saving the remaining data for later analysis. (From [31])

Data Analysis :

The analysis software available in Mantis consists of a number of options that allow an examiner to do comparisons in various ways. These include:

☐ Simple visual comparison

☐ Observation coupled with graphical information of the surfaces

☐ Observation, graphing, and statistical analysis of the surface

☐ Generation of virtual toolmarks from measured tool surfaces

☐Automatic determination of angle of incidence for a tool that created a given toolmark using virtual marking and an optimization routine.

Simple Visual Examination: Figure 7 shows an example of the simple visual comparison screen available to the examiner, illustrating a comparison made between two bullets fired from the same gun. The examiner can view the data gathered by the InfiniteFocus SL and compare the image files in the same way they currently view actual images using a comparison microscope. The images can be linked so they can be moved and magnified together or unlinked for individual translations. A slider bar at the bottom of the image allows the examiner to move back and forth across the samples, analogous to the comparison microscope.

Note that although the files appear as optical images, due to the method of acquisition the images shown in Figure 7 actually contain quantitative information produced through use of the system. Thus, in addition to looking at the images the examiner, if they choose, can look at graphs displaying quantitative measurements of the surface roughness of the samples. This is illustrated in Figure 8, which shows two toolmarks created by a specific screwdriver. The visual comparison is still available only now the graphical results are included and shown on the left.

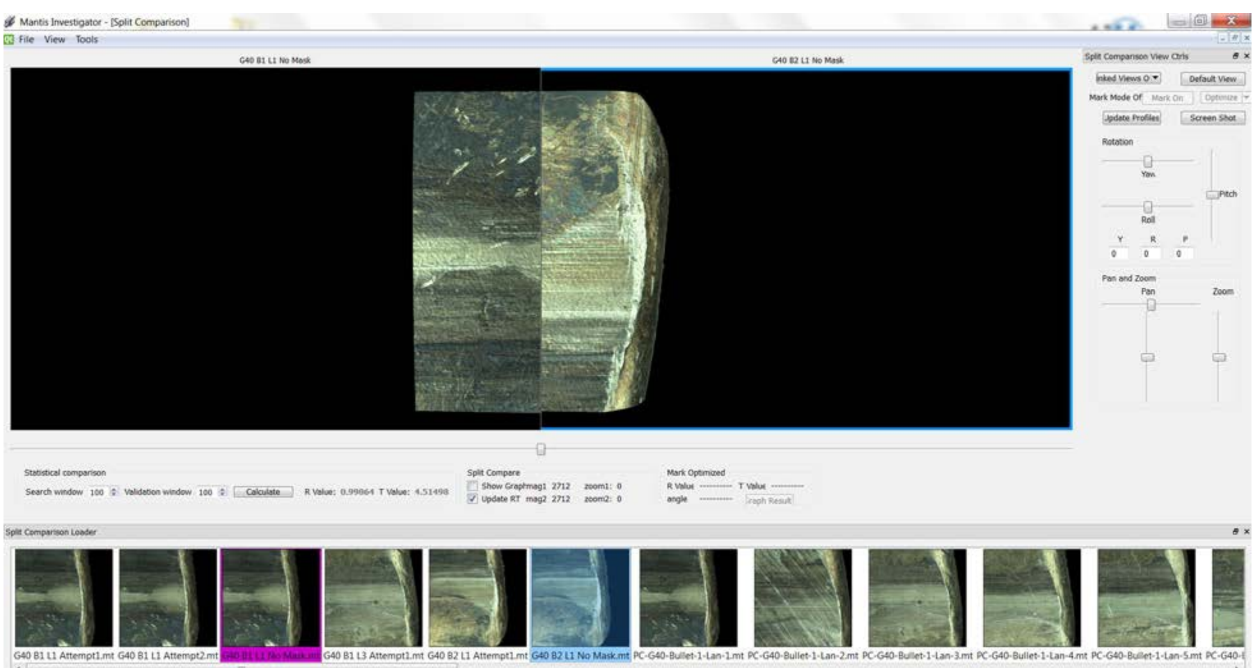


Figure 7: Simple visual comparison of two bullets.

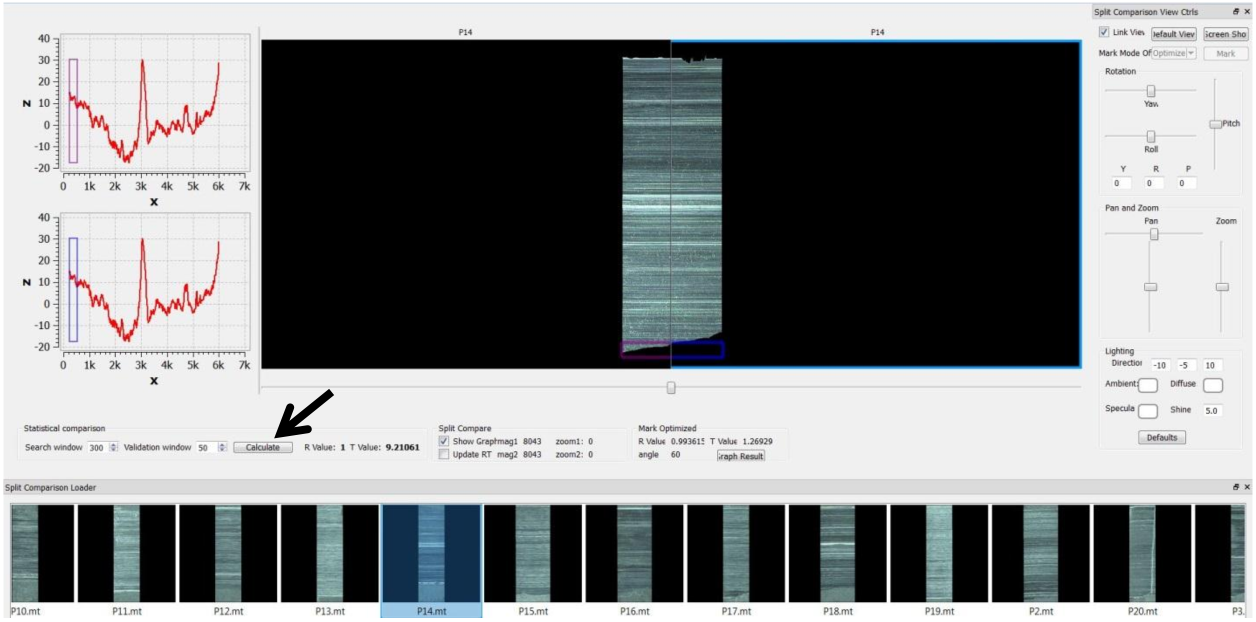


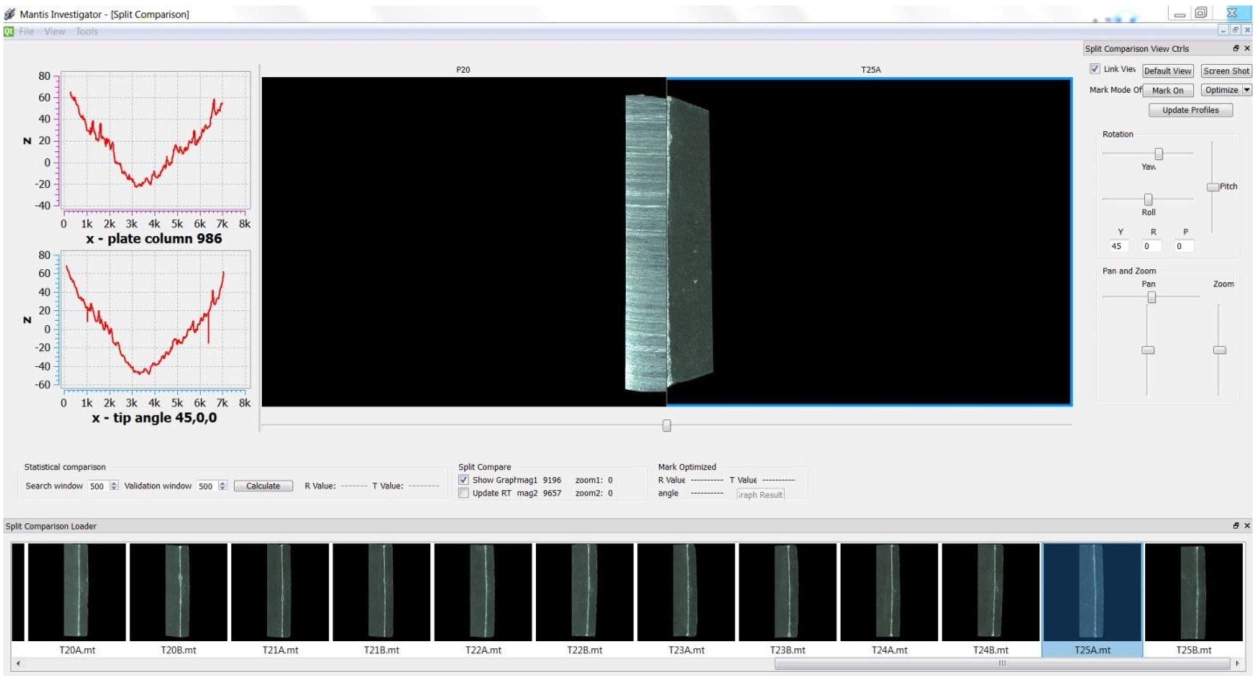
Figure 8: Comparison screen of prototype under development showing matching comparison with graphs and statistics displayed. The calculate button is arrowed.

Note that the linear plots shown on the left are not an average obtained from the entire scan; they display the raw data (after the cleaning and masking step) obtained from a single column of pixels that spans the sample, corresponding to the hairline position. As such the plots changes as the slider is moved back and forth between the images.

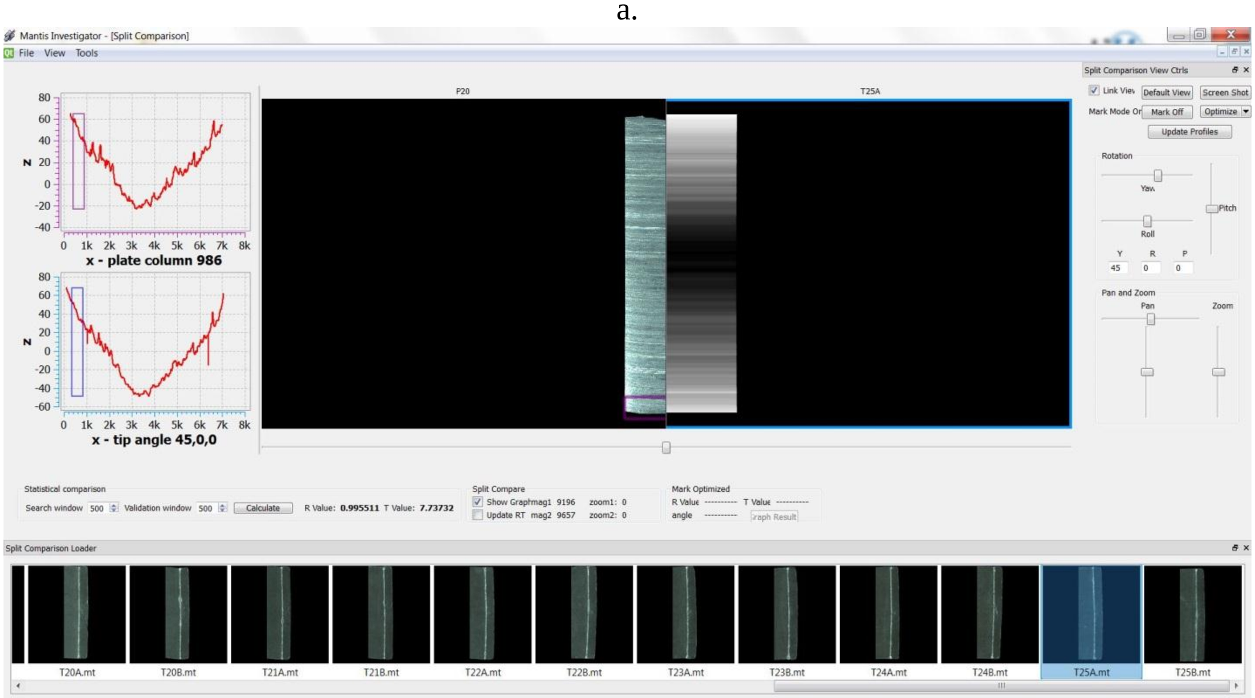
The operator can now choose to compare the two surfaces using the statistical algorithm discussed in section II.6. This is achieved simply by hitting the “calculate” button that appears below the images (arrowed, Fig. 8). Once the operator has selected “calculate,” information related to the objective analysis of the two samples under comparison is displayed in a number of ways. As discussed in Section II.6 the algorithm finds a region of “best fit”. This region is marked on the graphs and on the images by rectangles that correspond to the size of the search window used. The readout of the statistics used (R and T1 values) is calculated and displayed under the image. Figure 9 shows this display at a higher magnification. The size of the search and validation windows can be varied if desired and the statistical information can be selected to continually update as the slider bar below the pictures is moved back and forth.

Figure 9: Close-up of the statistical information available below the comparison window.

Since the prototype also has the ability to acquire data from surfaces that vary greatly in surface profile and roughness, data can be obtained from actual tool surfaces and the examiner may choose to directly compare one tool to another or, perhaps more importantly, a tool to the toolmark it created. An example of this is shown in Figure 10. In this instance a marked plate is compared to the screwdriver tip that generated the plate. The examiner can again carry out a simple visual examination or choose to take advantage of the objective, quantifiable data present in the images to do a statistical analysis. This is accomplished in the following manner.



a.



b.

Figure 10: Comparison of a plate to a) a tool tip and b) the virtual mark generated from that tip. Note that the quantitative measured surfaces match well (as evidenced by the graphical information on the left).

When data is acquired the software requires the user to specify whether they have acquired data from a tool mark or the actual tool itself. Data coming from a tool is quite different than that obtained from a tool mark, being typically much rougher and occurring over a greater variation in height than what is seen for a reasonably flat plate. The different designation for the raw data file alerts Mantis to the fact that this file is from a tool.

For the purposes of proof-of-concept, the prototype was used to characterize some of the set of 50 sequentially manufactured screwdriver tips referred to in Section II.5, creating a small database of tool files (as opposed to toolmark files). When a tool file is opened for comparison to a toolmark file, Mantis, alerted by the different designation to the file takes the raw tool tip data and uses it to generate a virtual surface that, in turn, can be used to generate what is termed a "virtual toolmark". The method by which this is done is discussed in [34, 35]. Briefly, data to generate the virtual toolmark is calculated on the basis of the highest points measured from the tool tip, under the assumption that these points would be creating the mark when in use.

Thus, when comparing a toolmark to an actual tool, the system has resident within the code the objective, quantitative information obtained from the tool itself. This information is used to provide the statistical data shown. In Figure 10a the graphs displayed on the left show the data obtained by measuring the toolmarked surface in comparison to the generated surface obtained from the actual tool by calculating a "virtual toolmark". In the example selected there is an obvious visual relationship between the graphical data obtained from the toolmark and the "virtual toolmark" generated from the actual tool. The operator, if they choose, can run the statistical routine and compare the toolmark to the "virtual toolmark" to see how well the tool matches to the true toolmark. This is done in Figure 10b, which also displays a generated image corresponding to how the calculated "virtual toolmark" might be expected to appear. The results for R and T1 are again displayed, with high T1 values indicating a high likelihood of a match.

There are two important features that must be noted at this point. Firstly, since the generated "virtual toolmark" is calculated based on the measured topography of the tool selected, the statistical analysis remains constant as the slider is moved back and forth across the two images in the comparison window. Secondly, the PIs freely admit that at present the calculated image is a poor representation. The image displayed is just an initial attempt based simply on the measured height of the tool tip in relation to a reference coordinate system. We hope to greatly improve this by generating "photorealistic" marks using advanced computer simulation methods, a project that is the subject of another proposal [38].

Note that the match shown in Figure 10 is only valid because the angle at which the tool tip is viewed and the angle at which the toolmark was created are the same. Examiners have long known and studies have shown [15, 16] that toolmarks must be made within approximately 10 degrees of each other in order to have a reasonable chance of determining identification. It is for this reason the software has incorporated within it an "optimization" routine for toolmarks of this nature. This function allows the angle at which a toolmark was created to be predicted for replication by an examiner if desired.

The optimization process is based on the fact that as the angle of the tool changes new regions on the tool tip will be presented as the highest points that contact a surface and create a toolmark. This, in turn, means that with the creation of a virtual tool, the resulting virtual toolmark will change continually as the angle is changed.

When acquiring quantitative data from the screwdriver tips used for the prototype development, an angle of 45 degrees was used so that information from both surfaces of the tip could be acquired simultaneously. This was done using a small sample jig designed and built at AL/ISU and shown in Figure 11.

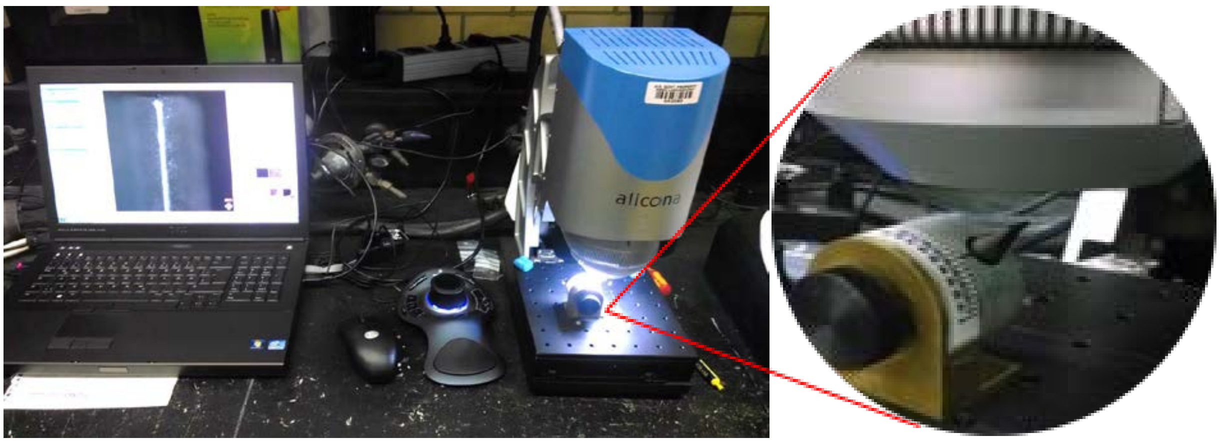


Figure 11: Jig used to acquire quantitative tooltip measurements at 45 degree angle.

Given the excellent performance of the InfiniteFocus SL the quantitative measurements obtained at 45 degrees produced data from both surfaces of each tooltip, i.e. the end of the tool and the sides of the tool. Software developed by PI Song's group and embedded within Mantis allows the 45 degree data to be manipulated to create "virtual toolmarks" at any chosen angle on either side of 45 degrees, from a high of approximately 85 degrees to a low of 20 degrees. At each angle a unique virtual toolmark is calculated using the measured high and low projections that are presented at that angle.

In operation, the examiner selects "Optimize" from the comparison screen (arrowed, upper right in Figure 12) and inputs the starting and ending angular range they wish to explore into the optimization routine, along with the angular spacing between each mark they want examined. In practice the angular spread is set to default to 5 degrees since marks made within that angular range are typically easily identifiable by an examiner as either matching or nonmatching. The routine then starts at one end of the angular range, computes the virtual toolmark, compares the virtual toolmark to the actual mark using the statistical algorithm to determine the T1 value, records this value in a data file, then moves on. Upon completion the parameters pertaining to the virtual mark that best match the actual mark are displayed, along with the ability to graph all of the results. An example of these results is shown in Figure 12.

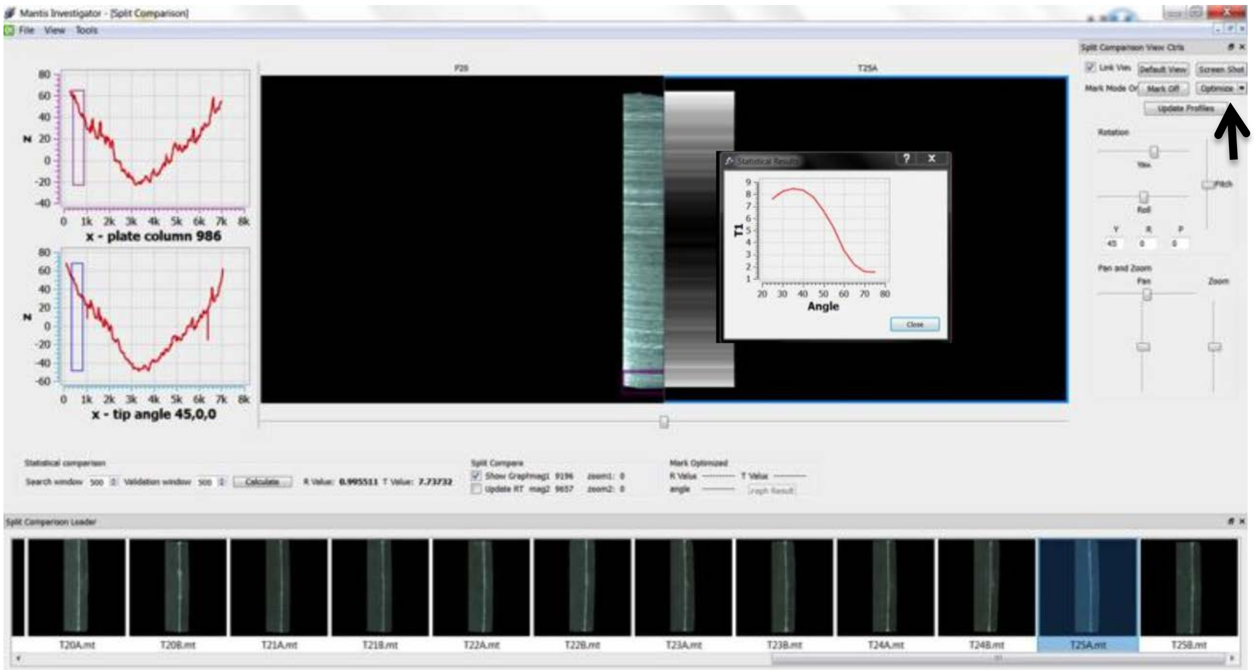


Figure 12: Results of the optimization process are displayed in a popup window. Optimize button is arrowed.

A blind study conducted to see the efficiency of the optimization process was able to correctly identify 20 out of 20 toolmarks to the tips that created them and the angle was predicted to within 10 degrees for all comparisons and within 5 degrees for 16 of the 20 comparisons [32]. It is noteworthy that the routine was able to detect a tip that had been added (without the knowledge of the testers) by the examiner who made the marks since those marks could not be matched to any of the tips in the researchers possession.

4. Performance Testing

As discussed above, all of the initial work regarding development of the prototype was based on fully striated marks as large data sets of these toolmarks had already been studied and were available to the PIs. However, as mentioned in Section II.5 various other data sets have been analyzed and the results detailed in refereed journals [30-32]. Screen shots illustrating the varying nature of the images produced by the system are displayed in Figures 12-15.

Figure 13 shows a comparison of surfaces from wires that had been severed using by-pass pliers. The shear cut surfaces are quite different from the fully striated markings seen in screwdriver drag marks. The prototype was able to effectively acquire the data and carry out the same type of analyses on these markings, although the images appear quite different and the data spread is larger, as detailed in [30-32].

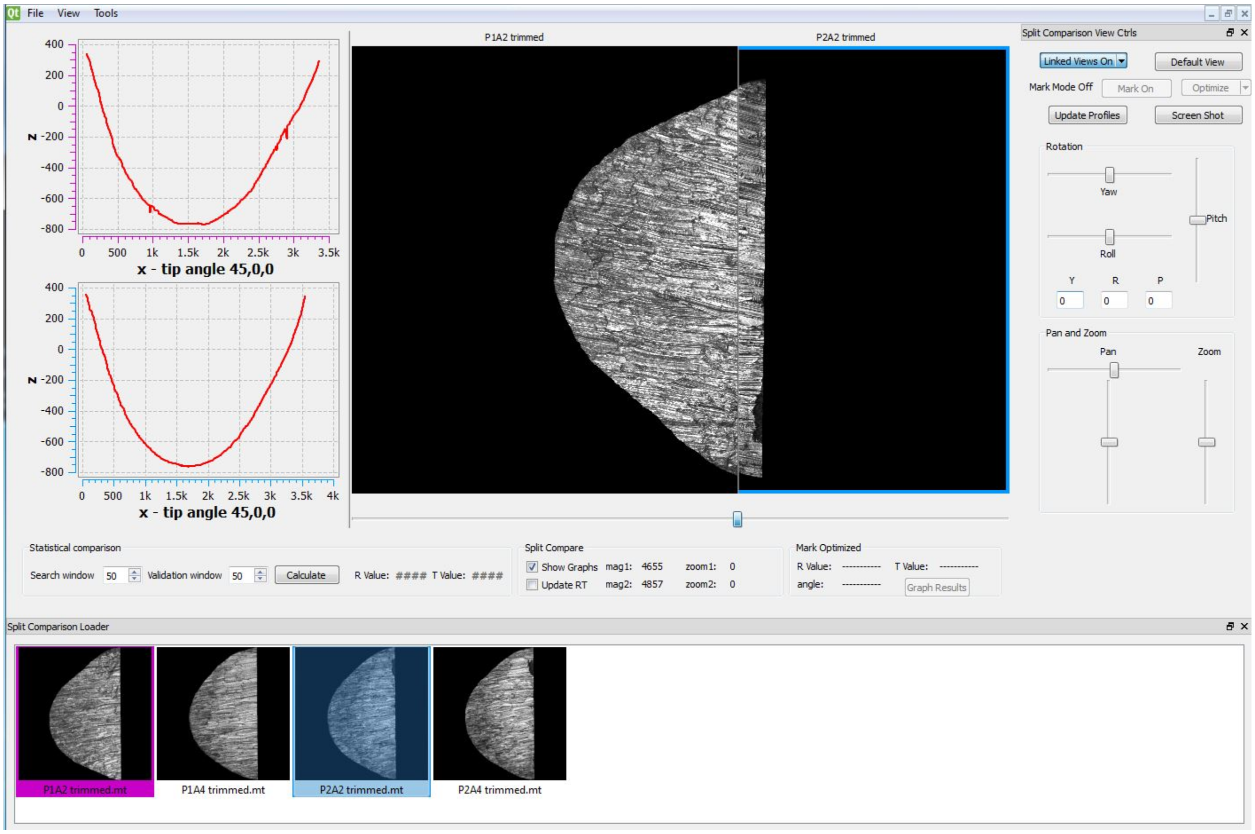


Figure 13: Comparison of plier data. Mark produced on copper wire.

Figure 14 shows a comparison of images obtained from the impression marks of cold chisels. Analysis of data of this type has been detailed in [31]. As for the shear-cut marks the algorithm embedded within the Mantis software was able to compare and identify matches in the data set, although as mark complexity has increased from the fully striated marks performance declines slightly, with wider data spread and more outliers.

Initial data has also been obtained on two different types of advanced marks, those produced from knife blades and from bullets. Samples for data collection were provided by Mr. Aaron Brudenell, who was asked to come and evaluate the system. Neither type of toolmark had been examined previous to Mr. Brudenell’s visit. Figure 15 shows examples of the data acquired from these samples. During the course of the examination it was discovered that the prototype has two issues that need to be addressed, both concerning the acquisition of data at what might be considered as the two extremes of data file size.

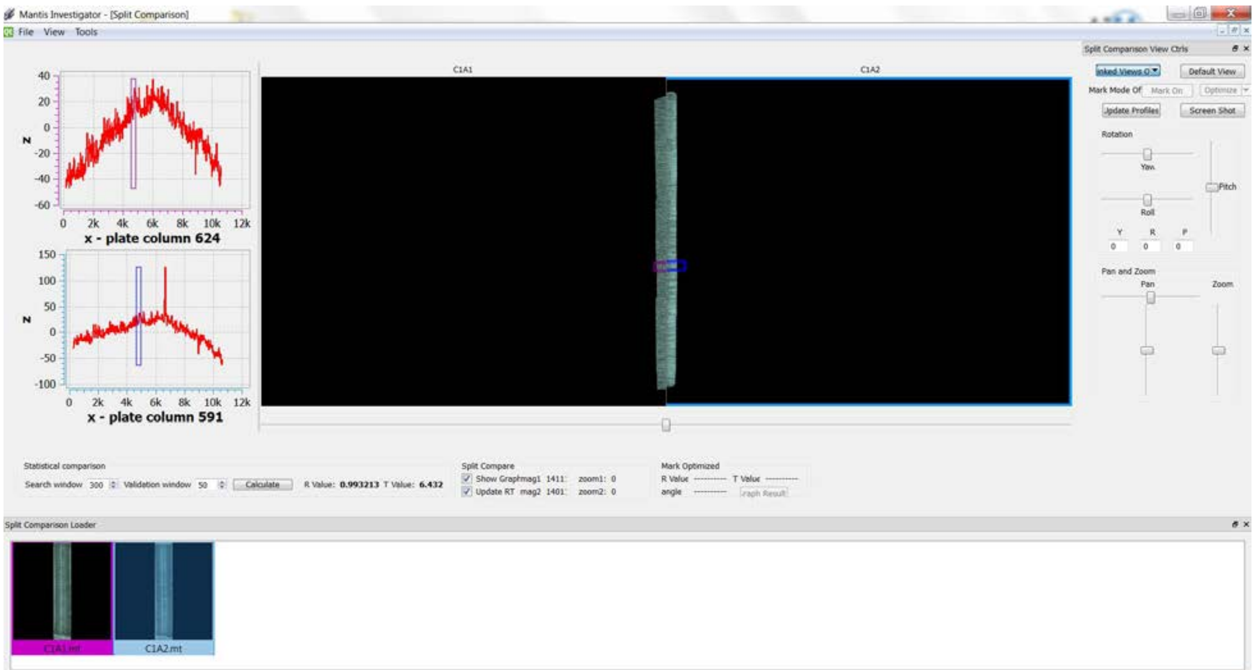
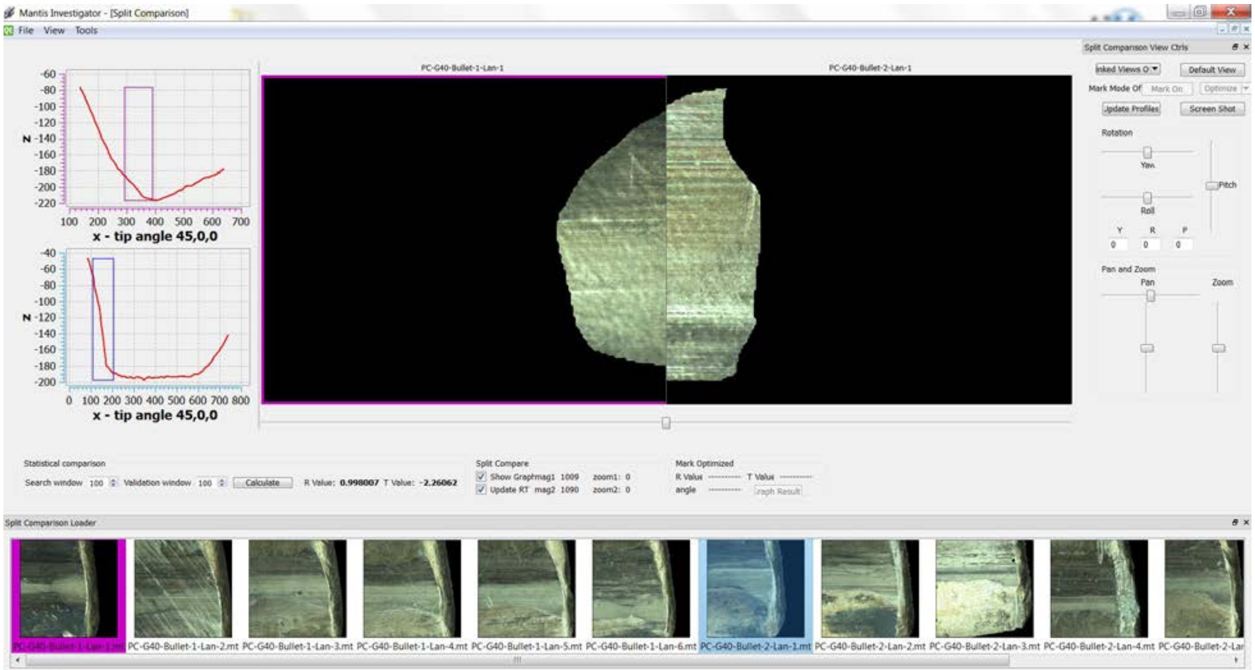


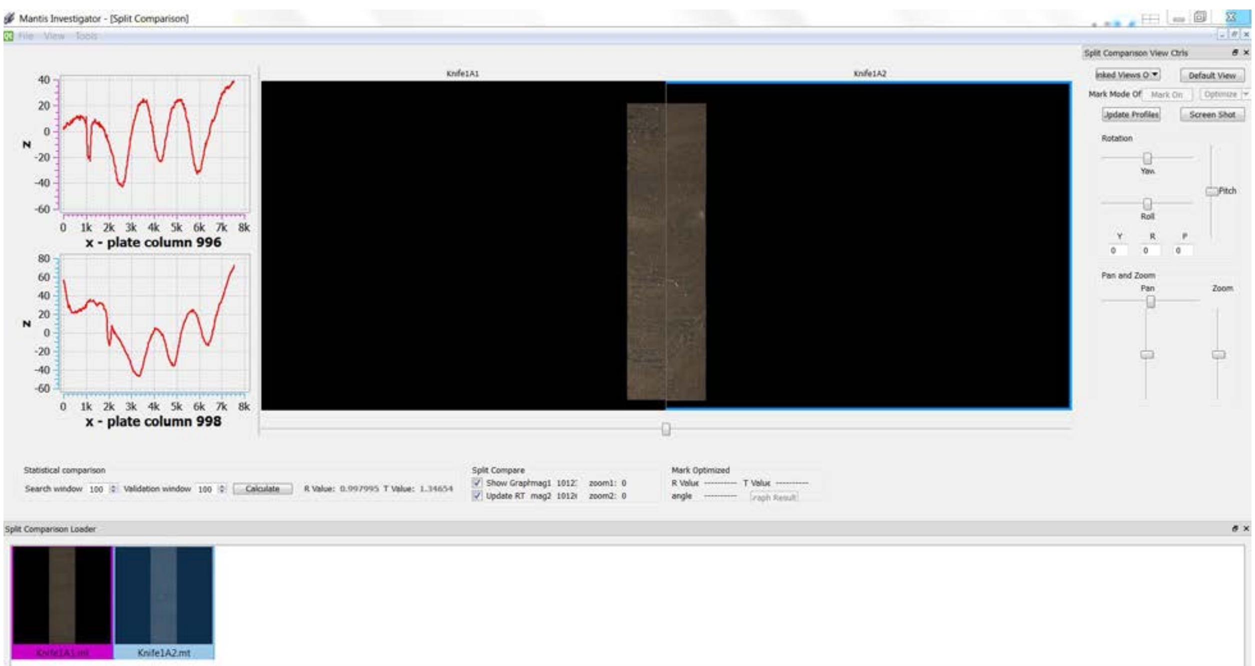
Figure 14: Comparison of impression data obtained from cold chisels. Mark produced on lead.

For our initial attempts on the bullets, Figure 15a, in order to obtain a data file that consisted primarily of parallel striations it was necessary to mask off a large amount of the data acquired from the bullet surface, leaving a fairly small data file. That meant that the amount of data left to actually characterize using the algorithm embedded in Mantis was really small – too small for any meaningful results to be obtained.

On the other end of the data file size range are the toolmarks left by knife cuts (Fig. 15b). These markings were created by pushing the knife through a polymeric material, leaving both class characteristics as well as unique markings. Because of the size of the knife these data files are very large in comparison to those left by screwdrivers or on wire when it is cut. A complete scan of the mark results in a huge data file, which requires considerable computing power to handle. In this case of the prototype system the laptop used essentially gets swamped with data, and processing times go from a few seconds to several minutes. The scans obtained from these marks consist of fine striae overlaid with the course class characteristics of the knife edge. Initial attempts on these markings reveal that the current algorithm requires addition of a better way to discriminate class characteristics, and a proposal to further develop algorithms to extend application of Mantis to other types of complex toolmarks such as knife marks is under consideration.



a.



b.

Figure 15: a) Cleaned and masked data obtained from the bullets shown in Fig. 7. Only the striae are being compared. b) Comparison of two knife cuts made through rubber molding compound.

The system was also examined by Dr. James Hamby, who provided valuable feedback and insight. Suggestions by Dr. Hamby include presenting the results at upcoming AFTE conferences and training seminars and expanding the use of the instrument by incorporation of a rotating stage to allow for acquisition of data from bullet samples. The PIs hope to accomplish both of these suggestions. Dr. Hamby was also interested in the “virtual toolmark” capabilities and felt that this was an excellent idea worth pursuing.

IV. Conclusions

1. Discussion of Findings

The overarching goal of this study was to determine the feasibility of developing a portable, semi-automated system for characterizing and analyzing toolmarks that could be used for conducting objective, quantitative studies. The PI’s feel the data and results outlined in this report and the papers published using the system developed clearly support our contention that this goal has been achieved to a large extent. The results obtained through various studies also lend credence to the primary assumption made in many forensic investigations, namely, that all tools leave unique marks.

From the studies conducted the following conclusions can be drawn:

1. The small, portable, optical system obtained from Alicona GmbH and used for the prototype can obtain excellent data from extremely variable surfaces in a fraction of the time of previous optical systems. The microscope and the laptop computer used for control can be packed, ready for transport within 20-30 minutes and deployed in as little as 15 minutes.
2. The optical system has been shown to be flexible enough to obtained data from individual bullet lans even though the sample surface is curved substantially.

3. Mantis, the application suite of software developed for the prototype, has reached a high degree of functionality. Although further improvements are warranted, currently the system allows the examiner to obtain objective data from samples and then conduct simple comparisons, statistical comparisons, and automated comparisons that involve the creation of a “virtual tool” from acquired data.

4. Application of the system to striated and quasi-striated toolmarked surfaces has allowed the statistical algorithm used for objective comparisons of toolmarks to be optimized using contextual information to obtain better results.

5. Application of the statistical algorithm to a variety of samples has had mixed results. Extremely good results have still been obtained on from fully striated toolmarks produced by screwdrivers [32], quasi-striated toolmarks produced from by-pass cut pliers [30], and impression marks produced from cold chisels [31]. However, as toolmark complexity has increased data scatter is seen to increase, as well as the number of outliers. Application of the algorithm to complex markings such as bullet marks and knife cuts has resulted in the identification of new problems and challenges that must be addressed.

6. Given the above results it is apparent that additional algorithms will need to be developed to handle specific toolmark types. Extremely small toolmarked regions may need higher resolution

scanning to produce data files with enough information for discrimination. Extremely large data files will need additional routines incorporated to remove class characteristics and data compression routines to provide files manageable in size.

7. The open source-code nature of the prototype as developed should allow new algorithms to be incorporated into Mantis, the operating software of the system.

2. Implications for Policy and Practice

This project could potentially have enormous implications in the field of comparative examinations if it can gain acceptance both by practicing forensic examiners and researchers working in the area of objective analysis. Work at AL/ISU has shown that objective measurements made impartially by computer analysis lead to the same conclusions held by forensic examiners [15]. Further improvement of the developed software and integration of the analysis routines into a working prototype model will show that objective, non-partisan, systems as called for by the recent NAS study [1] are not only possible but practical. The preliminary data provided by using the system to study different types of toolmarks will enable the construction of a second-generation system that is optimized for forensic examinations.

Research in progress suggests that in order to produce judgments with known probabilities of errors produced, examiners will be forced to expand the number of comparisons in order to establish baseline criteria for determining the validity of any match produced by the prototype. Automation of the comparison and analysis of the comparison methodology will certainly speed this process. However, it is becoming increasingly clear to the PIs that the role of a forensic examiner will become even more important. In addition to being conversant with the various types of toolmarks and the manner by which replicates are made for comparison, examiners should also be aware of the instrument itself and the factors that are crucial for obtaining reliable data. This points to increased training for examiners.

Successful development and implementation of the proposed project might also lead to a requirement for additional forensic examiners. This requirement would not be based on greater time required to do a comparison, but rather on an increased emphasis on the value of comparative evidence if it becomes clear the results provided are objective and valid. In the same manner that the success of DNA evidence has in many cases caused an expansion of those sections of forensic laboratories that deal with such evidence, the success of objective, automated forensic toolmark comparisons might cause this type of evidence to become more desirable, requiring a greater workforce to accomplish the increased load.

Should the methodology prove viable for a wide spectrum of tool marks the question then comes as to the cost of system implementation. While the cost of the prototype is still expected to be substantial, it is noteworthy to consider that the cost for construction dropped 1/3 in a single year, and is approximately 1/5 of the estimated cost of an IBIS system. The PIs believe that the costs can be kept sufficiently low so as not to preclude widespread implementation and that a stripped down, workable system as we envision might eventually be produced for significantly less than the cost of the prototype, and only a fraction of the cost of an IBIS system.

3. Implications for Further Research

The research already conducted using the prototype has pointed out the need for continued work in two distinct areas, namely, continued efforts to increase the flexibility and applicability of the prototype operating system itself and continued development of statistical algorithms for the analysis of complex toolmarks. Specifics concerning these two areas will be briefly addressed in turn.

Improvements to Mantis

At this time the PIs feel Mantis is really still in its infancy as regards possible uses and capabilities. Further improvements are needed in order to produce a fully functional, robust unit. The suggested improvements fall naturally into two categories:

> Area 1: Enhancement of existing software to provide additional capabilities, and increase flexibility.
> Area 2: Advancement of the entire system to include the capture of cylindrical objects (e.g. bullets).

Area 1 really relates to the desire to more fully incorporate the Alicona software into the Mantis suite to increase ease of use. Ideally, the desire is to have the Mantis software control the Alicona software so that only one software package needs to be opened. Alicona offers technical assistance to clients that use their products to do such things and the PIs suggest that enhancement of the Mantis software (with help from Alicona) to obtain this desired control is a logical step.

Area 2 involves research both at AL/ISU and elsewhere to increase in order to advance the capabilities of the prototype system we see two needs that currently exist, namely:

- Active solicitation of additional statistical algorithms from researchers to include in the prototype for testing.
- Expansion of the system into areas involving curved surfaces, e.g. bullets.

Under the first bullet, the PIs seek closer working relationships with other researchers in the field of toolmark analysis to obtain and adapt their algorithms into the operating software of Mantis. What is envisioned is that when an examiner chooses analyze their data they will have available different statistical algorithms they can utilize for their comparisons. While the actual interface seen by the examiner will remain the same, the “calculate” button would become a drop-down menu using, for example, “Using algorithm A, using algorithm B” etc. Incorporation of a feature such as this would involve i) acquiring algorithms developed by other researchers and ii) porting their software (with their permission of course) into the Mantis code.

While the plans discussed above will certainly advance the state-of-the-art of the system, the second bullet point above would expansion of the capabilities of the prototype by expanding into the characterization of samples with circular profiles, such as the circumference of a bullet. Alicona manufactures a motorized, rotating stage suitable for measurements such as these. An image of a stage from their promotional literature is shown in Figure 16. The stage is coupled with their acquisition software to allow the acquired cylindrical data to be displayed and analyzed as if it were a conventional plot of Z height vs X and Y location. While some additional fittings may need to be manufactured or purchased to accommodate bullets, the stage is expected to allow expansion of the prototype system into the field of firearms.

Figure 16: Alicona rotating stage (from promotional literature).

Expansion into the field of firearms will greatly strengthen the utility and appeal of the prototype system. Acquisition of data using the rotating stage will allow algorithms currently developed for toolmarks to be tested using the striated patterns produced on bullets. Numerous tests involving sequentially manufactured firearms and sequentially fired bullets are immediately available for characterization and analysis.

Development of Statistical Algorithms

The PIs have realized that as toolmark complexity increases algorithm performance decreases [30, 31], pointing toward continued research in the development of statistical algorithms for analysis. It is for this reason that Mantis was always designed using non-proprietary software, to allow researcher and developers to continue to experiment and use the system employing different routines for analysis. For example, while the IBIS system uses some type of sorting protocol to match data files associated with primer strikes, the software is proprietary (preventing further development by independent researchers) as pointed out by the NRC study [20].

One method that has been proposed is the congruent matching cells method [36]. This approach might be suitable for comparing areal surface marks that are not necessarily striated. It is designed to focus on similarities between relatively small sub-areas, as well as the similarities in distances and relative angles among such sub-areas. The intent of this approach is that the small-area characteristics represent individual-, rather than class-, characteristics, and that all corresponding sub-areas need not match well (due to imperfect tool contact in some sub-areas, et cetera) for true matches. While such an approach has promise, it is still a "black box" method in the sense that particular mark and surface characteristics (e.g. sheer deformation) are not taken into account. Regardless, research into this method for incorporation into Mantis is of interest.

The PIs do have considerable experience in dealing with more complex markings. In addition to the cited work on quasi-striated marks PI Morris conducted research in the early 2000's, described in Baldwin et al [26], in developing algorithms – in some ways similar to the more recently developed congruent matching cells methodology - that can determine whether two digital images of machined surfaces are actually representations of the same surface. Based on this work the PIs currently have a proposal under consideration [39] that would use a geometrically informed zonal matching model – nicknamed "Gizmmo" – to register and compare small 3D areas from two toolmarks using an internal validation method to establish significance.

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VI. Dissemination of Research Findings

Dissemination of the results of this project has already occurred to a certain extent by the publishing of the following papers, which were based on data taken using the system:

R. Spotts, L. S. Chumbley, J. Kreiser, L. Ekstrand, S. Zhang, “Optimization of a Statistical Algorithm for Objective Comparison of Toolmarks,” J. For. Sci., 60, 2 pp 303-314, March 2015.

R. Spotts, L.S. Chumbley, L. Ekstrand, S. Zhang, J. Kreiser, “Angular Determination of Toolmarks using a Computer Generated Virtual Tool”, J. For. Sci., 60, 4, pp 878-884, July 2015.

R. Spotts, L. S. Chumbley, "Objective Analysis of Impressed Chisel Toolmarks,” accepted, J. For. Sci.

These papers became part of the Master’s Thesis presented by Mr. Ryan Spotts entitled: “Objective forensic analysis of striated, quasi-striated and impressed toolmarks,” Iowa State University, 2014.

An additional paper has been prepared entitled: “Development of a Mobile, Automated Tool Mark Characterization / Comparison System,” which discusses the prototype hardware and details the development of Mantis, the software interface used by the prototype. Much of the Executive Summary of this document is taken from this paper. This paper has been accepted by Journal of Forensic Science.

Presentations that have already been given where results obtained using the system were discussed include:

R. Spotts, L.S. Chumbley, L. Ekstrand, S. Zhang, "Blind Study Comparison of Virtual Marks to Toolmarks", AFTE, Seattle, May 2014.

A description of the system and the current status was given by Chad Macziewski at a meeting in Washington, D.C. of the NIST optical topography for ballistics working group.

L.S. Chumbley, "MANTIS: Portable Prototype System for Toolmark Research," NIJ Grantees meeting, AAFS, Las Vegas, February, 2016.

Plans are to attend the Association of Firearms and Tool Mark Examiners (AFTE) training seminar, DoJ sponsored training and informational events (e.g. Impression Evidence and Trace Evidence symposiums) when time and funds permit. Additional papers will be submitted to the Journal of Forensic Science, the AFTE journal, Technometrics, and other relevant publications.