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PAPER

CRIMINALISTICS

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Development of a Mobile Toolmark Characterization/Comparison System

ABSTRACT: Since the development of the striagraph, various attempts have been made to enhance forensic investigation through the use of measuring and imaging equipment. This study describes the development of a prototype system employing an easy-to-use software interface designed to provide forensic examiners with the ability to measure topography of a toolmarked surface and then conduct various comparisons using a statistical algorithm. Acquisition of the data is carried out using a portable 3D optical profilometer, and comparison of the resulting data files is made using software named "MANTIS" (Mark and Tool Inspection Suite). The system has been tested on laboratory-produced markings that include fully striated marks (e.g., screwdriver markings), quasistriated markings produced by shear-cut pliers, impression marks left by chisels, rifling marks on bullets, and cut marks produced by knives. Using the system, an examiner has the potential to (i) visually compare two toolmarked surfaces in a manner similar to a comparison microscope and (ii) use the quantitative information embedded within the acquired data to obtain an objective statistical comparison of the data files. This study shows that, based on the results from laboratory samples, the system has great potential for aiding examiners in conducting comparisons of toolmarks.

KEYWORDS: forensic science, toolmarks, portable prototype, quantitative measurements, statistical comparisons, optical profilometer

In recent years the field of toolmark 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 (1–4) (see foot note 1). These charges come despite the existence of research studies aimed at establishing the applicability and science of comparative examination (5–7) systems. Such studies have resulted in the development of objective methods of analysis (7,8) and systems (9,10) (see foot note 2), that enable objective measurements based on sound scientific principles to support 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 (7,11); however, it has also been noted that (i) objective automated systems cannot perform to the same level of accuracy as human examiners and in their current state of development are not expected to and (ii) algorithms developed and optimized for analysis of one type of toolmark do not perform equally well when employed on other types of toolmarks (12,13) (see foot note 3). 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 widespread acceptance.

For the past several years, researchers at Ames Laboratory/Iowa State University (AL/ISU) have been involved in 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 toolmarked 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 3D optical profilometer manufactured by Alicona GmbH (see foot note 4). This device was selected as it allows noncontact acquisition of data from both flat and curved surfaces but also provides

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[1]http://www.Innocenceproject.org (accessed March 1, 2016).
[2]http://firearmsid.com/A_historyoffirearmsID.htm (accessed March 1, 2016).

[3]Baldwin D, Morris M, Bajic S, Zhou Z, Kreiser MJ. Statistical tools for forensic analysis of toolmarks. Ames Laboratory, US DOE; 2004 Report No.: IS-5160; http://www.osti.gov/scitech/servlets/purl/825030. (last accessed March 1, 2016).
[4]http://www.alicona.com/home/ (accessed March 1, 2016).

excellent data from steep sided samples such as the end of a screwdriver.

Comparison of resulting data files is made in an objective manner using developed software algorithms detailed in Refs (7,12). While efforts continue to further develop and refine statistical algorithms suitable for the comparison of a wide range of toolmarks, currently samples that have been characterized and evaluated with a high degree of success include fully striated marks such as those produced by screwdrivers (7), quasistriated markings produced by shear-cut pliers (12), and impressed chisel marks (13). Initial testing on rifling marks left on fired bullets and cut marks produced by knives has also been carried out (14), and research on these types of marks is continuing.

The purpose of the study was to describe the current status of the system, outline its operation and current capabilities, and invite other researchers to develop additional statistical algorithms that might be adapted for use by the prototype.

Methods

The equipment around which the prototype is based was obtained from Alicona GmbH and is shown in Fig. 1. The basic system consists of an optical profilometer (Fig. 1*a*) that operates on the principle of focus optimization. The system is small enough to be portable, is lightweight, and can be packed into a medium-sized hard-shell traveling case (Fig. 1*b*). Despite the size, the optical head still offers outstanding performance, typical parameters used producing a complete scan in 1–2 min 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 (see foot note 4).

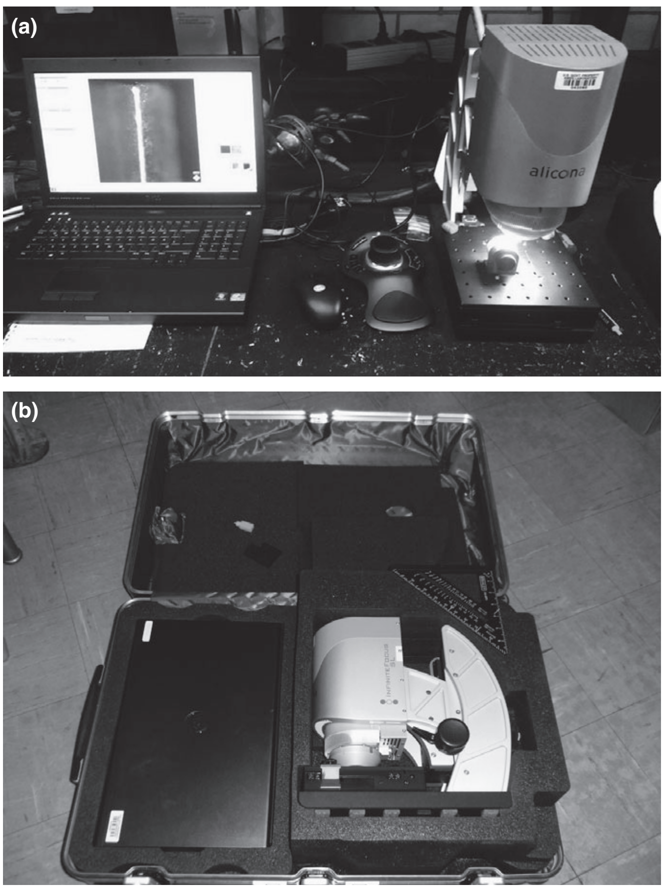

FIG. 1—*(a) Prototype hardware showing the optical head (right) and the controlling laptop (left). (b) Hardware and laptop packed into travel case.*

Control of the hardware is accomplished using a modified version of Alicona's system software (Fig. 2). 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 contains a simplified tutorial that can be referred to when setting up the initial scan of the data.

Once data has been acquired it can then be compared and characterized using the software suite currently under development at AL/ISU termed MANTIS, for Manipulative Toolmark Inspection Suite. The MANTIS software is written in C++ and makes use of open-source libraries and the following software: Open GL and a graphical processing unit to produce virtual marks of tools at any given angle and resolution and to visualize geometric data on the screen; QT to create the graphical user interface (GUI); and Java to interact with computers through command lines. While development of the basic software, consisting of the cleaning and data analysis routines, was carried out at AL/ISU (7,12,15,16), transforming the initial code into a more user-friendly interface was achieved by working with Chris Hanson and Brian Bailey (Alphapixel, Evergreen, CO). A screenshot of the startup screen of the analysis suite is shown in Fig. 2*b*. Currently, using the software an examiner can (i) clean raw data files obtained using the Alicona hardware, (ii) compare the cleaned toolmark files in a manner similar to a comparison microscope, (iii) obtain objective statistical evaluation of comparisons made between those data files, and (iv) elucidate factors that existed when certain types of toolmarks were made, for example, angle of the tool.

Results

As stated above, currently the raw data are obtained and saved initially using the Alicona software and then 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, and then display the data for visual comparisons or statistical analyses. The software contains the functions and routines developed at AL/ISU embedded in an intuitive, user-friendly interface. The performance of the embedded statistical algorithm when used to analyze different types of toolmarks has been documented previously (7,12,13,17), and data cleaning has been described in Refs (15,16). Briefly, data cleaning involves removal of minor imperfections due to random scattering from the surface (which appears as either holes or spikes in the data). These are removed based on a filtering routine. As described in Refs (15,16), holes are filled by analyzing the surface of the valid regions surrounding the holes, while spikes are reduced to a reasonable value, again based on analysis of the immediate surroundings. The number of holes and spikes that must be filtered has always been very small and holes and spikes are relatively rare in the latest Alicona system used for the prototype. A detrending routine removes the slight slope associated with all raw measured data, rendering the surface to be analyzed flat.

Actual operation of MANTIS consists of selecting the appropriate area for analysis by masking unwanted areas followed by choosing the method of comparison desired. As the acquisition

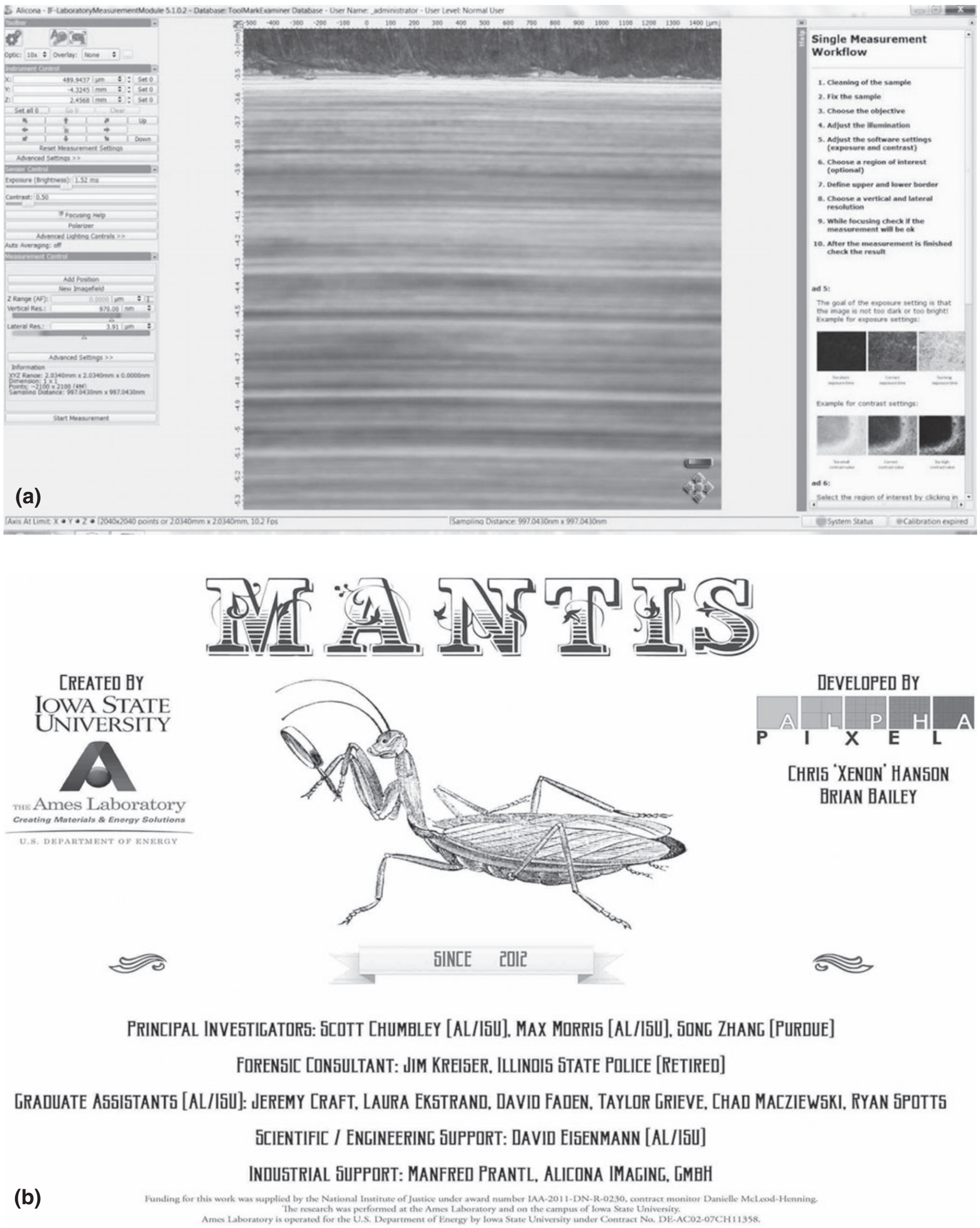

FIG. 2—*(a) Screenshot of modified Alicona acquisition software. (b) Mantis startup screen.*

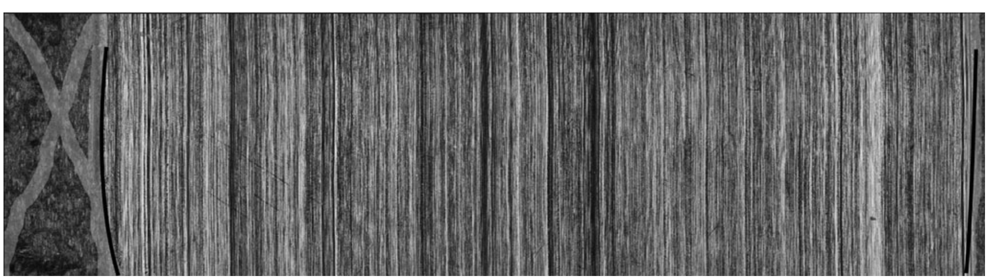

FIG. 3—*Masking of undesired data. Masking is achieved by "painting" the data to be ignored with a translucent color on the computer screen. The left and right sides of the scan will not be considered in the subsequent analysis. The approximate position of the painted band is delineated using a black line. The translucent mark is seen at the top of each black line and most clearly as the "X" on the left side.*

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. This is illustrated in Fig. 3, which shows data obtained from a screwdriver mark. In this example, the scan overlapped the mark to include the unmarked lead substrate on either side of the desired impression. The undesired parts have been marked for removal using a simple script. Options provided in the script give maximum flexibility when using the masking tool.

Data analyses available in MANTIS consist of a number of options including simple visual comparisons, visual and graphical comparisons, objective comparisons using the statistical algorithm, and the ability to generate virtual toolmarks and predict conditions that existed when a toolmark was created using a given tool.

Simple Visual Examination

Figure 4 shows an example of the simplest option, 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 together or unlinked for individual translations. A slider bar at the bottom of the image allows the examiner to move the hairline back and forth across the samples, analogous to the comparison microscope. A continuous zoom is provided to alter the magnification, again either in a linked manner or individually.

Visual and Graphical Examination

Although the files appear as optical images when opened in MANTIS, due to the method of acquisition the images seen by the viewer contain quantitative information. Thus, in addition to looking at the images the examiner, if they choose, can look at graphs displaying the quantitative measurements of the surface roughness of the samples. This is achieved by simply hitting the "Show Graphs" radio button below the images. As illustrated in Fig. 5, when this option is selected, the two large visual panes containing the images for comparison are reduced in size (basically, this simply eliminates some of the black region at the sides of the images) and a new window opens showing the graphical results of the quantitative data resident in the file. The displayed graphs are color-coded with the visual panes for easy identification, and the profiles displayed relate to the position of the hairline controlled by the slider bar. As the bar is moved back and forth across the images, the graphs continually update showing the data at that hairline location.

Objective Comparison using Statistical Algorithm

The operator can choose to compare the two surfaces using the statistical algorithm embedded in MANTIS simply by hitting the "calculate" button that appears below the images (Fig. 5). This implements the statistical algorithm described in Refs (7,12) resulting in the display of several types of information. As described in Ref. (7), the algorithm works by first identifying a region of "best fit" for the operator-defined search window and then compares the results obtained to a number of validation windows that are also user-defined. The size of the search and validation windows can be set using the buttons located below the graphs (left-hand side of Fig. 5), and once "calculate" is pressed, the search window of best fit is displayed as rectangles both on the graphs and on the visual images. At the same time the statistical information related to the objective analysis of the two samples, namely the *R* and T1 values, is displayed under the images. The size of the search and validation windows can be varied if desired and the statistical information recalculated again if desired. If the "Update RT" button is selected, the statistical information will continually update as the hairline is moved back and forth across the images, reflecting the objective, 3D data that exist in the data files at that particular hairline location.

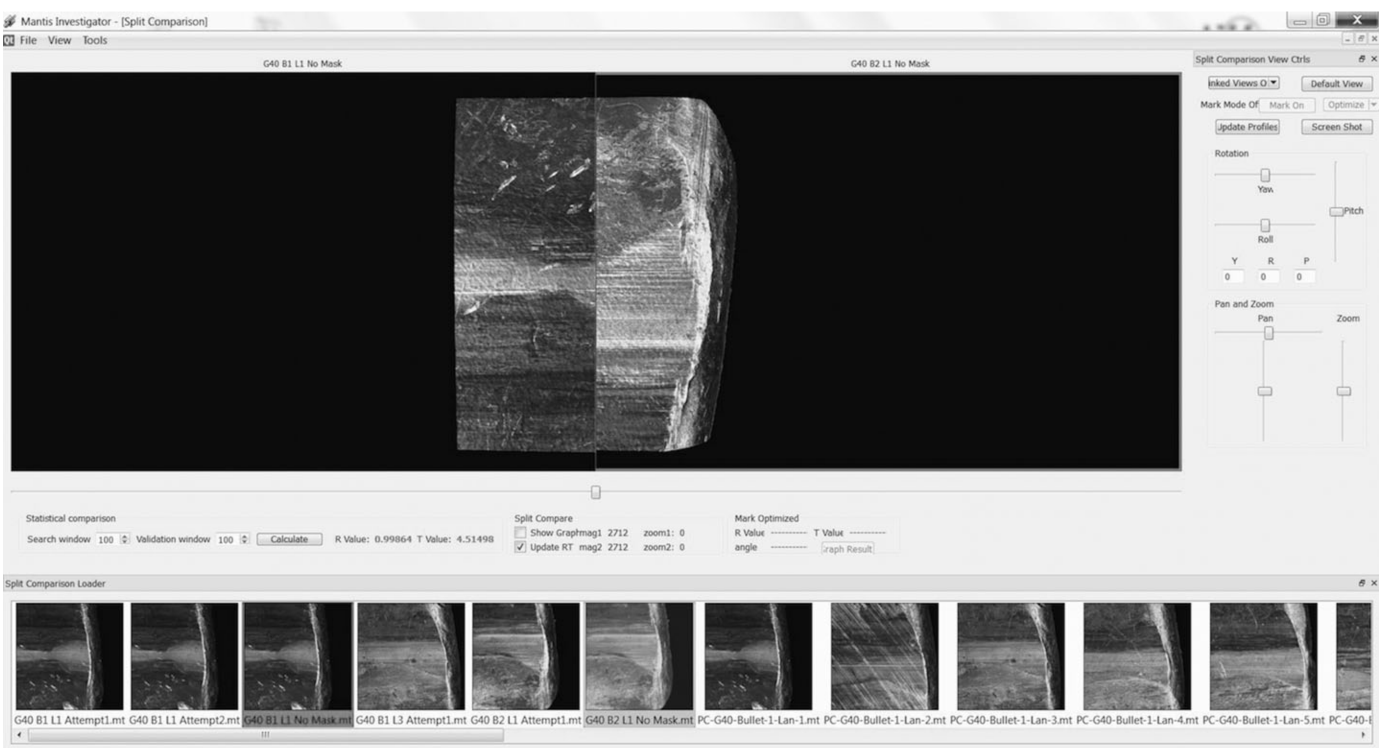

FIG. 4—*Simple visual comparison. Two separately acquired data files from a fired bullet are compared, separated by the hairline.*

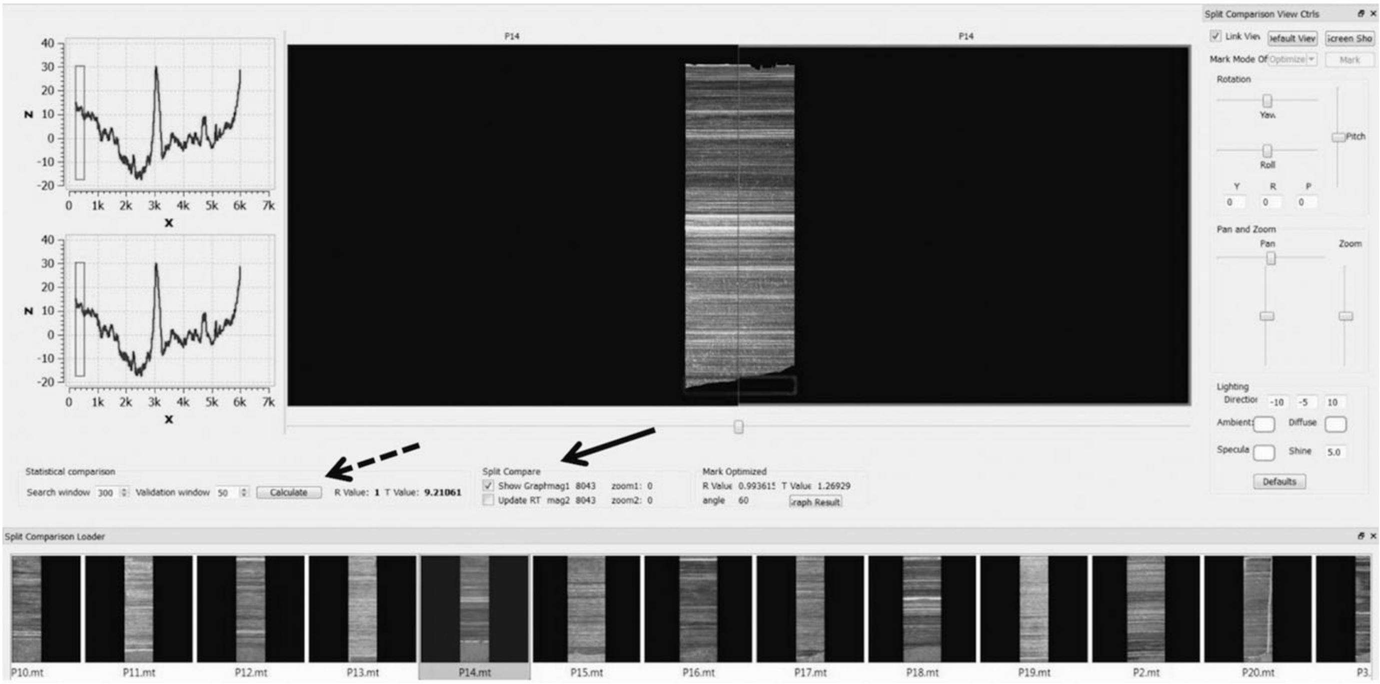

FIG. 5—*Comparison screen of prototype under development showing matching comparison with graphs and statistics displayed. "Show graphs" and "calculate" options are indicated using solid and dashed arrows, respectively.*

Virtual Toolmarks/Tool Angle Analysis

The ability of the Alicona system to acquire data from surfaces that vary greatly in surface profile and roughness presents the examiner with comparison possibilities unique to the prototype system. For example, an examiner can conduct a simple, direct visual comparison of a toolmark to the tool used to create that mark. This is illustrated in Fig. 6 where the end of a screwdriver is compared to a toolmark created by that screwdriver. For an examination such as this, the tooltip was placed at a 45 degree angle so that information from the end of the screwdriver and one of the sides could be obtained simultaneously with one scan. Note that the screwdriver tip can be rotated back and forth using the pitch, rotation, and roll controls (e.g., right-hand side of Fig. 6*a*) to allow the examiner to inspect various regions on the tip that may have produced the resultant toolmark.

With the measured data from the tooltip in hand, it is possible to reconstruct the surface of the tooltip and create a "virtual tool" within the computer that can in turn be used to create "virtual toolmarks" (18). The basic assumption is that when a toolmark is made by a tool, the highest points projecting out from the tool will logically be the first to contact the tool surface. On this basis, a coordinate system can be established from the measured tooltip data, the surface topography determined and inverted, and the results displayed on a flat surface as a first approximation to the expected toolmark topography. What makes this analysis so unique is that the "virtual tool" generated by a single measurement taken at 45 degrees can now be manipulated and the highest points at any given angle can be recomputed and a new "virtual toolmark" calculated for essentially any angle. This virtual toolmark then can be compared to a real toolmark using the same statistical analysis already discussed, and an example of this is shown in Fig. 6*b*. By analyzing the results of comparisons between a real toolmark and a series of "virtual toolmarks" made at varying angles, the angle at which the actual mark was made can be determined.

A blind study to test the above hypothesis was carried out involving data obtained from actual screwdriver tips and toolmarked surfaces marked by those same tips (17). Briefly, twenty different comparisons of tooltips to toolmarked surfaces made by Mr. James Kreiser, a retired forensic examiner, were compared using the prototype system. The marks provided by Mr. Kreiser were made using a jig to fix the angle of attack of the screwdriver, and Mr. Kreiser inserted an additional screwdriver tip unknown to the investigators at Ames Lab/ISU as an additional test. Although the relationship between the tools and toolmarks was unknown to the authors, the prototype system running the MANTIS software was able to correctly identify the tools used to make the 20 toolmarks examined, the additional screwdriver being identified by exclusion. In addition, the fixed angles used by Mr. Kreiser in making the toolmarks were correctly predicted to within 10 degrees for all comparisons and to within 5 degrees for 16 of the 20.

Automated Angle Prediction

The ability to generate "virtual toolmarks" at essentially any angle provides the user of the MANTIS system with another unique capability. The software has incorporated within it an optimization routine that allows automatic comparison of a series of virtual toolmarks to an actual toolmark. In operation, the examiner selects "Optimize" from the comparison screen (upper right in Fig. 6*b*) and inputs the starting and ending angular range they wish to explore, along with the angular spacing between each mark they want examined, with a 5 degree variation set as default because marks made within that angular range are typically easily identifiable by an examiner as either

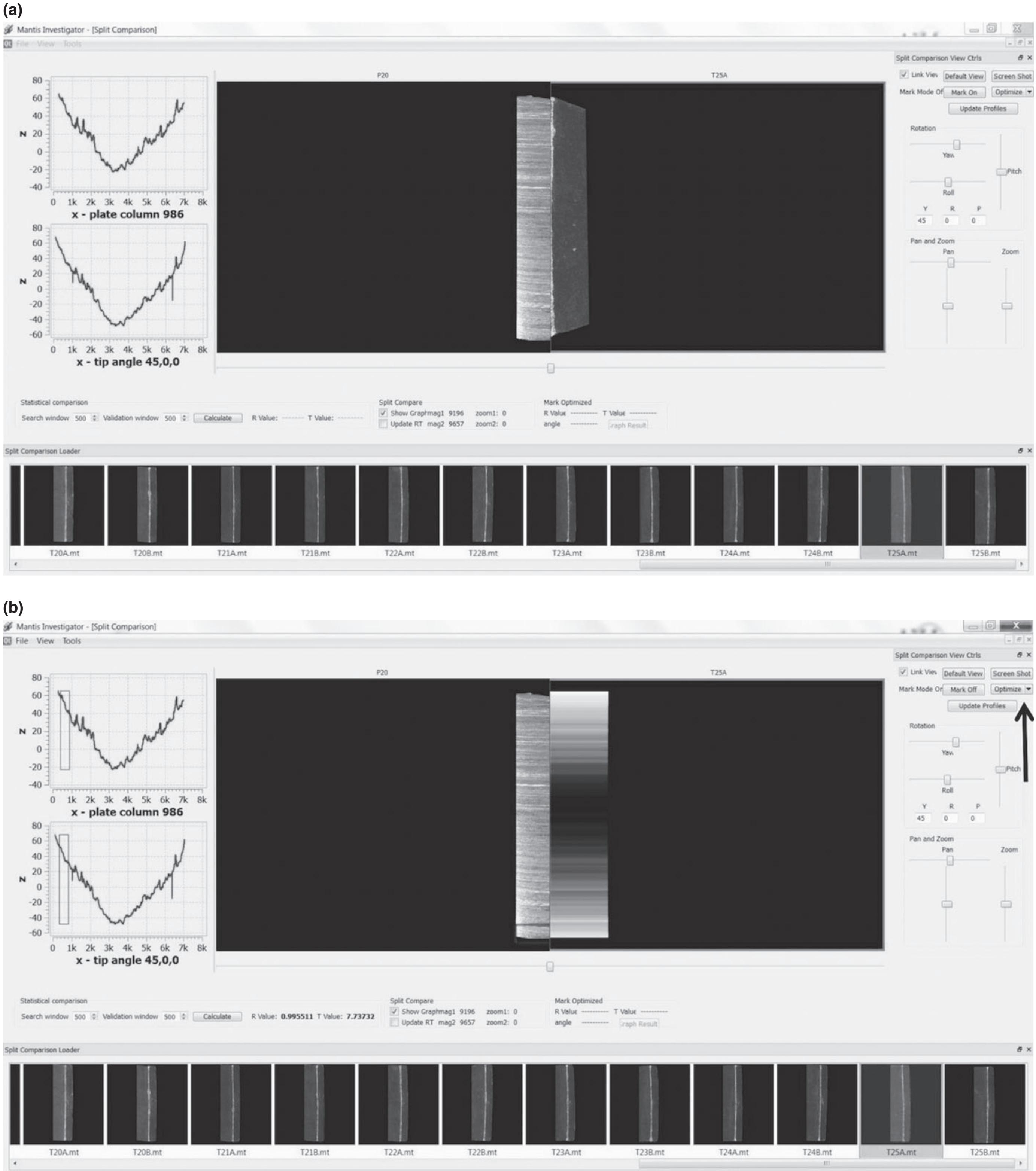

FIG. 6—*(a) Comparison of a plate to a tool. The tool is the tip of a screwdriver, angled at 45° with respect to the viewer. The edge responsible for creating the toolmark is aligned with the mark itself. The mark (left) and the tool tip (right) are separated by the hairline. (b) A toolmark compared to the virtual mark generated from that tip, separated by the hairline. The optimize button for automatic angular determination is arrowed.*

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 the results is shown in Fig. 7.

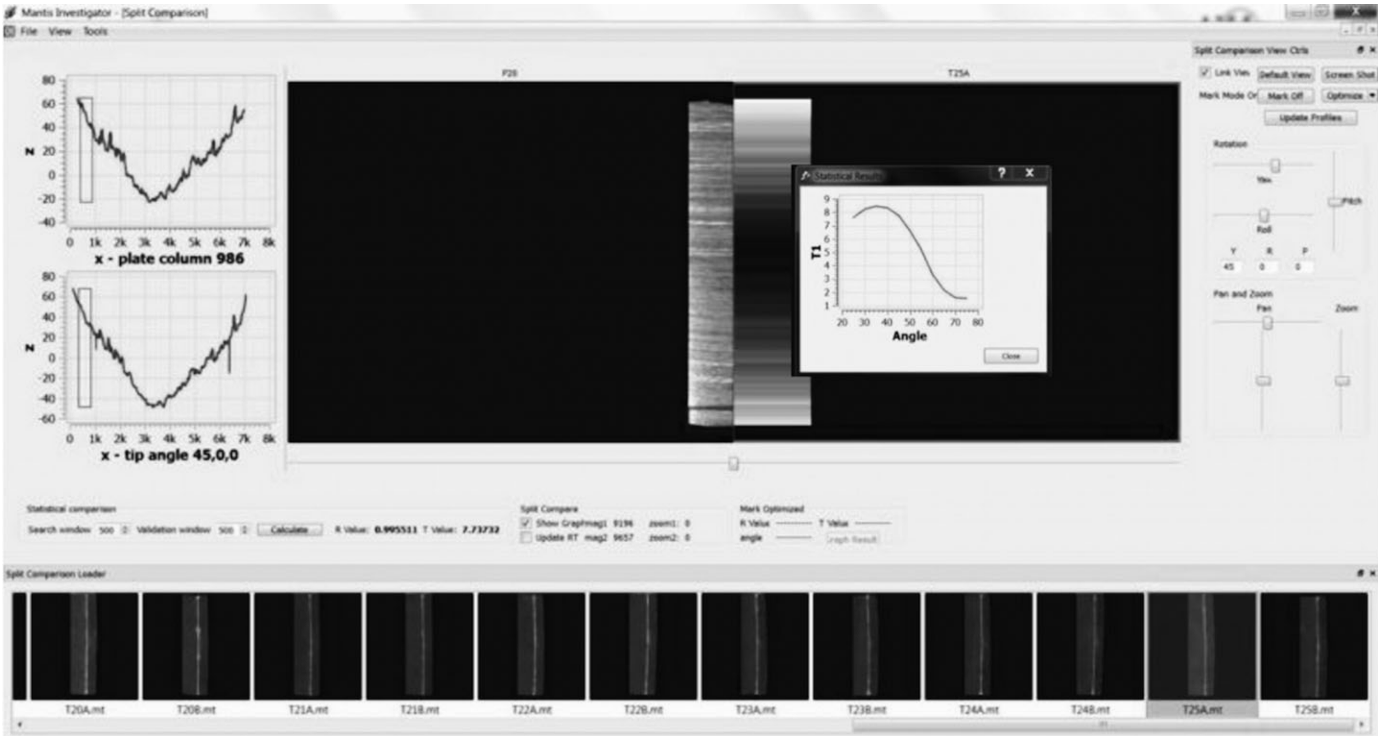

FIG. 7—*Results of the optimization process, used for comparing the real mark to the virtual mark in Fig. 6*b*, displayed in a pop-up window.*

Complex Toolmarks

Screenshots illustrating the varying nature of the images produced by the system are displayed in Fig. 8. At this time, the system has been used to image shear-cut surfaces (Fig. 8*a*), chisel impression marks (Fig. 8*b*), and knife-cut marks (Fig. 8*c*). The embedded algorithm in MANTIS has been used to evaluate data from these marks with some success (12,13); however, it is clear that as mark complexity increases, new and better statistical analysis routines will need to be developed and implemented into the prototype.

Discussion

During the course of system testing, it was discovered that the prototype has several issues that need to be addressed, all of which are associated with problems encountered as mark complexity increased. As discussed in Refs (12,13), the current algorithm was designed for regularly striated markings, so as complexity increases, algorithm performance decreases. Other statistical algorithms have been developed (11), and the PIs continue to work on more advanced methods. It is fully anticipated that development of new algorithms, specifically designed to address the wide range of possible toolmarks, will continue and in fact is necessary if the prototype is to stay current. In an effort to prepare for this, the MANTIS software as part of the file management system allows data to be saved with different designators to indicate whether it is a flat plate that was scanned, information from a bullet, a knife cut, etc. It is hoped that this will allow easier incorporation of new algorithms into the system.

A second issue that needs to be addressed concerns acquiring data from nonflat samples. For example, bullets present a cylindrical sample that needs to be scanned. The manufacturer of the optical system used has available a rotatable stage which would be suitable for obtaining data from cylindrical samples such as bullets. As this has yet to be attempted, it is suspected some slight modifications to the acquisition software will be necessary as will updating of the data cleaning and masking routines. Once acquired the data obtained from a cylindrical sample can be flattened and treated in a manner similar to that of a flat plate.

A third issue associated with more advanced marks concerns the acquisition of data at what might be considered as the two extremes of data file size. For example, the initial attempts on obtaining data from a fired bullet resulted in data files that were much smaller than the striated markings acquired from a screwdriver mark or plier cut, as the markings spanned only a single land (or groove) or part of a land (or groove) of the bullet. Such a small data file means that the amount of data left to characterize it using the algorithm embedded in MANTIS was restricted—the normal method of selecting fairly large comparison and validation windows had to be greatly reduced in size. In these cases, it might be advisable to use a very high-resolution scan to obtain data on a finer scale and produce a larger data set for comparison.

On the other end of the data file size range are large toolmarks that create extremely large data files. One example of this is the knife cuts illustrated in Fig. 8*c*. Because of the size of the cut, a complete scan of the mark results in a huge data file, which requires considerable computing power to handle. In this case, the laptop used essentially gets swamped with data, and processing times go from a few seconds to several minutes. While processing time can be reduced simply by providing a faster computer, the question of how one efficiently handles large data files remains. One possibility might be to use class characteristics to conduct an initial screening.

The knife-cut markings were created by pushing the knife through a polymeric material, leaving both class characteristics

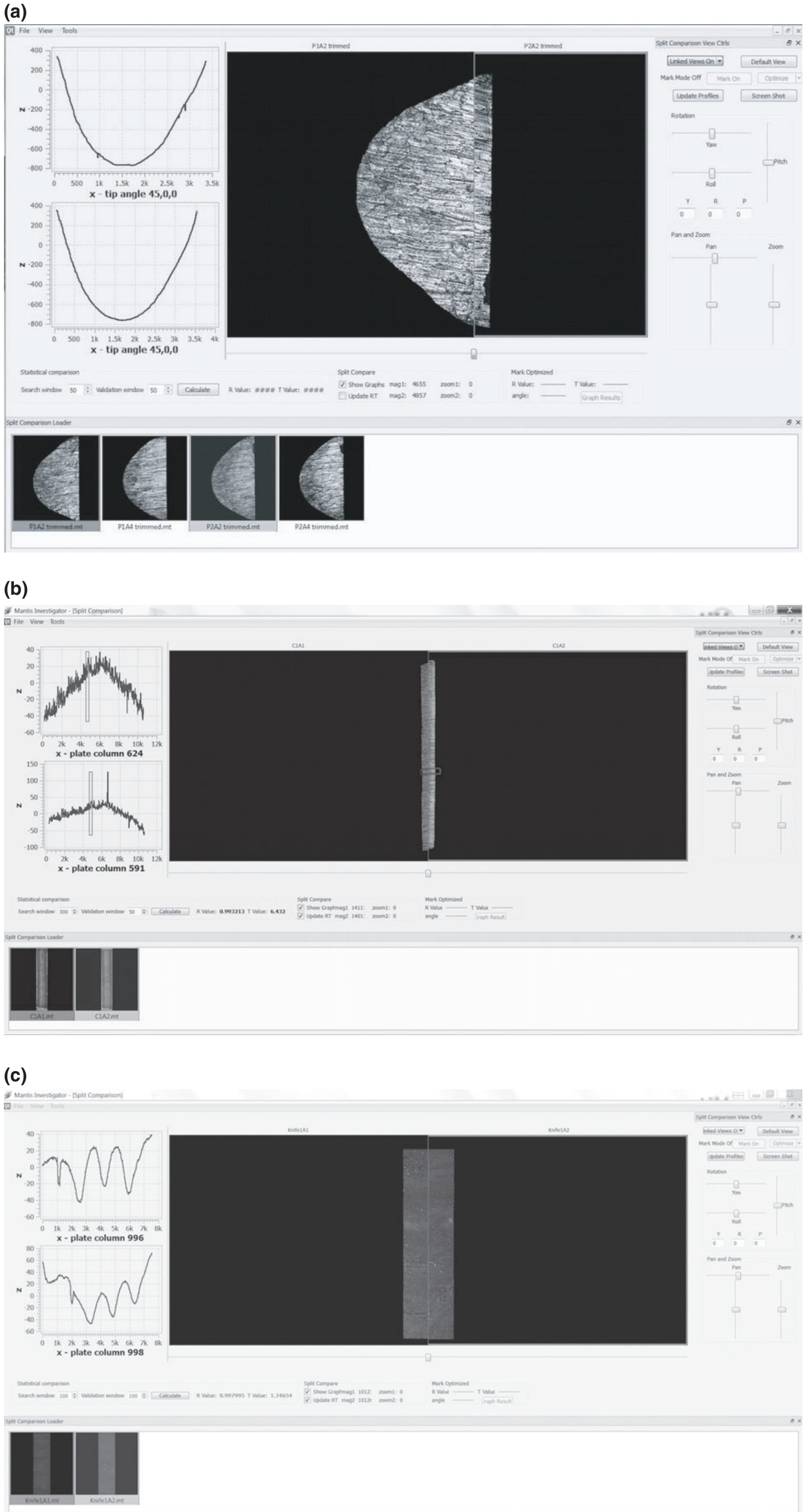

FIG. 8—*(a) Comparison of data files obtained from bypass pliers producing shear-cut marks in copper wire, separated by the hairline. (b) Comparison of two impression mark data files produced on lead plates using cold chisels, separated by the hairline. (c) Comparison of two knife-cut markings produced when cutting rubber molding compound, separated by the hairline.*

and unique markings consisting of fine striae. The current algorithm does not have a coarse filter to discriminate class characteristics (it is assumed the examiner can distinguish these features, so it is not necessary), and at this time, no experiments have been conducted to see what effect these features may have on performance. However, it is conceivable that class characteristics might be used to constrain the comparison area of a statistical algorithm to a specific region of the entire mark, eliminating the need for a more time-intensive survey of the entire mark.

In summary, while the prototype developed running the MANTIS software shows great potential for a portable system that can aid comparative examinations, much work and development remains to make its use applicable to the wide range of toolmarks that exist. By making the system as open as possible, it is hoped further research can be quickly and easily incorporated into the system to spur continued developments.

Summary and Conclusions

The goal of this study was to determine the feasibility of developing a portable, semiautomated system for characterizing and analyzing toolmarks that could be used for conducting objective, quantitative studies. The MANTIS system has been demonstrated to obtain excellent data from extremely variable surfaces, ranging from flat plates to curved bullet surfaces to the tips of actual tools such as screwdrivers. The microscope and the laptop computer used for control can be packed, ready for transport within 20–30 min, and deployed in as little as 15 min. 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 toolmark" from acquired data. The embedded algorithm used for statistical comparisons has given extremely good results for comparisons of fully striated toolmarks, quasistriated toolmarks, and impression marks produced from cold chisels. 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. It is apparent that additional algorithms will need to be developed to handle specific toolmark types. The open-source-code nature of the prototype as developed should allow new algorithms to be incorporated into the MANTIS system.

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