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Non-Contact Handheld Reader for Reflective Particle Tags

Heidi A. Smartt, Michael B. Sinclair, William C. Sweatt, Michael McDaniel, Juan A. Romero, Keith M. Tolk

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Heidi A. Smartt, Michael McDaniel, International Safeguards and Technical Systems
Michael B. Sinclair, Electronic, Optical, and Nano Materials
William C. Sweatt, Fluid Sciences and Engineering
Juan A. Romero, Coatings and Surface Engineering
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185

Keith M. Tolk
Milagro Consulting, LLC
Albuquerque, New Mexico 87109

Abstract

Reflective particle tags derive their unique identities through utilization of thousands of microscopic reflective elements randomly suspended in a clear adhesive matrix. For verification of a tag's authenticity, an illumination/imaging system is used to "read" information about precise positions and orientations of faceted particles. SNL developed the original Reflective Particle Tag (RPT) system, comprising a tag and an imager, in the 1990's to identify treaty-accountable items. Since then, the RPT system has evolved with advances in computing, imaging, and materials, and is considered a robust, low-cost, hard-to-counterfeit passive tagging system for treaty verification. However, a limitation of the current system is the need to mechanically dock the reader with the tag, which prevents its use in many situations. This paper discusses R&D at SNL to develop a non-contact handheld imaging system that will allow RPT system use in new scenarios and allows automation.

ACKNOWLEDGMENTS

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NOMENCLATURE

C/S	Containment and Surveillance
CoK	Continuity of Knowledge
DOE	Department of Energy
RPT	Reflective Particle Tag
SNL	Sandia National Laboratories

1. INTRODUCTION

Containment/Surveillance (C/S) measures are critical to any verification regime in order to monitor declared activities, detect undeclared activities, verify the integrity of equipment or items, reduce inspector burden, and to maintain CoK between inspections. A tag is an example of such a C/S measure that is used to establish the identity of an accountable item and maintain CoK of that item over time. Tags must also provide evidence of tampering of the tag itself (e.g. counterfeiting and substitution), and if applied in an appropriate manner (e.g. across a seam of a container), a tag may also provide evidence of tampering with the item. Continual improvement of C/S measures such as tags is required to counteract technical advances of adversaries which could render C/S equipment obsolete with a single technical advancement. Furthermore, new architectures are required to respond to changing requirements arising from the introduction of new procedures or approaches, and it is often desirable to incorporate technological advances that provide efficiency gains or allow deployment in new application spaces.

The Reflective Particle Tag (RPT) was developed in the 1990's to tag treaty-accountable items. It is a field-applied tag composed of specular hematite particles randomly dispersed in a clear, adhesive polymer matrix. The hematite particles are of size ~80 µm and exhibit flat, reflective facets (see Figure 1). The current reader is based on a custom camera and collimated illuminators arranged at four different angles. To inspect a tag, the reader is physically attached to the tag frame (Figure 2) for precise alignment and records images using each of the four illuminators. For each of the illumination angles, only a subset of the hematite facets will be oriented in such a manner as to redirect the incident illumination beam toward the aperture of the camera (this will be referred to as the reflection criterion). This subset will appear as small bright spots in the recorded image (Figure 3). In this manner, a sequence of four, complex and highly unique patterns is obtained that can be used to physically authenticate the tag. In addition, a unique, barcode-like identifier (ID) is placed at the midline to identify the tag (see Figure 3) and allow rapid retrieval of reference images. Once a tag is set, an inspector can return to the item, attach the reader, compare IDs, then reflective patterns to determine if tag sets match.

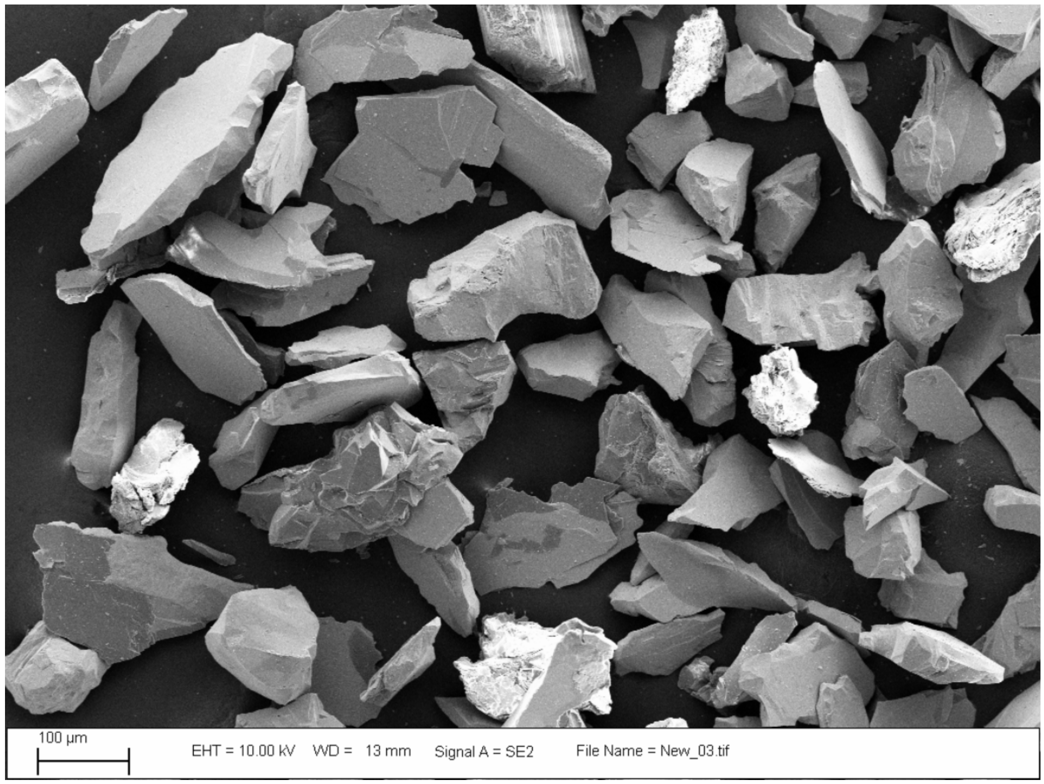

Figure 1: A scanning electron microscope image of the faceted specular hematite particles used in the RPT system.

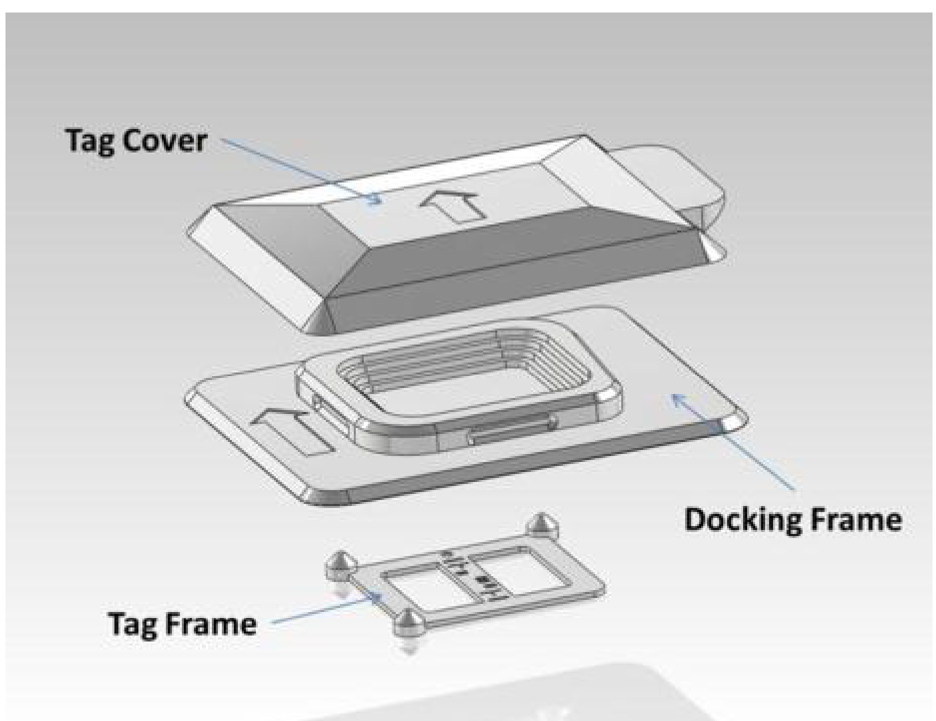

Figure 2: The contact RPT tag cover, docking frame, and tag frame.

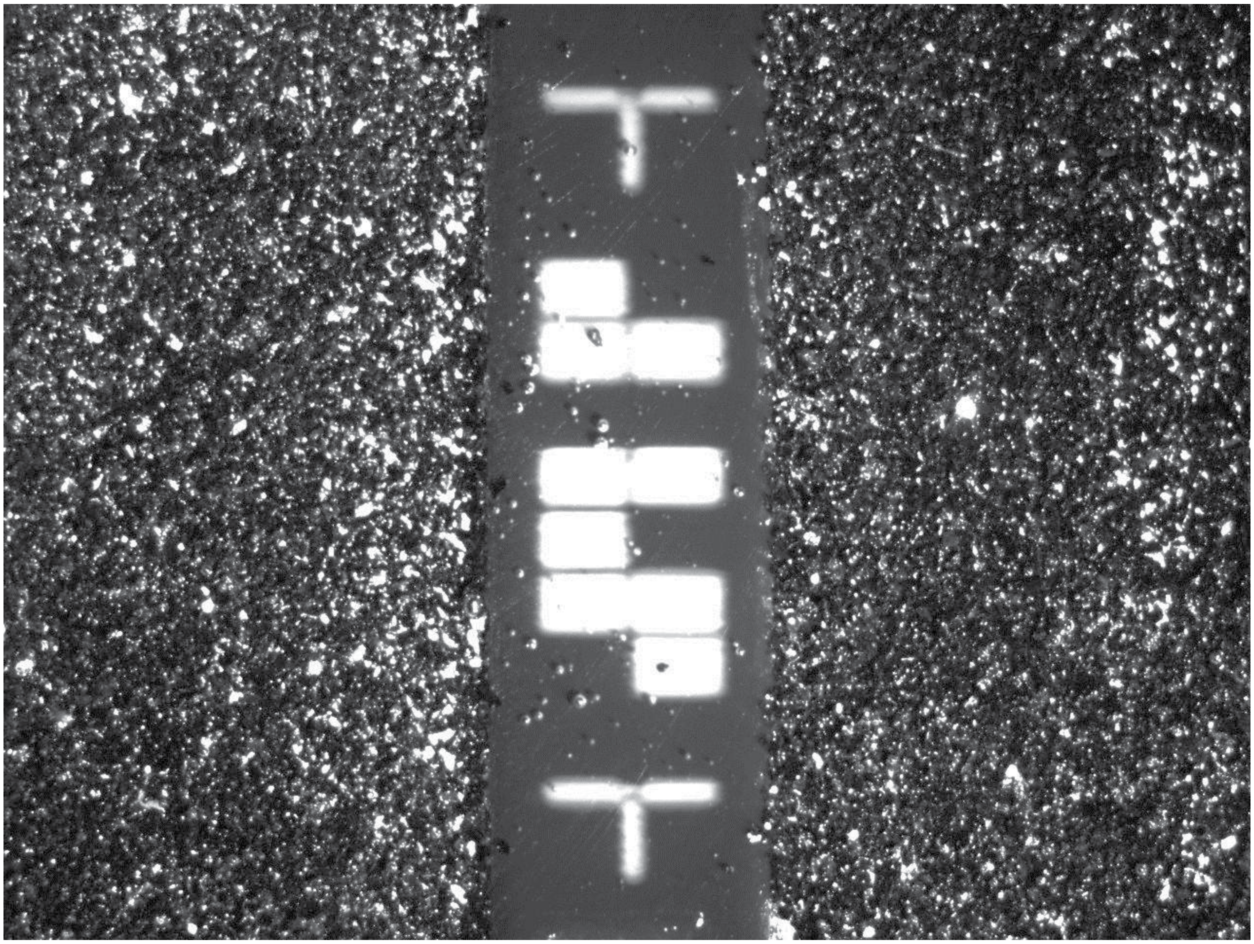

Figure 3: Reflective particles create unique patterns that are difficult to duplicate. A strip located in the middle of the tag contains a unique binary code ID.

The RPT architecture has proven resistant to counterfeiting and removal without detection. Furthermore, the tag requires no power, and is stable through temperature extremes, rough handling, and years of service. Such a combination of attributes makes the RPT an appropriate choice for applications with strict facility acceptance requirements and for deployments in which a semi-permanent tag should be attached to an item's surface. However, the current RPT system (which will be referred to throughout this paper as the contact RPT system) suffers from drawbacks which limit potential applications. It derives much of its security through precise alignment and relies on tightly collimated illumination beams and a small aperture to allow only facets oriented within ~1 degree of the optimal direction to contribute to the recorded image. Achieving such precision forces reliance on physical contact of the reader with the flat tag frame. In many cases, such physical contact is undesirable or not allowed by the facility owner. In addition, the use of a flat frame is incompatible with situations in which tags must be affixed to complex geometries such as curved surfaces.

These limitations can be overcome by the development of a non-contact handheld tag reader. Such a system would not require physical contact of the reader with the tagged item, be compatible with complex geometries, and minimize the time that inspectors spend in harsh or environmentally restricted locations. In addition, such a system could allow for automation in repetitive tasks such a reading tags on UF_6 cylinders. This paper will describe recent efforts at Sandia National Laboratories to develop a non-contact handheld tag reader. We first describe the attributes of the new reader system, then the results of testing the system. We will finish with a comparison of the security of the new system to that of the contact RPT system – in particular resistance to counterfeit and removal without detection.

2. NON-CONTACT HANDHELD TAG READER

Design Philosophy

The new design approach shares many characteristics in common with the contact RPT system, such as utilization of multiple illumination angles to record unique images of only those particles whose orientations match the reflection criterion. However, since a non-contact handheld system will invariably be subject to motions and misalignments resulting from the operator's motions, the design philosophy of the new system reduces, but does not eliminate, emphasis on precise registration of the imager with the tag. We emphasize that it is still highly desirable to achieve the highest precision possible in terms of alignment, and a key aspect of the new design is the ability to recognize when an acceptable alignment condition has been momentarily achieved. A discussion of the security implications for the new design philosophy will be presented in a following section.

Challenges associated with the non-contact handheld tag reader are the design of an optical system and vision processing software that will allow the acquisition of high quality images in spite of the non-contact handheld format. To address these issues without adding unnecessary complexity, the current embodiment relies on a non-contact handheld "read head" that is tethered to a desktop computer. [A next generation prototype would replace the desktop computer with a tablet computer and custom circuit boards.] Thus our approach is to use the current tethered system to assess the compatibility of software and hardware designs with the human factors associated with non-contact handheld operation.

Illumination and Imaging System

A schematic diagram of the read head of the current embodiment is shown in Figure 4. It consists of a lightweight, but rigid, circular frame with handles. Three high-power LED illuminators are mounted to the frame and aimed toward a point approximately 10 cm below the center of the frame. In contrast to the tightly collimated illumination beams of the contact RPT system, the illuminators of the new system project ~ F/2 beams containing a larger range of illumination angles. This is achieved using collimation optics and diffusers. Note that the LEDs emit in a relatively narrow spectral band so that a narrow bandpass filter can be used to reject most of the ambient illumination. The illuminators can be individually or simultaneously powered and can also be rapidly strobed.

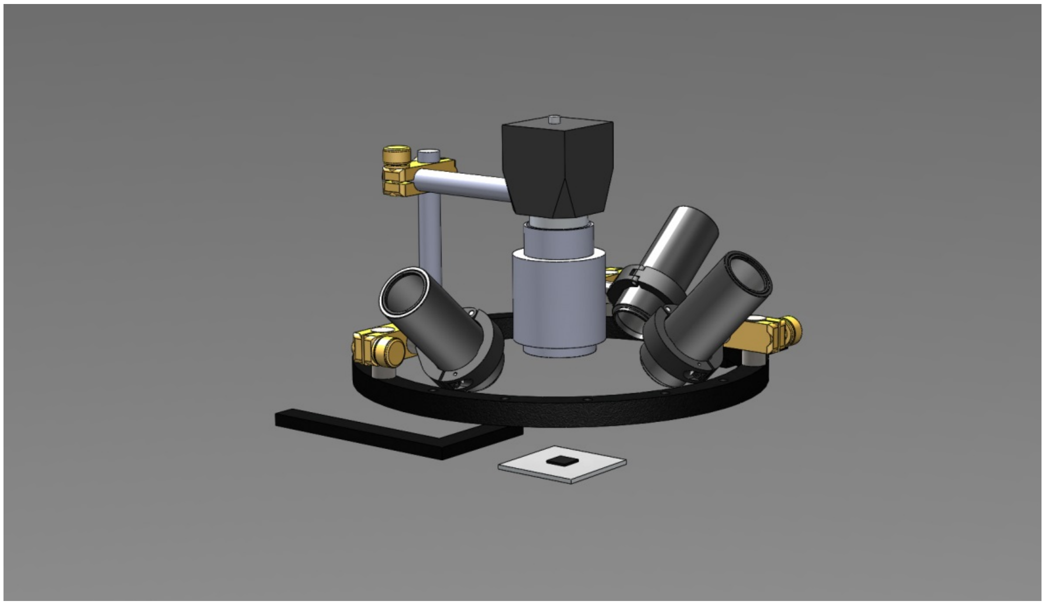

Figure 4: A schematic diagram of the read head of the current non-contact handheld system showing the three LED illuminators, along with the camera and lens. The tag is shown at the bottom.

A high frame rate, 4 megapixel (2048 x 2048) CMOS camera and lens are mounted along the axis of the frame and focused at the location of the tag 10 cm below the ring. The camera features a fast USB3 interface and is capable of recording and transferring full resolution frames at a rate of 90 frames per second. The object space f-number of the camera lens (~ F/5.6) has been reduced relative to the contact RPT system to allow for collection of a larger range of ray angles. Thus, for each illuminator, a larger subset of hematite particles will satisfy the reflection criterion and appear in the recorded image. It is important to emphasize that since the angular positions of the different illuminators differ greatly, a different subset of particles is recorded for each illuminator. In addition, the reduced f-number and increased pixel count improves the spatial resolution of the new design, thereby providing increased information content regarding the shapes of the particles.

Computer Vision System

To achieve the best possible alignment of the reader with the tag we rely on a high frame-rate computer vision processing system that quantifies positional and angular alignment errors of the reader with respect to the tag. With each frame, a set of fiducials is projected on-screen as an aid to the operator/inspector to improve the alignment. When the alignment satisfies a predetermined criterion, a rapid burst of frames is obtained in synchronization with the strobing of the illuminators, to be used for verification of the image sets. Thus the computer vision system essentially comprises two major components – alignment and verification.

The computer vision system relies on “image features” and “focus measures” that are recorded at the time the tag is first placed on the item. For each tag, a set of features (in particular features calculated from the Speeded Up Robust Features or SURF algorithm), their descriptors, and focus measures is stored on the non-contact handheld system’s computer. During alignment, the vision system analyzes each new frame recorded by the camera and rapidly determines a new set of image features for the incoming frame. These features are compared to the stored features, and, using only features that provide a good match between the current and stored feature sets, a homography matrix is calculated which provides the lateral displacement and azimuthal rotation between the current and stored features. A set of crosshair fiducials is projected on the computer screen, with one crosshair representing the coordinate system of the imager chip and the other representing the coordinate system of the stored feature set. When the fiducials are brought into alignment, three of the six possible degrees of orientation/rotation have been aligned. The other three degrees of freedom are aligned using the current and stored set of focus measures. Each of these focus measures is obtained at a different spatial location within the image. If the reader is tilted relative to the conditions that were used for the stored data, then better focus measures will be obtained for some regions of the image than others. Other parts of the image will be sharply imaged on nearby frames. A "balance bubble" fiducial is projected on the computer display to indicate relative balance of all the focus measures. When the cross hair fiducials are matched, and the balance bubble is centered then all degrees of freedom have been aligned. Figure 5 shows a screenshot of the computer display with the projected fiducials. Note that in practice it is not possible for the operator to perfectly align the fiducials, so a predetermined set of tolerances is utilized to judge whether the alignment is sufficient for image acquisition. Using binned images to reduce the data set size eightfold, the system software can complete the image analysis and fiducial projection at a rate of 25 frames per second. During this alignment phase, all three illuminators are constantly illuminated.

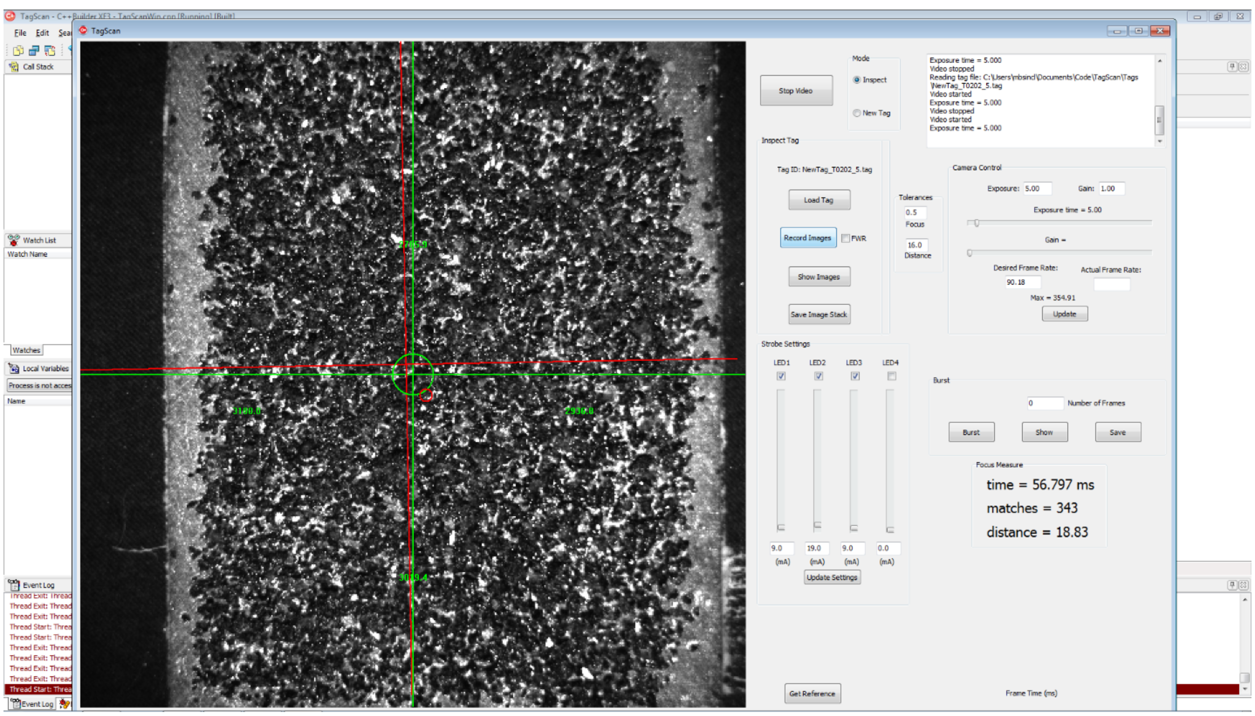

Figure 5: A screenshot of the tag reader application during the alignment phase. The green crosshairs are aligned with the imager and the red crosshairs are aligned with the tag. The red and green circles indicate the focus and tilt errors. When the crosshairs are overlapped to within a pre-specified tolerance, and the circles are centered at the origin, the system acquires a rapid burst of high resolution images that can be used for verification.

Once the computer vision system deems that the alignment is appropriate, the system acquires a burst of ~100 full resolution (2048 x 2048) frames at a rate of 90 frames per second. During the burst acquisition, the illuminators are sequentially strobed to allow acquisition of frames using each illumination condition. Note that, for the highest possible acquisition speed, no vision processing tasks are performed during the burst. After the burst acquisition, the image sequence is analyzed based on best focus measures and the top four images per illumination condition are retained for a total of twelve images per acquisition. These high quality frames are saved and are further processed using another SURF algorithm for verification processing. Note that the ability to align the reader with the tag and acquire images for verification is likely sufficient for tag verification; however, we still acquire full resolution images and proceed with a more rigorous verification procedure for increased confidence.

3. EXPERIMENTAL RESULTS

We tested the non-contact handheld reader and computer vision system to determine if an operator/inspector could acquire images of an initial tag for reference, remove the reader from the tag and then verify the tag was the same by comparing the image sets. We also tested the scenario that the inspector would acquire images of an initial tag, remove the reader from the tag, and that a counterfeit tag (or other non-ideal conditions) would not be able to be verified. We have arbitrarily set the verification threshold at five percent (the percentage of SURF features that match between image sets). In Table 1, we compare the reference images and verification images from the same tag under the same conditions. The variable is the change in inspector position in time. The results show that the reader and computer vision system successfully allow non-contact tag verification.

Table 1: Results of matching SURF features using reference and verification images from the same tag. Two existing RPT tags were used, with IDs Tag201 and Tag204.

Reference Tag	Verify Tag (yes/no/percent match)
Tag201 LED0 image 0	Yes 28.81%
Tag201 LED0 image 1	Yes 23.46%
Tag201 LED0 image 2	Yes 23.20%
Tag201 LED0 image 3	Yes 12.14%
Tag201 LED1 image 0	Yes 13.24%
Tag201 LED1 image 1	Yes 7.93%
Tag201 LED1 image 2	Yes 9.06%
Tag201 LED1 image 3	Yes 8.53%
Tag201 LED2 image 0	Yes 30.59%
Tag201 LED2 image 1	Yes 27.34%
Tag201 LED2 image 2	Yes 32.18%
Tag201 LED2 image 3	Yes 23.99%
Tag204 LED0 image 0	Yes 30.86%
Tag204 LED0 image 1	Yes 22.75%
Tag204 LED0 image 2	Yes 26.86%
Tag204 LED0 image 3	Yes 20.02%
Tag204 LED1 image 0	Yes 29.76%
Tag204 LED1 image 1	Yes 29.06%
Tag204 LED1 image 2	Yes 23.25%
Tag204 LED1 image 3	Yes 22.81%
Tag204 LED2 image 0	Yes 32.23%
Tag204 LED2 image 1	Yes 32.82%
Tag204 LED2 image 2	Yes 25.09%
Tag204 LED2 image 3	Yes 35.62%

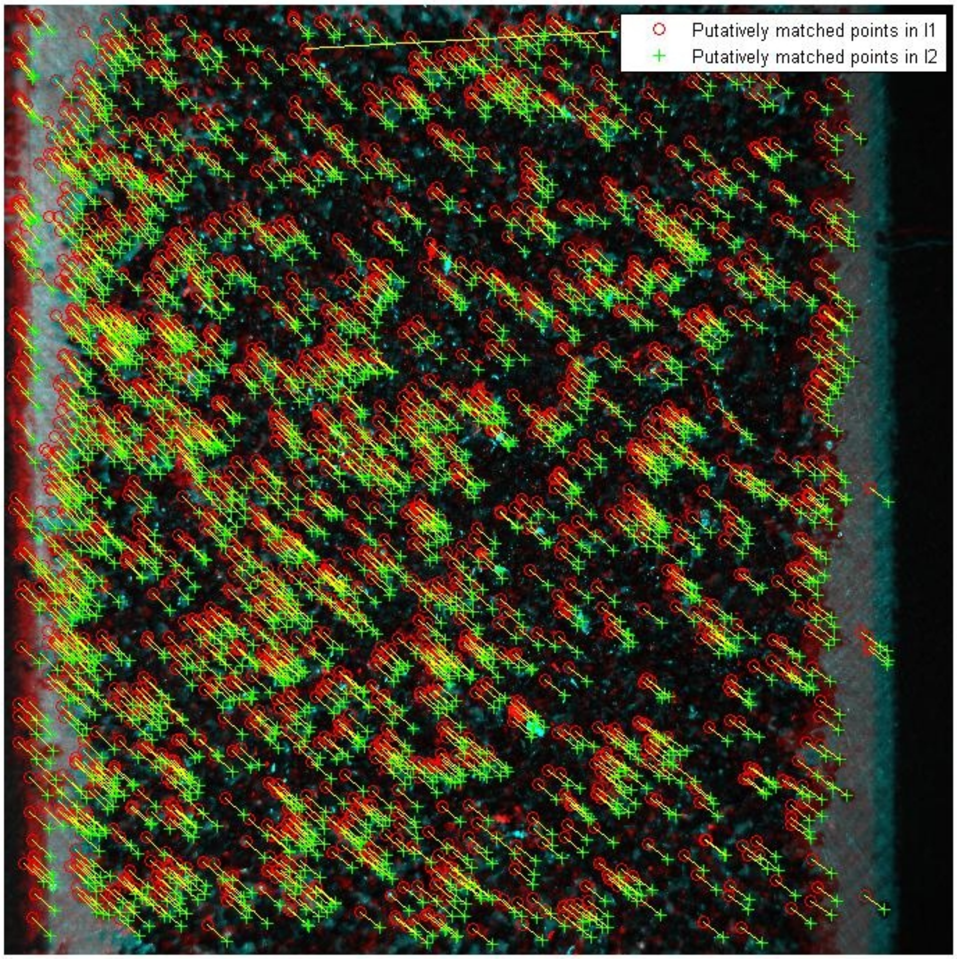

Figure 6: Matching SURF features between the reference and verification images for tag201 LED 2, image 2. The spatial translation between the reference and verification image is noticeable but consistent.

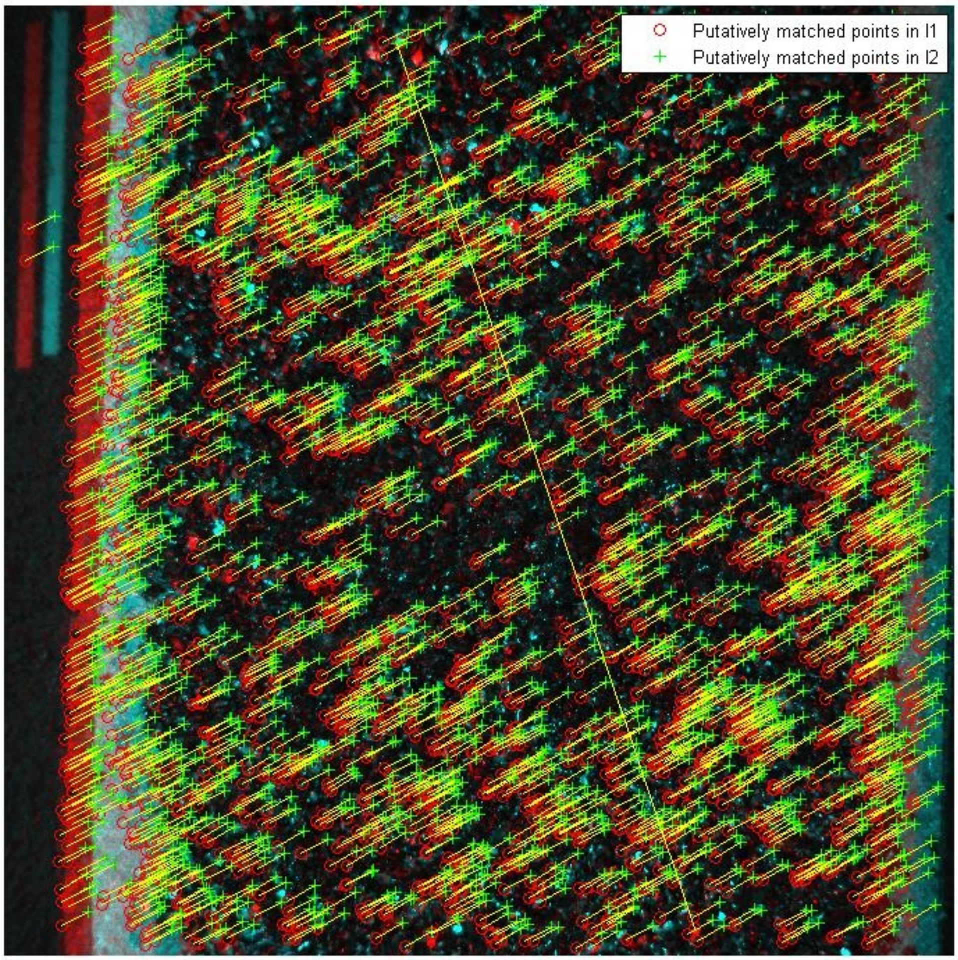

Figure 7: Matching SURF features between the reference and verification images for tag204 LED 0, image 2. Translation is in a different direction than Figure 6.

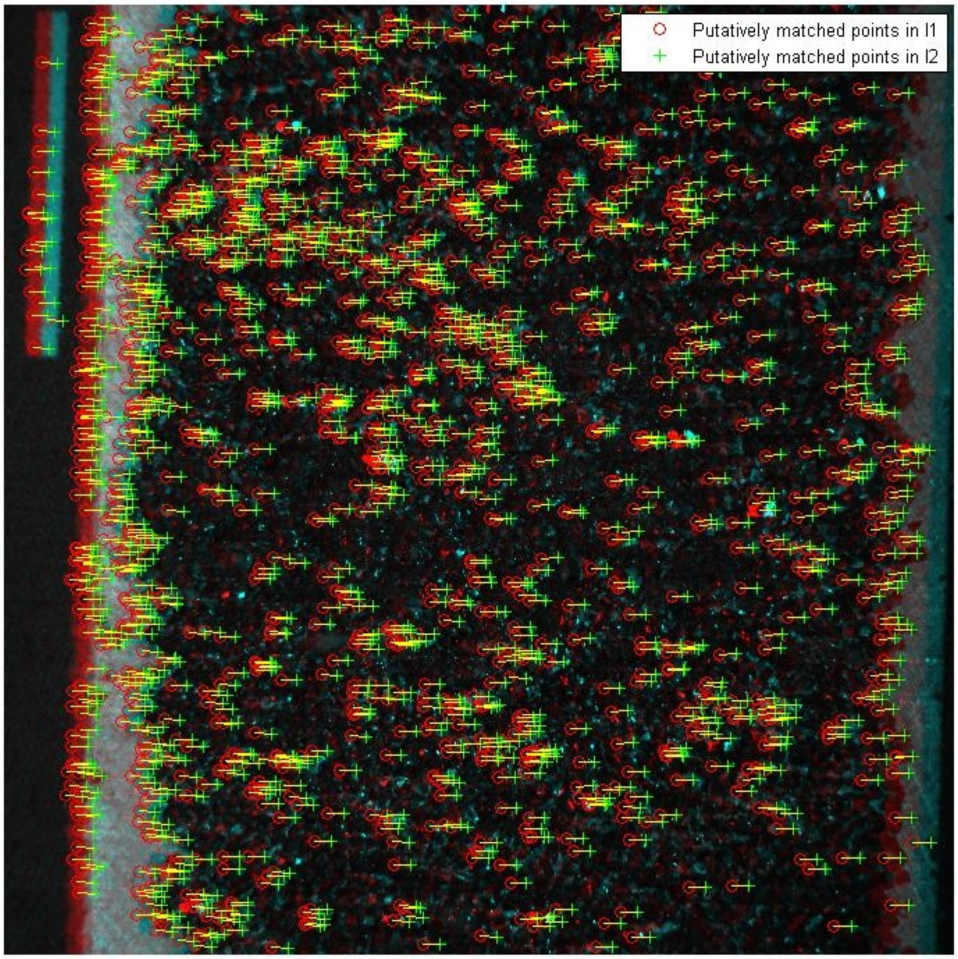

Figure 8: Matching SURF features between the reference and verification images for tag204 LED 2, image 0. Translation is minimal in this image.

We also tested comparing reference images to images that were either not associated with the tag in which the reference image was taken, or under variable conditions. As shown in Table 2, comparing with a different tag causes almost no matching SURF features to be detected and different LEDs result in very low percentages.

Table 2: Results of matching SURF features using verification images that vary from the reference image.

Reference Tag	Verify Tag	Percent	Notes
Tag201 LED0 image 0	Tag201 LED0 image 1	25.48%	Different image number
Tag201 LED0 image 0	Tag201 LED0 image 2	27.91%	Different image number
Tag201 LED0 image 1	Tag201 LED1 image 1	0.73%	Different LED
Tag201 LED0 image 2	Tag201 LED2 image 2	0.52%	Different LED
Tag201 LED0 image 3	Tag204 LED0 image 3	1.3941e-04	Different tag
Tag201 LED1 image 0	Tag204 LED1 image 0	3.87e-04	Different tag
Tag201 LED1 image 1	Tag204 LED2 image 0	2.1697e-04	All factors different
Tag204 LED1 image 2	Tag201 LED1 image 2	0	Different tag
Tag204 LED1 image 3	Tag201 LED1 image 3	0	Different tag

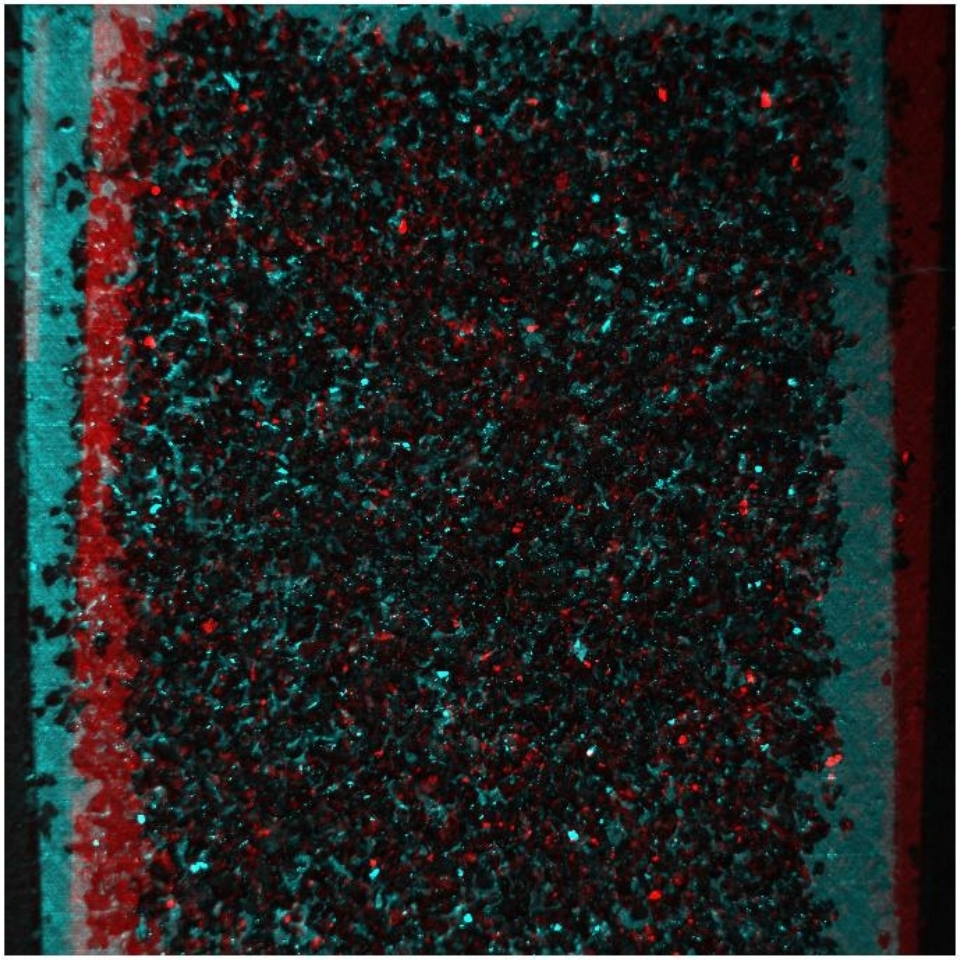

Figure 9: No matching SURF features are found between the reference image from tag204 and verification image from tag201 under same illumination conditions.

4. SECURITY CONSIDERATIONS

The security of an RPT system depends upon a number of factors including: the number of particles appearing in each image; the angular tolerance for satisfying the reflection criterion (*i.e.* some of the light specularly reflected from a facet is collected by the camera lens); the positional tolerance for locating the centroid of a facet; and the amount of spatial information related to the shapes of the facets. The design philosophy of the new non-contact handheld system differs in several important aspects from that of the contact RPT system, so it is instructive to make some estimates of the relative security of the two systems. Unfortunately, there is no formalism that will allow us to arrive at an absolute value for the system "security", since an element of system security depends upon how difficult it would be for an adversary to replicate an existing tag. We will thus settle for a crude estimate of security based on the number of particles within the images, their angular and positional tolerances, and a shape information factor. To do this, we define a security figure of merit (confidence in uniqueness of tag image) as:

$$S = \frac{N \cdot P}{(\Delta\theta)^2 \cdot (\Delta x)^2}$$

Where N is the number of particles appearing in the images, P is the number of degrees of freedom describing the shape of the particle, $\Delta\theta$ is the measurement tolerance of the particle's tilt angles, and Δx is the measurement tolerance of the particle's centroid. For each system we will assume that the camera images a 15 mm x 15 mm field of view. Also, we assume the tag utilizes hematite particles with an average size of ~ 80 μm. The other parameters of the two RPT systems that contribute to our estimates are shown in Table 3.

Table 3: Optical parameters of the non-contact handheld and contact RPT systems.

	Contact RPT System	**Non-Contact Handheld RPT System**
Imager size	1.3MP	4MP
Object space f-number	8.4	5.6
Number of illuminators	4	3
Illuminator f-number	20	2
Resolvable spot diameter (referred to tag plane)	19 μm	12 μm

The average number of particles that will appear in each image depends upon the f-numbers of the illuminators and the camera lens, and is larger by a factor of ~ 12 for the non-contact handheld system due to its faster optics. However, this increase comes at the expense of a factor of ~ 3.5 loosening of the measurement tolerance of the particle's tilt angle which is $\Delta\theta \approx \pm 1.7$ degrees for the contact RPT system and $\Delta\theta \approx \pm 6$ degrees in the non-contact handheld system. Note that since the number of particles visible in the images scales as the square of the angular tolerance factor, these factors will cancel in the comparison of the security figures of merit.

The higher spatial resolution of the non-contact handheld system directly leads to a larger number of degrees of freedom describing the shapes of the particles. To estimate this effect, we assume an average particle perimeter of 300 μm. This value is chosen to be somewhat larger than the perimeter of an 80 μm circular particle to account for shape irregularities. Using this value we obtain the number of resolution elements along the perimeter as P=25 for the non-contact handheld reader, and P=16 for the contact RPT. In a similar fashion, the improved spatial resolution of the non-contact handheld reader allows the particle centroids to be determined more precisely. This is partly due to the smaller resolution element size and partly due to the larger number of resolution elements appearing on the surface (perimeters of the particles). We estimate that the centroids can be located to an accuracy of $\Delta x \approx \pm 3.4$ μm for the non-contact handheld system and $\Delta x \approx \pm 6.7$ μm for the contact RPT system.

Assembling these estimates we find that the security figure of merit, S, for the non-contact handheld reader is larger than that of the contact RPT by a factor of three. It is important to emphasize that this comparison of system security is, of necessity, very rough. However, this comparison shows that the design decisions leading to the new non-contact handheld reader have not significantly diminished the overall system security (confidence in uniqueness of tag image) relative to the contact RPT.

5. CONCLUSIONS

We were able to successfully design, build, and demonstrate a non-contact handheld reader for Reflective Particle Tags (RPTs). We have demonstrated that our system is able to read reference tags from a distance of approximately 10 cm and subsequently verify these tags at a later time. If the tag is not the same, the system will not verify the tag.

The current computer vision system operates on a PC and the LEDs are operated from a small driver system. We envision a fully handheld system to be operated on a tablet computer with custom circuit boards.

Such a system can broaden the application space for RPTs to scenarios in which a reader is not allowed to contact the monitored item, as well as to scenarios in which items have curved surfaces or complex geometries and where automation is advantageous.

6. REFERENCES

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