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PASSIVE OPTICAL TAG FOR COMPLEX GEOMETRIC APPLICATIONS WITH NON-CONTACT READER

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ABSTRACT
Reflective particle tag systems can employ thousands of microscopic, randomly located and oriented reflective elements suspended in a matrix, to be read and verified with an optical system. Sandia National Laboratories developed the original Reflective Particle Tag (RPT) in the 1990's to identify treaty-limited items under the START framework. The RPT has evolved with advances in computing technology, imaging, and material science, and in its current generation is considered a robust, low-cost, high security passive tag for treaty verification and safeguards applications. The current RPT reader system docks to the frame encompassing the tag. In some situations, however, a non-contact reader system is preferred. Sandia National Laboratories is currently researching such a non-contact reader system for tags based on mono- and polychromatic reflective elements and developing a prototype system. Interrogation of the tag will include illumination with multiple wavelengths and multiple incidence angles. The new approach expands the information collected from tags beyond spatial locations and orientations of the particles, to allow spectral, morphological, and topographical attributes. To address image registration challenges, a low concentration of "tracer particles" are added to the tag to allow for precise alignment. This paper discusses the research and status of the prototype system.

INTRODUCTION
Containment/Surveillance (C/S) measures are critical elements of any monitoring regime to ensure Continuity of Knowledge (CoK) during inspector absence on verifying movement of nuclear material, weapons, equipment and samples, and preserving integrity of treaty-relevant data. Their continual improvement is required because (1) the adversary continues to technically advance (which could render C/S equipment obsolete with a single technical advancement), (2) requirements could change based on the introduction of new procedures or approaches, and (3) as technology advances there may be new options for C/S measures, including options that provide efficiency gains or allow deployment in new application spaces.

A tag is one such C/S measure and is intended to establish identity of an item as accountable, maintain CoK of status of that item over time, and provide evidence of tampering. Tags may provide evidence of tampering with the item if applied in such a manner, e.g. across a seam of a container, and must provide evidence of tampering with the tag itself, e.g. counterfeit and duplication.

The Reflective Particle Tag (RPT) was developed in the 1990's to tag treaty-limited items under the START framework. The tag has proven resistant to duplication, counterfeiting, and removal without detection. It is stable through temperature extremes, rough handling, and years of use. As a passive tag, it requires no energy source while attached, making it a unique and robust option for many inspection applications.

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The RPT is a field-applied tag composed of specular hematite particles in a clear, adhesive polymer matrix (**Error! Reference source not found.**Figure 1). A reader (based on a custom camera and illuminators) is physically attached to the tag frame for alignment and illuminates the tag from four angles (**Error! Reference source not found.**Figure 2). When illuminated by the reader, each tag presents complex patterns of millimeter-scale light reflections unique to the tag. These patterns are used to physically authenticate the tag. The reader acquires and transfers a set of 4 images per tag (one image per illumination angle). A unique identifier (ID) at the midline identifies the tag and enables automated tag reading. An inspector can subsequently return to the item, attach the reader, compare IDs, then reflective patterns to determine if tag sets match (verify or reject).

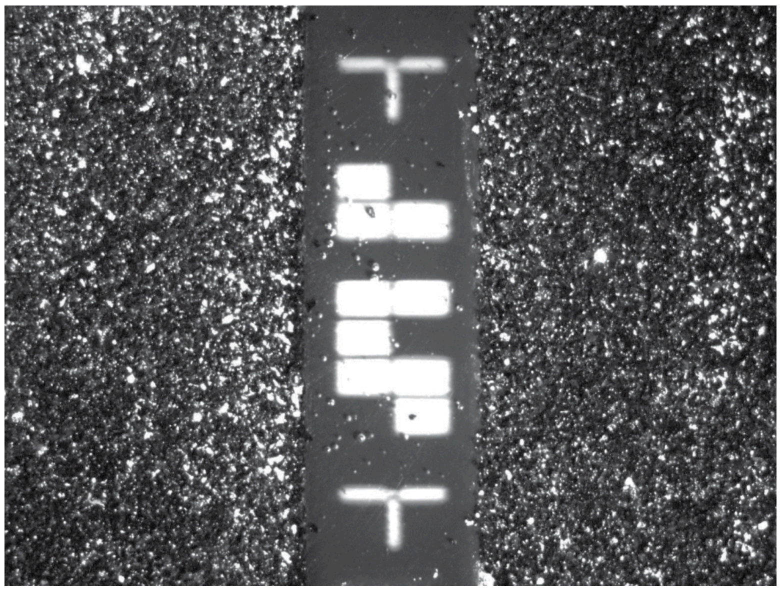

Figure 1: Reflective particles create unique patterns that are difficult to duplicate. Astrip located in the middle of the tag contains a unique binary code ID.

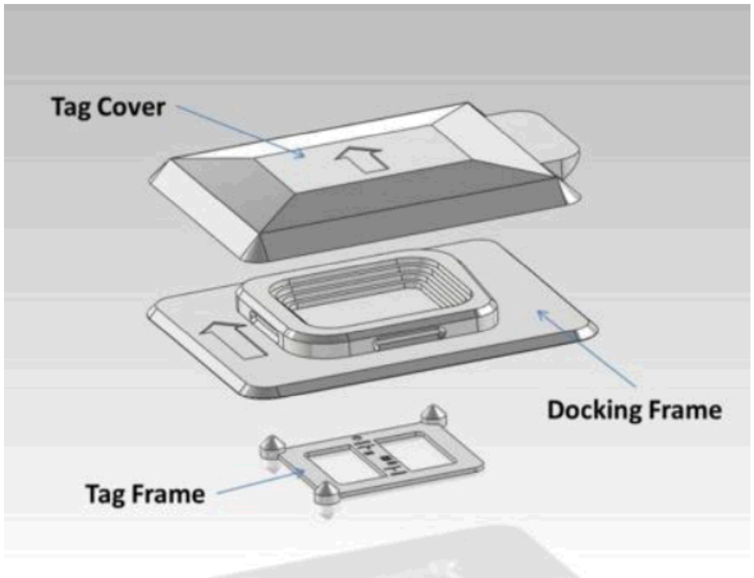

Figure 2: RPT tag cover, docking frame, and tag frame.

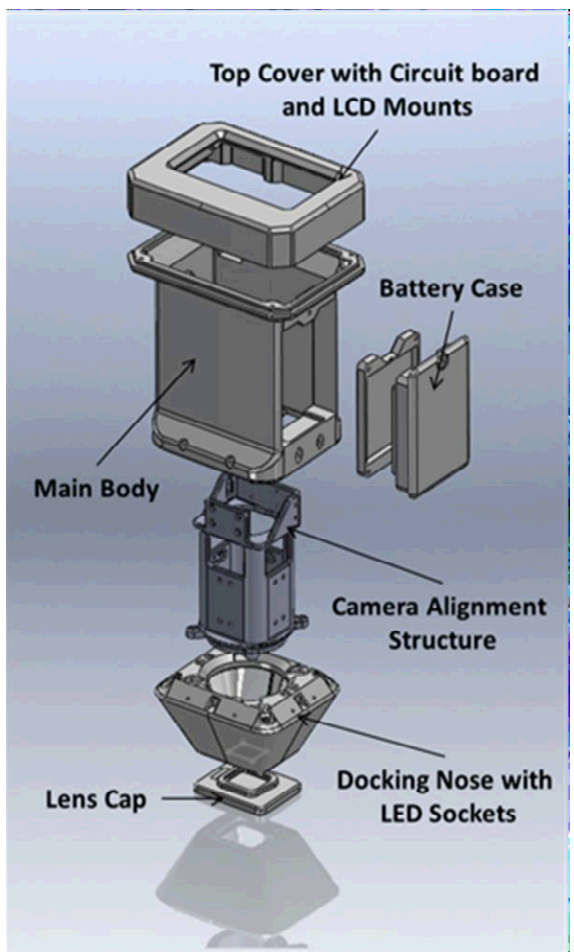

Figure 3: RPT reader, including four illumination LEDs.

The combination of a counterfeit-resistant reflective tag with an integrated unique ID in a passive, robust technology makes RPT the 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, it is embodied in a frame which limits its use in some complex geometric applications, e.g. curved surfaces. Furthermore, verification of RPT requires physical contact with the RPT docking frame attached to the tagged item. The RPT system can be enhanced by (1) offering the option of removing the frame, which allows broader deployment options such as application to curved surfaces (**Error! Reference source not found.**Figure 3), and (2) developing a non-contact reader system. In some treaty verification scenarios, physical contact of the reader to the item may not be desired nor allowed. A non-contact readout system can minimize the time that inspectors spend in harsh or environmentally restricted locations, and allows automation, e.g. reading seals on UF_6 cylinders. In some scenarios, the host applies the seal and reads it in view of an inspector and does not want the inspector touching the monitored item. Furthermore, in some scenarios, certification becomes easier if the reader does not touch the monitored item.

Figure 4: "30B" type UF_6 cylinder. Tag would typically be placed on the end cap for protection. Image courtesy Westerman Companies.

The purpose of this project is to develop a system with a tag that can be applied to complex geometries, read with a non-contact readout system, and meets additional verification regime requirements such as security, durability, low cost, and ease of application.

CHALLENGE 1 – REMOVING FRAME

There are three issues associated with removal of the frame – (1) the tag is not confined to application on a flat surface and thus might be curved or uneven, (2) the reader must know how to initially orient itself relative to the tag for acquiring the reference image and subsequently how to re-orient itself in the same position for verification, and (3) as the reader is handheld and non-contact, images must be acquired rapidly as the user is limited in ability to maintain stability above the tag.

We will address the first issue by acquiring multiple images with varying parameters at each illumination location. Acquisition of multiple images at each illumination location also partly addresses the second issue since it helps to compensate for tip/tilt errors once the reader is in place. Another method for addressing the second issue is to redesign the illumination beams. We have a candidate design that is currently being fabricated for testing.

Finally, we can use fiducials for alignment in all directions – both translation and rotation. We are considering two types of options – either embedding a small number of large fluorescing particles into the matrix, or more standard fixed fiducials such as those used in the current RPT system (see **Error! Reference source not found.**Figure 1). The larger fluorescent particles will be randomly mixed into the tag. The tag will be illuminated using blue light from a GaN (gallium nitride) LED with wavelength on the order of 400nm. This blue light "fiducial" illuminator is in addition to the multiple illuminators used for illuminating the reflective particles. The resulting fiducials will fluoresce in the visible and will be for accurate positioning of the reader.

If we proceed with the standard fiducials, we can use Augmented Reality (AR) for registration. A prototype AR tool has been developed to aid in manual alignment of our optical system. The AR system uses the RPT fiducial as a frame of reference for projecting a 3D image within a camera's view screen. When the images are in the correct location in the view screen, the camera is at the correct x, y, z coordinates and oriented properly in roll, pitch, and yaw. The user only has to move the camera to the proper position using real-time optical feedback in order to obtain the proper location and orientation of the unit for repeatable exposures. We will next need to interface the developed application with our actual system such that when the user is "locked" into the correct position our system will trigger and the camera will begin imaging. As a further benefit, using the RPT midline fiducial allows us to borrow the RPT algorithm for acquiring tag ID number.

The final issue is user stability while positioned above the tag. Based on our initial design, we believe that we can acquire a sequence of exposures in a couple of seconds. The user should be able to hold the camera reasonably steady for this length of time, and then the alignment algorithms can do the precise centering required for comparing the new images against the stored images taken previously.

CHALLENGE 2 – ILLUMINATION OF THE SEAL

The RPT reader docks directly onto a frame surrounding the tag, eliminating ambient light. For our system, we are challenged by the ambient light from undesired directions interfering with the illuminators. We approach the issue by replacing the white LED illuminators used in the RPT reader with multiple bright LEDs (the response of red, green, and blue are shown in **Error! Reference source not found.**Figure 4). A candidate illumination system has been designed and fabricated.

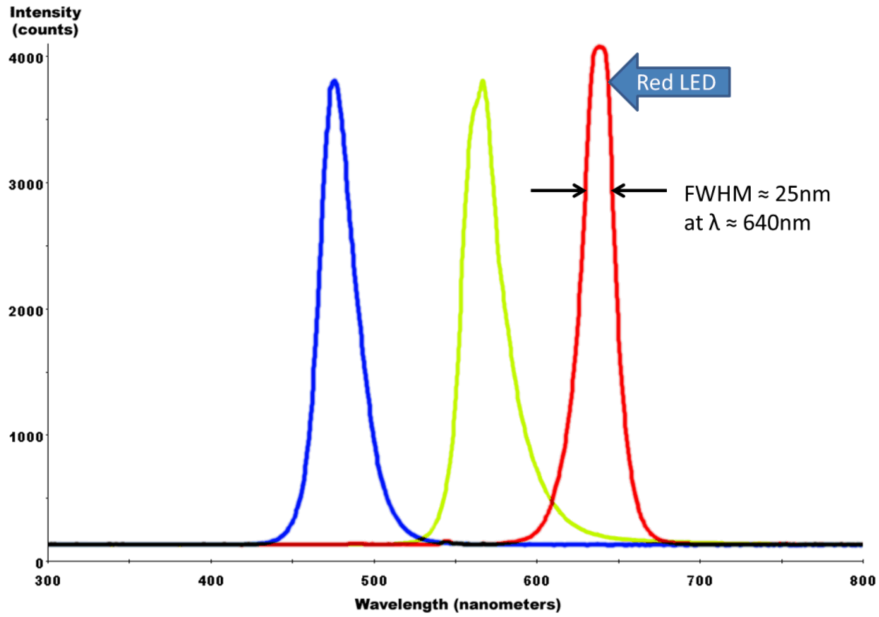

Figure 5: Emission spectra of commercial red, green, and blue LEDs. Image from Wikimedia.

The multiple LEDs in each illuminator location are physically separated, but our initially-designed compact optical system will allow the illumination patterns from the LEDs to overlap nicely. Without this correction, the images acquired from each LED would not co-register and the reflective particles that "light up" would be slightly different for each LED image. This has been a difficult challenge to overcome.

CHALLENGE 3 – MAINTAINING SECURITY

Due to the redesign of the illumination and optical system, the handheld readout system will be more tolerant to tilts, rotations, and translation. Hence, the spatial pattern of reflections recorded by the detector will remain relatively stable over a small range of angles. In contrast, the current RPT system will yield a completely different spatial pattern even with minimal movement. Thus, the current RPT system is capable of discerning smaller orientation errors of particles within a potentially counterfeited tag. In order to maintain security, we chose to explore options besides the position and reflection of the particles, including spectral properties, shape of the particles, and topographical information. This approach requires examination of particle type and camera resolution.

We are exploring two types of reflective particles: (1) hematite particles used for the RPT system and (2) engineered spectrally selective faceted particles. The use of these spectrally selective particles will allow us to investigate the value of including channels of spectral information in the recorded images. Although we have designed and fabricated a set of these particles, they have not yet been tested and will not be discussed further in this manuscript. Instead, we will focus on the existing specular hematite.

Hematite particles of approximately 80 to 100 micron size were used for initial testing. Hematite is an attractive particle as it is highly reflective; its shape is non-uniform and varies widely with particle; and it exhibits flat facets for strong specular reflections. For increased security we propose to exploit the variability of the particle shapes, and record spatial information regarding each particle's shape. Using this approach, the comparison of new and reference images will also include the shapes of each of the particles. To achieve this, the readout optical system employs a high resolution camera.

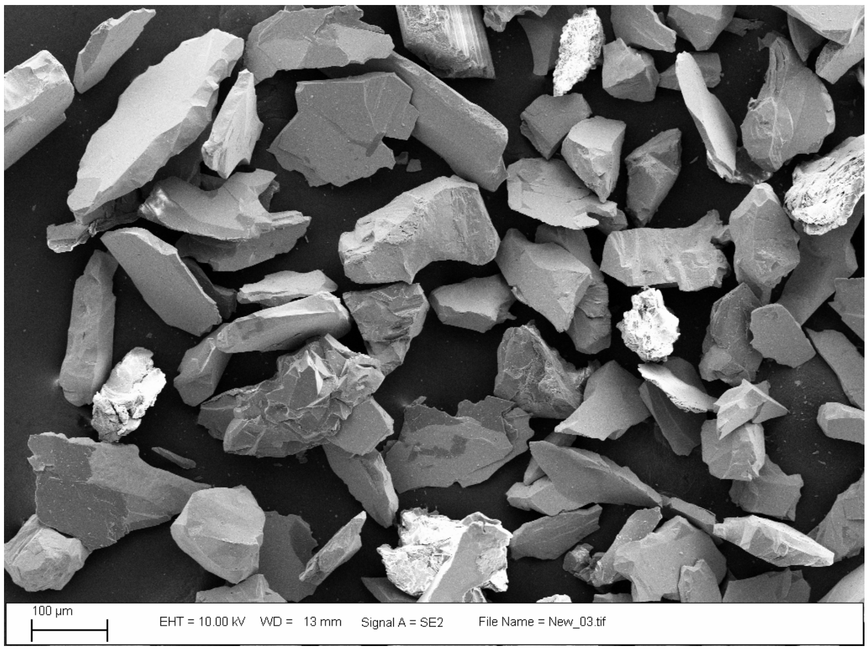

Figure 6: Specular hematite.

NEXT STEPS

The next steps in this project can be divided into six primary activities: (1) benchtop optical system assembly and testing, (2) testing of engineered spectrally selective faceted particles, (3) fluorescent particle development for fiducials, (4) continue development of registration tools, (5) conceptualize miniaturization, and (6) begin development of interface architecture for software.

ACKNOWLEDGEMENTS

All images and pictures have been created or taken from Sandia National Laboratories unless otherwise noted in the caption.

REFERENCES

[1] Thompson, G.E., Wilson, C.W., Little, C.Q., Novick, D.K., Merkle, P.B.; *Reflective Particle Tag System Performance Evaluation*; INMM Annual Meeting Proceedings; Orlando, FL; 2012.