Development of a Non-contact Reader System for Reflective Particle Tags

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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 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 include spectral and morphological attributes. To address image registration challenges, a low concentration of larger, fluorescent "tracer particles" are added to the tag to allow for precise alignment. This paper discusses the research and status of the prototype system.

Keywords: Reflective particle tag; Containment and Surveillance

1. 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 1990s to identify (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.

The RPT is a field-applied tag composed of specular hematite particles in a clear, adhesive polymer matrix. 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. When illuminated by the reader, each tag presents complex patterns of millimetre-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).

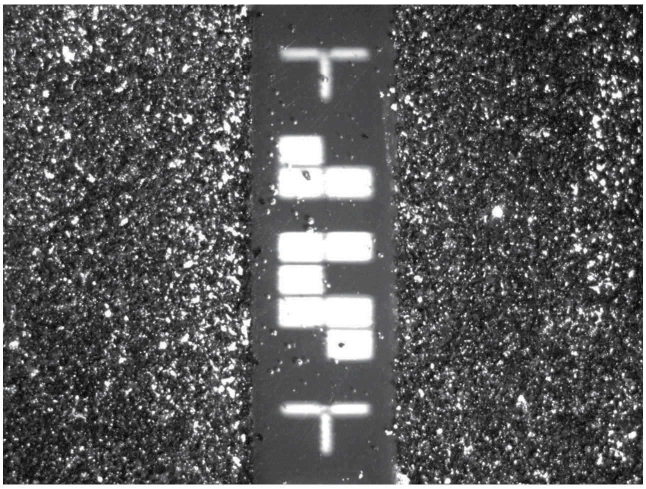

Figure 1: Reflective particles create unique patterns that are difficult to duplicate. A strip located in the middle of the tag contains a unique binary code ID. Image courtesy SNL.

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 (Figure 2), 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 2: "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.

2. Challenge 1 – Removing Frame

There are two primary challenges 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, and (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. Furthermore, 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 address the first issue by acquiring images at multiple focal depths at each location. Thus one end of the tag might be inside of focus while the other end is outside focus. To start, we are considering taking images at approximately seven different focal depths separated by $\Delta z \sim 80\mu m$. This will allow sharp imaging over a 1.5cm tag tilted by as much as 2°. (Alternatively we could focus on the whole length of a 1.5cm tag with a curvature of a 10cm radius.) We expect the system to find the best focus and then move off of that position by

$$\Delta z = N \times 80\mu m \text{ where the numbers } N=-3, -2, -1, 0, 1, 2, 3$$

The seven focal depths sum up to $\Delta z \approx 0.56mm$ measured in air. This allows a tag to be tilted and it can also be several hundred microns thick with particles anywhere within the tag's depth. Acquisition of images at multiple focal depths also partly addresses the second challenge since it helps to compensate for tip/tilt errors once the reader is in place.

Another design feature that addresses the second challenge is a change to the cone angles of the illumination beams. The cone angles of the illumination beams of the current RPT reader are small and therefore modest rotations of the reader, if handheld, would cause the illumination beam to be reflected at the wrong angle such that it would miss the camera optics. We have increased the cone angle of the illumination beam to F/1.5 (±20°). This angle dwarfs tilt or rotation errors that we expect from a handheld unit (1-2°).

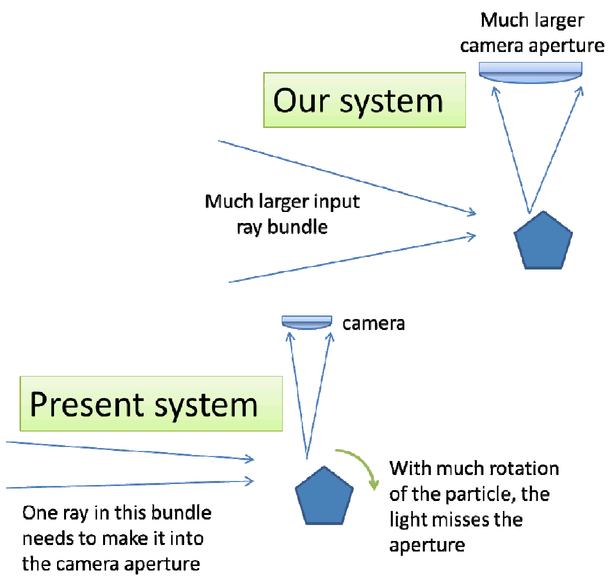

Figure 3: A comparison of new readout system with current RPT system ("Present system"). The new system illuminates the tag with a larger range of incidence angles and features a larger collection aperture to increase the overall system tolerance to tip/tilt misalignment of the reader. Image courtesy SNL.

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 (~0.25mm) fluorescing particles into the matrix, or more standard fixed fiducials such as those used in the current RPT system (see Figure 1). The larger fluorescent particles will be randomly mixed into the tag, and can either be non-uniformly sized (we call this the blueberry scone method), or they can contain particles with recognizable features for commercial algorithms such as the method used by the Viola Jones algorithm for facial recognition in smartphones. For either, the tag will be illuminated using blue light from a GaN (gallium nitride) LED with wavelength on the order of 400nm. The resulting fiducials will fluoresce in the visible and will be for accurate positioning of the reader and finding focus.

If we proceed with the standard fiducials, we can use Augmented Reality (AR), COTS processing tools, and tools developed for the RPT system for registration. A prototype AR tool has been developed to aid in manual alignment of our optical system. The system uses the Unity3D software (actually a gaming engine from Unity Technology) combined with Vuforia (AR framework) as the technology stack. The Vuforia AR system uses the RPT fiducial as a frame of reference for projecting a 3D image of two virtual rectangles within a camera's view screen (currently an Android tablet). When the rectangles are coincident with each other and parallel with the edges of 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 tablet to the proper position using realtime 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 LED timing 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.

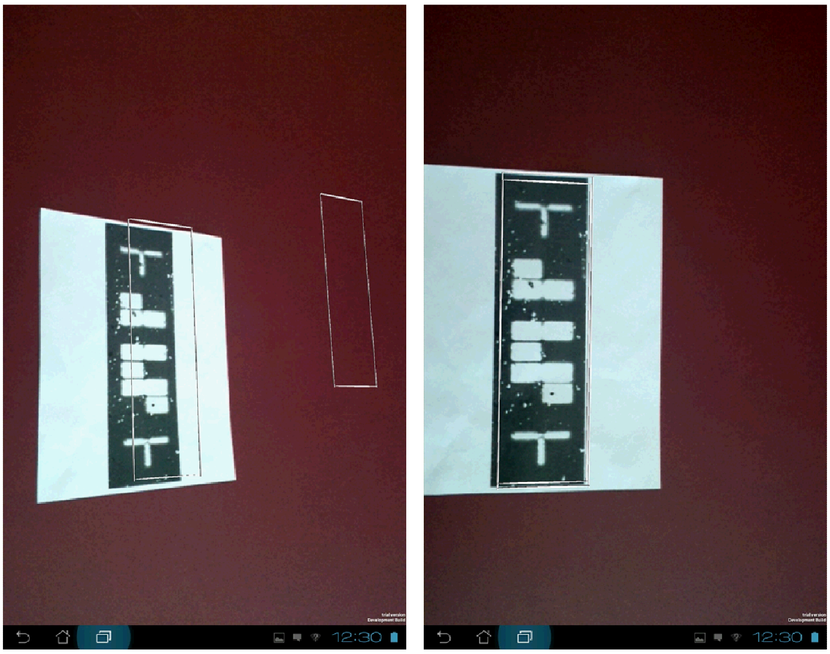

Figure 4: Augmented Reality tool for image orientation. User orients handheld device with camera until two rectangles coincide. Image courtesy SNL.

We describe the optical system in more detail later, but generally we have six illuminators equally spaced around a camera, each with red, green, and blue (RGB) LEDs, and thus at each of these seven focal depths the system will take 18 frames. The product is 126 separate images. We have designed a breadboard version of an LED driver that takes voltage and routing commands from a National Instruments Board and converts them to current to drive all 18 LEDs. The board can control the LEDs at a speed of a few hundred Hertz. The camera can take 168 frames per second so the minimum time for a sequence of exposures is about 0.9 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.

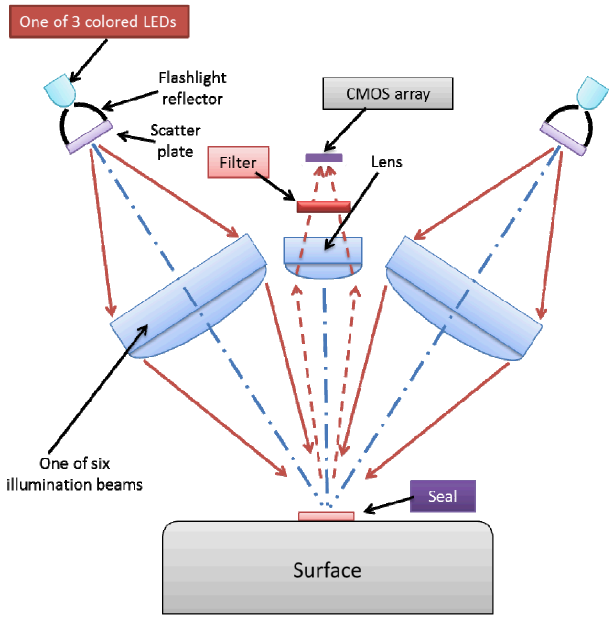

Figure 5: Early concept. A filter containing red, green, and blue transmission bands is placed in front of the CMOS array to minimise the amount of ambient light reaching the detector. Image courtesy SNL.

2. 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 from our six directions. We approach the issue by replacing the white LED illuminators used in the RPT reader with super-bright red, green, and blue LEDs (response shown in Figure 6) and placing a filter with three transmission bands at the RGB wavelengths in front of the CMOS camera. The super-bright LEDs have higher intensity at the tag than the ambient light and the filters block the ambient light in the out-of-band regions, reducing interference.

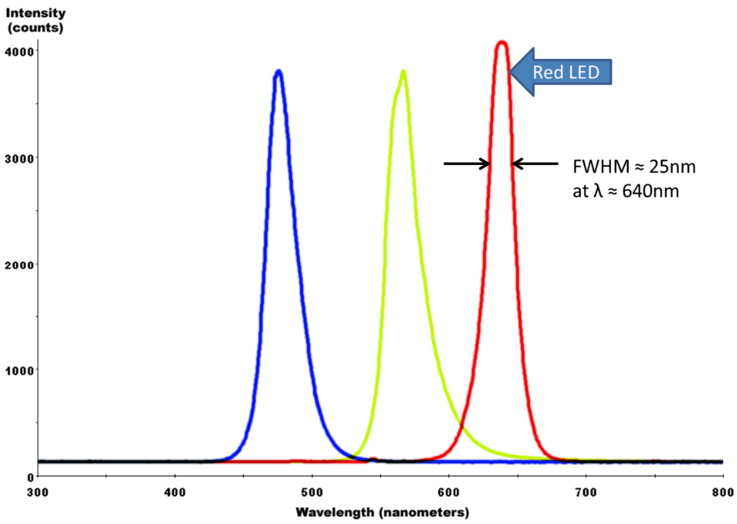

Figure 6: Emission spectra of commercial red, green, and blue LEDs. Image from Wikimedia.

Figure 7 shows the response of solar radiation (sunlight), fluorescent light, and a compact fluorescent light. The silicon detector sensitivity in the CMOS camera is 600nm (from 400nm to 1000nm) and each LED covers 25nm; therefore, each LED bandpass will transmit approximately 4% of the solar spectrum. Both fluorescent light and compact fluorescent light are 6% of each band.

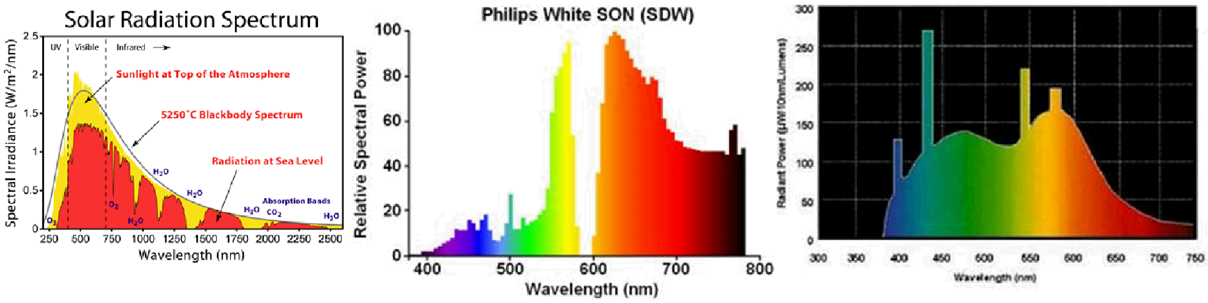

Figure 7: Spectra of possible background lighting. 4% of sunlight is in band, 6% of fluorescent tube (Philips) in band, and 6% of compact fluorescent in band (GE daylight). Solar radiation spectrum image created by Robert A. Rohde/Global Warming Art. Philips spectrum image from www.lamptech.co.uk. Compact fluorescent image from L. David Roper.

The three LEDs in each illuminator location are physically separated, but a compact optical system based on dichroic beam splitters will allow the illumination patterns from the three LEDs to overlap nicely. Without this correction, the images acquired from each LED would not co-register and the reflective particles that "light up" will be slightly different for each LED image. This has been a difficult challenge to overcome. We are on a second generation optical design to correct the non-uniform illumination for the physically separated color LEDs.

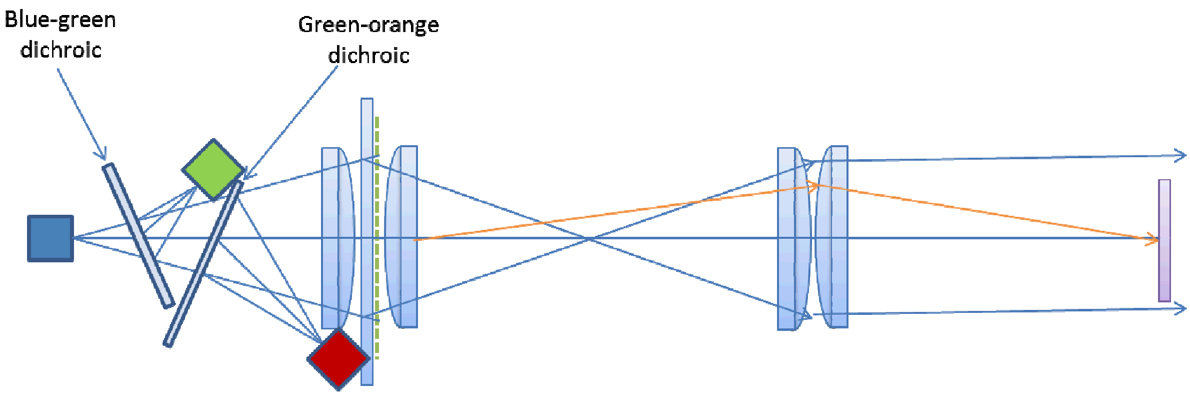

Figure 8: A single illuminator based on dichroic plate beam splitters. Image courtesy SNL.

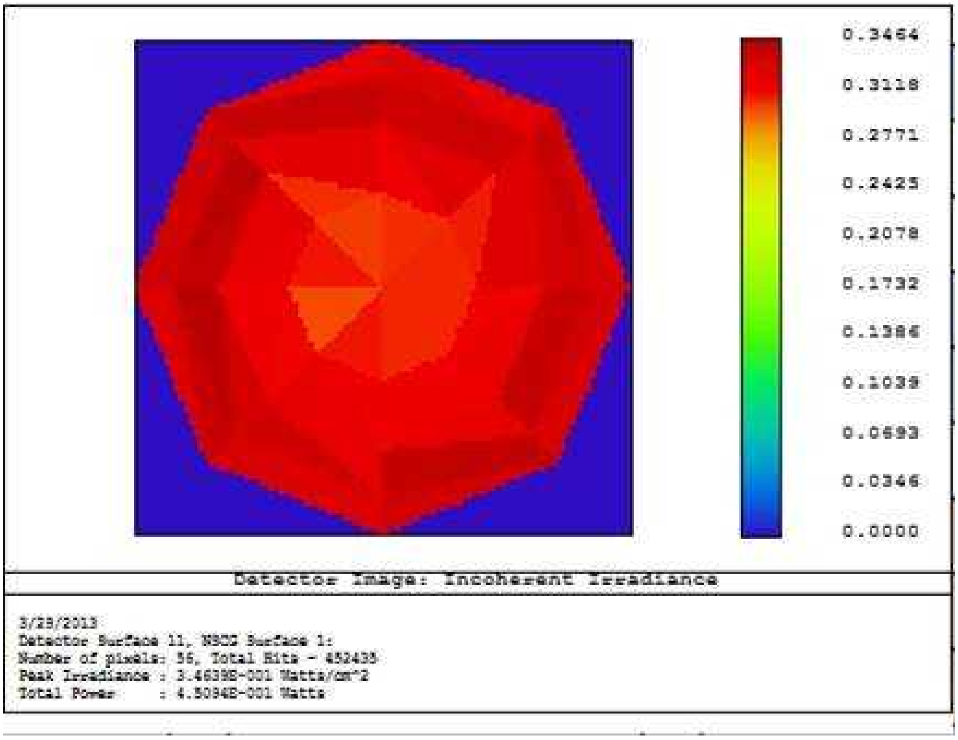

Figure 9: Computer simulation of the distribution of illumination light from a single illuminator at the tag. The light appears uniform across the tag. Each LED should have the same uniformity in the same location. Image courtesy SNL.

3. Challenge 3 – Maintaining Security

Since we are increasing the illumination cone angle (numerical aperture) as well as the detector aperture, 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 slope or topographical information. This approach requires examination of particle type, camera resolution, and exploitation of already-available information.

We are exploring two types of reflective particles: (1) hematite particles used for the RPT system and (2) crushed glass particles coated with optical multilayers which act as etalons. The multilayers will be designed to exhibit different reflectivities at each of the LED wavelengths. Furthermore, the coatings will vary from particle to particle, such that red-to-green-to-blue reflectivity ratios will also vary with the particle. The use of these spectrally augmented particles will allow us to investigate the value of including 3 channels of spectral information in the recorded images. Although we have designed and fabricated a set of spectrally augmented particles, these particles have not yet been tested and will not be discussed further in this manuscript. Instead, we will focus on the existing micaceous specular hematite.

Micaceous hematite particles of approximately 80 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 4 megapixel camera (2432 x 1728 pixel array), along with F/4 optics and automatic focus control. Each pixel has ~10 micron resolution, and the resulting image is ~ 20mm x 20mm. The tag is 15mm x 15mm and therefore the resolution is such that we have about 64 pixels per particle (a particle is about 8x8 pixels).

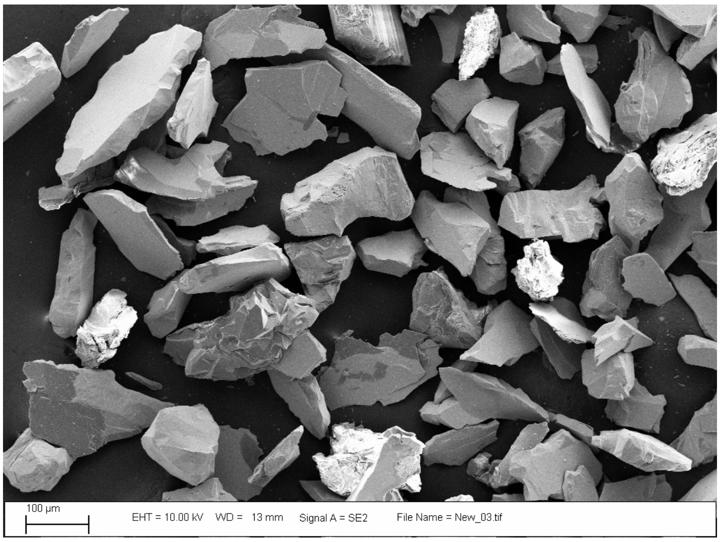

Figure 10: Specular hematite. Image courtesy SNL.

4. Next Steps

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

5. Acknowledgements

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6. 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.