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CHARACTERIZATION OF DEBRIS FROM THE DEBRISAT HYPERVELOCITY TEST

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The DebriSat project is an effort by NASA and the DoD to update the standard break-up model for objects in orbit. The DebriSat object, a 56 kg representative LEO satellite, was subjected to a hypervelocity impact in April 2014. For the hypervelocity test, the representative satellite was suspended within a "soft-catch" arena formed by polyurethane foam panels to minimize the interactions between the debris generated from the hypervelocity impact and the metallic walls of the test chamber. After the impact, the foam panels and debris not caught by the panels were collected and shipped to the University of Florida where the project has now advanced to the debris characterization stage.

The characterization effort has been divided into debris collection, measurement, and cataloguing. Debris collection and cataloguing involves the retrieval of debris from the foam panels and cataloguing the debris in a database. Debris collection is a three-step process: removal of loose debris fragments from the surface of the foam panels; X-ray imaging to identify/locate debris fragments embedded within the foam panel; extraction of the embedded debris fragments identified during the X-ray imaging process. As debris fragments are collected, they are catalogued into a database specifically designed for this project. Measurement involves determination of size, mass, shape, material, and other physical properties and well as images of the fragment. Cataloguing involves a assigning a unique identifier for each fragment along with the characterization information.

I. INTRODUCTION

The collision in 2009 between Cosmos 2251 and Iridium 33 generated a debris field inaccurately predicted by National Aeronautics and Space Administration's (NASA) and the United States Department of Defense's (DoD) standard break-up models for objects in orbit. The inaccuracies in the prediction were attributed to the use of modern materials and components in the Iridium satellite not accounted for in the standard break-up model.[1]

The DebriSat project is an effort sponsored by NASA and DoD to update the standard break-up model. The DebriSat object, shown in Fig. 1 was a 56 kg satellite designed and fabricated to include components and materials common in modern low Earth orbit (LEO) satellites. After fabrication, DebriSat was delivered to the Arnold Engineering Development Center (AEDC) where a hypervelocity test was performed in April 2014.

The hypervelocity test at AEDC involved the launching of a 580 g aluminum cylinder projectile (see Fig. 2) at DebriSat with the aim of causing the catastrophic destruction of the projectile and DebriSat. This was done by using the Range G two-stage light gas gun at AEDC to launch the projectile at a speed of 6.8 km/s. The collision between the projectile and DebriSat resulted in a release of 12.3 MJ of energy, sufficient to emulate an in-orbit collision and cause catastrophic failure of the DebriSat object.

To maintain the integrity of the resulting debris, DebriSat was suspended in the impact chamber and surrounded by a 'soft-catch' arena consisting of bundles of polyurethane foam panels of varying densities (see Fig. 3). The density of the foam panels increase with depth within each bundle to protect the debris from post-impact damage by preventing collision with the metal walls of the test chamber. A total of 564 foam panels were used to construct the soft-catch arena.

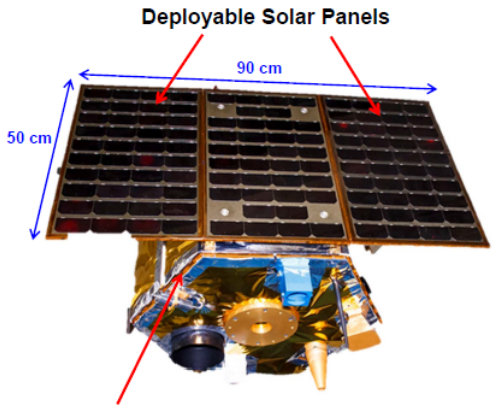

Fig. 1: The completed DebriSat object

The test chamber post impact is shown in Fig. 4. It contained loose debris fragments, whole and partial bundles with embedded fragments, and foam pieces. The test chamber was cleaned and everything recovered from the chamber was packaged and shipped to the University of Florida for processing. The debris

fragments that were collected directly from the chamber were packaged for shipping and the packaging contained information defining the location within the test chamber where the debris was recovered. The foam panel bundles that remained intact (or partially intact) after the impact were carefully wrapped in a plastic sheet and boxed for shipping. The bundles that were broken into smaller foam pieces were bagged and tagged with their recovery location and then boxed for shipping.

Fig. 2: Projectile (right) with a soda can (left) for comparison

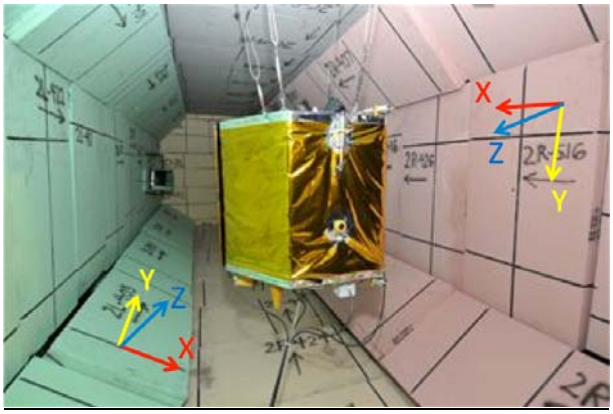

Fig. 3: DebriSat in the test chamber surrounded the 'soft-catch' arena.

Fig. 4: Test chamber post-impact

Since June 2014, a team at the University of Florida has been collecting debris from the foam panels. As of early September 2015, the team has managed to perform an initial processing of 304 foam panels and collected more than 90,000 debris fragments with at least one dimension of 2 mm or greater. Fig. 5 and Fig. 6 show the progress made by the team in processing the foam panels and collecting debris over the past year. The remainder of the paper describes the process by which the debris is collected, characterized, catalogued.

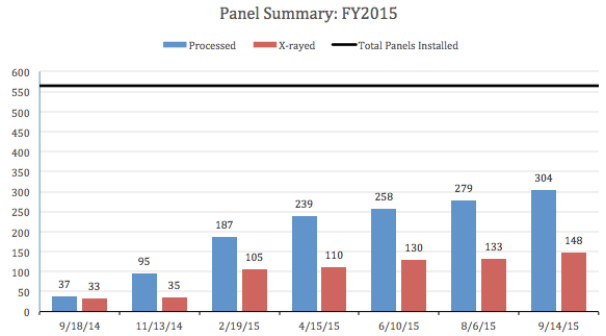

Fig. 5: Chart showing progress of foam panel processing and imaging over past year.

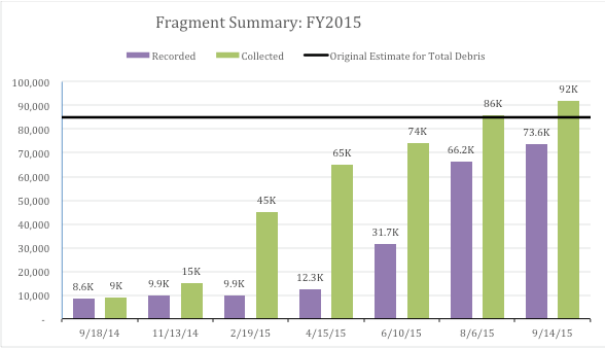

Fig. 6: Chart showing progress of debris collection and recording over the past year. The database was brought online in March 2015, hence the sudden rise in recorded debris.

II. DEBRIS COLLECTION

Debris collection involves pre-imaging, imaging, and post-imaging activities. These activities are sequential and are organized with the goal of collecting 90% of DebriSat's original mass. Using current standard break-up models it was estimated that the number of fragments would be on the order of 85,000. To date, we have collected in excess of 90,000 debris fragments, mostly from the surface of the approximately 50% of the panels. Furthermore, while we've just started the extraction of embedded fragments from the foam, our X-ray images have shown that the low density foam panels contain large quantities of embedded fragments. Based on this information, the goal was revised to *the*

collection of fragments with at least one dimension of 2 mm or greater.

II.I Initial Processing

A dextral orthogonal coordinate system is used in the debris collection process to ensure proper correlation of all recorded positional information. The coordinate system is defined such that the z-direction points inward towards the center of the test chamber, the y-direction (or x-direction) is collinear with the direction of travel of the projectile, and the x-direction (or y-direction) forms the dextral system (see Fig. 3).

To aid in the processing of each panel, two sets of frames (physical) were fabricated and used: (i) a Foam Grid Frame and (ii) an X-ray Grid Frame. Structurally, both frames are identical and are used to subdivide the panels into smaller sections for improved fragment location identification. The grid spacing is different for each frame type. The Foam Grid Frame and corresponding coordinate system are shown in Fig. 7. Starting at the origin, the grids along the x-direction are labelled A-D and along those along the y-direction are labelled 1-6 (e.g., grid D3 is highlighted in the figure). No gridding is required along the z-direction and the surfaces are denoted +Z face and –Z face in accordance with the dextral definition. The same coordinate system is used for the X-ray Grid.

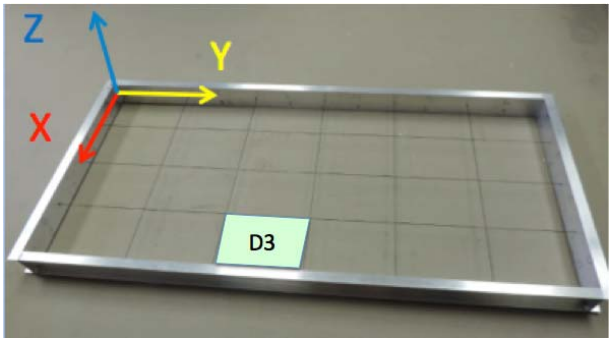

Fig. 7: Foam Grid Frame with corresponding coordinate system. The X-ray Grid Frame is similar in form and uses the same coordinate system.

II.II Pre-Imaging Processing

Debris collection during the pre-imaging stage involves *loose* and *embedded* debris fragments. Loose fragments are defined as debris laying on the surface of the panel (without surface penetration), whereas embedded fragments are defined as debris that have penetrated the surface of the panel or found within a crater in the panel. The debris fragments are collected using tweezers and stored individually in anti-static plastic bags. The bags are labelled identifying the location where the debris was found: 'L' for loose debris and the grid location (e.g. D3) for embedded debris. The panel details as described in Table 1 are also entered in the DCS to provide complete traceability of each debris fragment location.

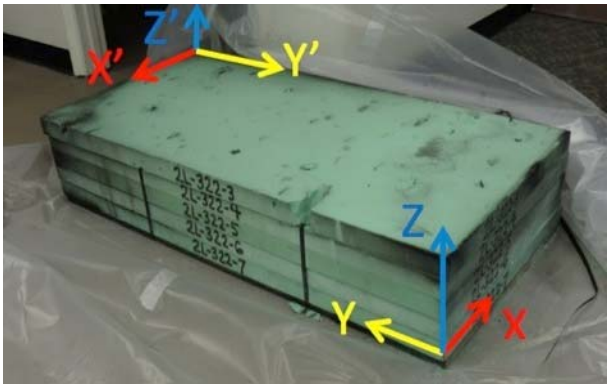

Fig. 8: Foam panel bundle with possible coordinate systems attached. Note the panel ID visible on edge of panels.

One of the main concerns during the debris characterization process is to ensure that any actions taken do not damage the debris. This is challenging since a significant amount of the debris is fragile. A standardized process was developed to ensure that all personnel working with the fragments will handle them in the same manner and thus minimize the chance of damage. The processed is as follows:

1. Clean the work area (both floor and worktable)
2. Carefully remove a foam bundle from its shipping box and place the bundle on the floor with the plywood backing resting on the floor (this defines the coordinate system as shown in Fig. 8). Inspect the bundle and the box and record any observed anomalies as well as the box ID
3. Carefully open the plastic wrapping to display the bundle. Choose one of the two corners shown in Fig. 8 as the reference point for the coordinate system; if discernible, preference should be given to the corner which aligns the y-direction (or x-direction) with the direction of travel of the projectile, however, this is not critical since that correlation can be determined from the plywood once the last panel has been processed (under no circumstance should the bundle be rotated such that the +Z face points downward as this will allow loose fragments to fall on the floor.)
4. Remove the top panel and transfer to worktable ensuring that the +Z face remains upright at all times.
5. Assign a foam ID number and enter panel data (see Table 1) in the Debris Categorization System (DCS)
6. Place the Foam Grid Frame on the panel (see Fig. 9) consistent with the choice in item #3.

7. Mark the panel as shown in Fig. 10. This ensures a consistent identification of the panels throughout the rest of the debris processing steps.
8. Photograph the panel and associate the images with the foam ID (see Fig. 11, Fig. 12, Fig. 13).
9. Collect and catalogue loose and surface embedded fragments.
10. Once all fragments have been collected from the +Z face, carefully rotate panel 180 deg. about the y-axis to expose the –Z face and repeat #9
11. Once all fragments have been collected from the +Z face, prepare panel for shipping to X-ray facility.
12. Clean worktable and repeat steps #4 through #11.

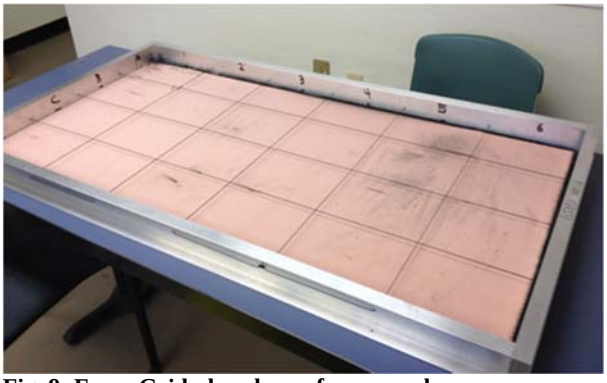

Fig. 9: Foam Grid placed on a foam panel.

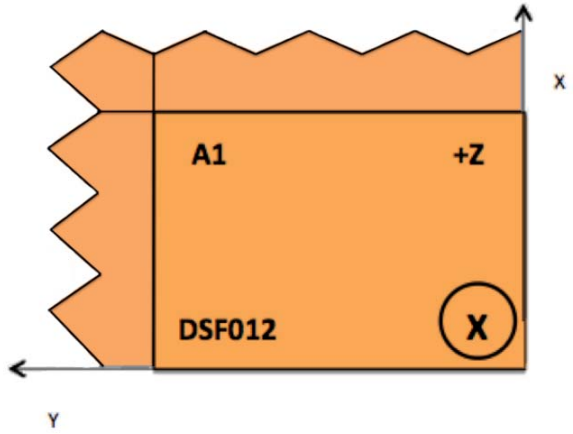

Fig. 10: Identification information written in the A1 grid on the panel. The 'x' marks the corner of the panel by the origin of the coordinate frames.

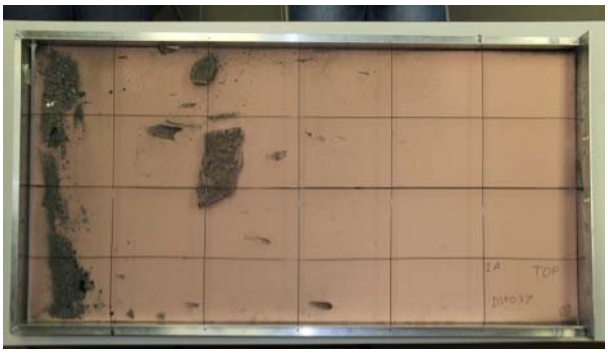

Fig. 11: Photograph of the +Z face of a panel for documentation in the DCS.

Fig. 12: Photograph of the panel identification number of the panel for documentation in the DCS.

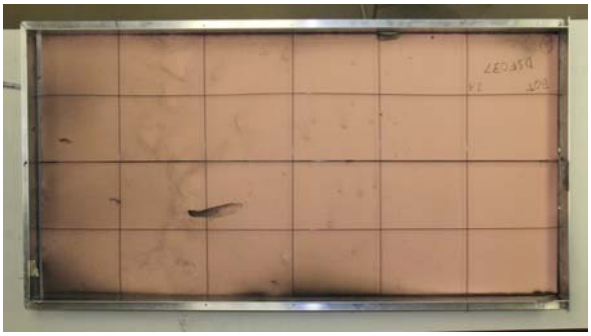

Fig. 13: Photograph of the –Z face of the panel for documentation in the DCS.

Table 1: Panel data recorded in the DCS.

Data Type	Description/Example
Foam ID	A unique identifier assigned sequentially by the database
Panel ID	ID number given to the panels at the impact chamber
Foam Color	The foam panels were organized by color in the impact chamber: green, tan, terra cotta, gray, natural
Section	The chamber was divided into 11 sections along its length (to identify the location the panels post impact). Most panels were found within the section of the soft-catch arena (Section 5)
Row	The soft-catch arena was divided into five rows (1-5) extending along the length of the chamber
Area	The soft-catch arena was divided

	into three areas (Left, Middle, Right) along the diameter of the chamber
Box Number	The boxes used to pack the panels and debris were numbered chronologically for tracking (e.g. X-23, Y-11)
Special Notes	Comments about anything of interest noticed while working on the panel

Once all visible debris is collected from both Z-faces, the panel is individually sealed in a plastic bag for transportation to the X-ray imaging facility. This is to ensure that any debris dislocated during the imaging process is at least recovered, even though its original location may not be known; any debris recovered from the transportation bags are denoted loose (L) in the DCS.

The debris collection procedure described is repeated for each foam panel in the bundle. The last layer of the bundle is a plywood panel that was used to mount the bundle in the chamber at AEDC. The underside of the plywood panel was marked with an arrow indicating the mounting direction of the bundle in the impact chamber. The direction of the arrow is recorded in reference to the coordinate system attached to the bundle for use in later modelling of the debris field.

This plastic sheet used to wrap the bundle for its transportation from the test facility during shipping (see Fig. 8) contains foam dust and debris fragments. Debris fragments meeting the 2 mm threshold is collected, identified as loose and given identification information created to indicate the plastic wrapping for the bundle. In the case of foam panels that were collected individually from the chamber, the debris found in the wrapping is associated with that panel in the DCS. The remaining fragments (smaller than 2 mm) and the foam dust is packaged, identified and stored; it is not entered into the DCS. Again, the objective is to collect as much debris as possible to ensure the availability of a significant amount of reliable data.

II.III X-ray Imaging

The bagged foam panels are transported to the X-ray facility on the University of Florida campus for the identification of embedded fragments that are not visible. The civil engineering department at the University of Florida operates an X-view CT scanner (see Fig. 14) used for two-dimensional X-ray and digitally constructing three-dimensional images.

The X-view CT allows for adjustment of the power settings of the X-ray source making it possible to generate an image that mostly eliminates the foam panel from view while showing various types of debris embedded inside the foam (see Fig. 15). The scanner also has the capability to change the position of the detector and source as well as reposition the specimen with a motorized table. The detector has an active area with dimensions of 285x406 mm (11.2x15.9 inches). By comparison, the foam panels are mostly 24x48 inches with some panels being 12x48 inches.

Fig. 14: X-view CT scanner at University of Florida

Due to the detector size constraint, 12 individual X-ray images are captured and stitched to generate an image of the pane. To assist in the acquisition of the individual X-ray images, X-ray Grid Frame is used. The X-ray Grid Frame was designed to divide the area of the panel into detector-sized sections to aid the imaging operator in capturing images of the entire panel and to function as a support structure to hold the panels upright during imaging. An example of the image from one of the grid sections is shown in Fig. 15 is. A combination of movement of the source and detector and also the motorized table allow for the imaging of each section of the X-ray Grid. However, since the foam panels are larger in the Y-dimension than the source and detector are capable to actuate, the panel/frame is rotated about the Z-axis to finish imaging the panel. The subdivision provided by the X-ray Grid Frame and the imaging pattern are shown in Fig. 16.

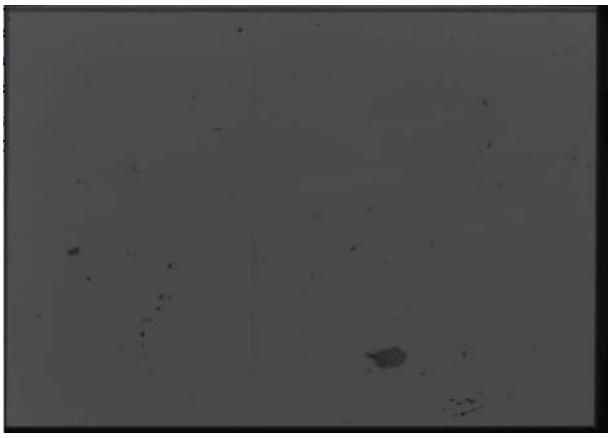

Fig. 15: Example X-ray image from panel DSF035. This is one section as defined by the X-ray Grid.

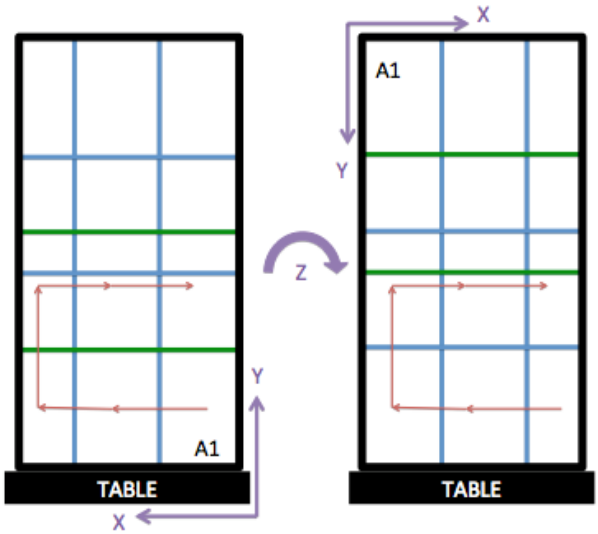

Fig. 16: X-ray Grid Frame as seen by the detector. X-ray Grid is shown with blue and green lines. Red arrows indicate sequence of images. First position on the left then the frame is rotated about the Z-axis to the second position on the right.

Due in part to time and cost constraints, only a two-dimensional image of the foam panels is collected. This was also in part due to a general decision that only a two-dimensional map of the location of the debris would be practical and sufficient for the extraction activity in the post imaging processing stage. The X-ray images are saved to the DCS.

II.IV Post Imaging Processing

Post imaging processing involves the assembly of the X-ray images from the X-view CT scanner, the detection of debris in the images and the extraction of the debris from the foam panels.

An algorithm was developed to stitch the X-ray images and create a single composite X-ray image the foam panel. An image processing algorithm was developed to analyze the composite X-ray image for the presence of embedded debris fragments. The algorithm creates a record of all debris detected in the image and marks the location of the debris on the image (see Fig. 17). This image detection algorithm was applied to panel DSF035 where more than 1500 embedded debris fragments were identified as compared to a visual inspection of the X-ray image which identified approximately 400 embedded debris fragments.

The identified fragment locations in the composite X-ray image are projected onto the surface of the corresponding panel, taking care to match the orientations of the panel and the image. The projection is then used to map the location of debris fragments onto the panel using permanent markers and mapping pins (see Fig. 18 and Fig. 19).

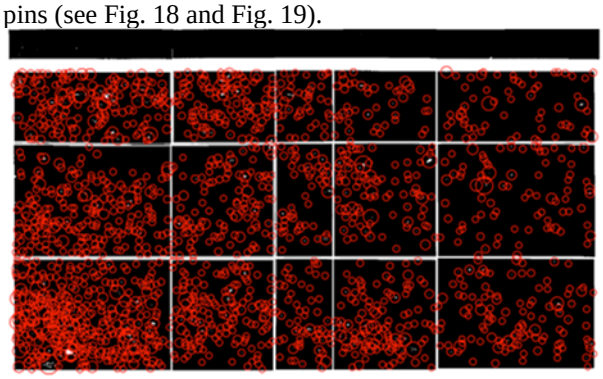

Fig. 17: Stitched X-ray image of panel DSF035 with detected debris marked by red circles.

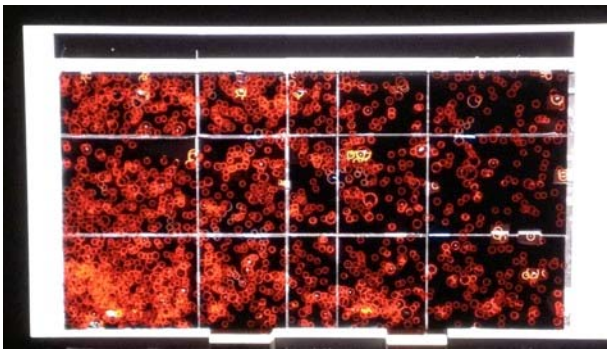

Fig. 18: Panel DSF035 with image of detected debris projected onto its surface.

Fig. 19: Panel DSF035 with locations of debris marked by map pins.

Next, the Foam Grid Frame is placed over the foam panel as was done in the pre-imaging processing to provide fragment location identification.

The approach for extracting debris from the foam panels is slightly different for the different density foams. The main difference is the choice of tools used in the extraction process. For low-density foam panels simply scraping away at the surface with tweezers is sufficient to reveal the debris. In the case of higher density foams it becomes necessary to use X-acto knives and an oscillating power tool (see Fig. 20). The power tool and knives are used to cut out the section of the foam panel containing the debris fragment and then the knives and carving tools are used to shave off the foam until the fragment is revealed.

Fig. 20: X-acto knives and oscillating power tool used for extracting debris from high-density foam panels.

Debris fragments are bagged and labelled in the same manner as described in section II.II. It is important to note that during the extraction activity, it is impossible to know if the debris marked on the map meets the collection criteria of a dimension of at least 2 mm. The X-ray image only provides a cross-sectional view of the debris orthogonal to the XY face of the panel and it is possible that even if the debris appears to be too small in the image, the 2 mm dimension of the debris may be along the Z-axis of the panel and hidden from view in the X-ray image. Another uncertainty in discriminating which debris to extract depends on the density of the material of the debris. Low densities of material will appear faint in the X-ray image, if at all. In some cases, only small dots were detected in the image for debris because only those spots were dense enough to be noticeable in the image. One such case is shown in Fig. 21 where the debris fragment found was a 10 mm sheet of carbon fiber that was embedded orthogonal to the XY face of the panel. In the X-ray image only a pair of small dots (see Fig. 22) are visible but the hole created by the sheet of carbon fiber also held a number of carbon fiber needles and a small amount of metal similar to that from a wire.

Fig. 21: Debris fragment found at the location of the two dots from Fig. 22

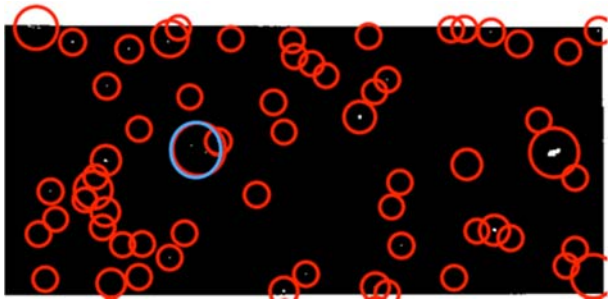

Fig. 22: X-ray image shows two small dots.

However, this is only one case and there are instances in which the detected debris is smaller than the 2 mm threshold set in the project requirements. Sufficient panels have not been processed in this manner to make definitive statements about the quality

of the identification based on the image detection algorithm. We are closely monitoring the process and report on this later.

III. DEBRIS CHARACTERIZATION SYSTEM

The Debris Characterization System (DCS) is a database created to record all of the debris collected from the hypervelocity test and the foam panels from which the debris is collected. A user interface was also developed for the specific needs of entering foam panel and debris data into the database. The home screen of this interface is shown in Fig. 23.

The DCS generates identification numbers for the foam (foam ID) and for the debris fragments (debris ID). These numbers are generated when foam and debris data is saved to the DCS. The foam ID is written on the foam panel as described in section II.II and shown in Fig. 10. The data needed in the DCS for foam is listed in Table 1.

Once the data listed in Table 2 is saved for a debris fragment, the DCS will generate a label with a barcode and the debris ID for attaching to debris bag (see Fig. 24). The debris fragment data is later edited to include measurements and other information.

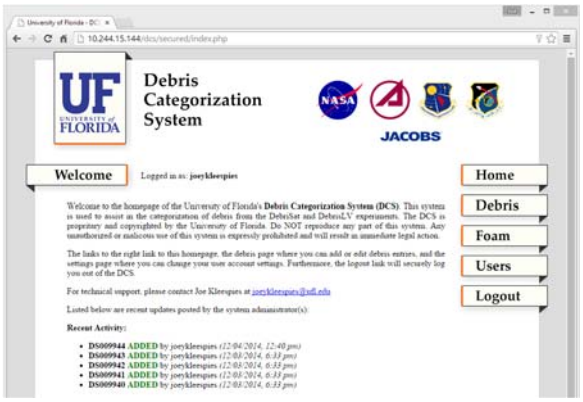

Fig. 23: Screen capture of the home screen for the DCS user interface.

IV. DEBRIS MEASUREMENT

At the time of writing, measurement activities have not begun and so this is a description of the plan for performing mass and size measurements.

IV.I Mass Measurement

One of the data requirements for the DebriSat project is to determine the mass of each debris fragment. For the larger debris, this can be accomplished with a regular laboratory scale. The debris fragments of concern for this activity are the carbon fiber needles and other miniscule debris fragments in the 2 mm size range. Through a theoretical calculation and a trial, it was determined that a microbalance is needed to measure the smaller debris. It is predicted that the carbon fiber needles will have a mass of approximately one microgram. An Ion BM-22 microbalance has been acquired and is currently being installed. One of the features of this balance, other than its accuracy, is its ability to directly interact with the database for data input. This feature minimizes the human error that may occur during data entry, considering the volume of fragments to be processed.

Handling of debris fragments in the 2 mm size range is also an issue. It is difficult to manipulate the fragment without applying pressure to it, even when using tweezers. A solution to this handling problem has taken form as a keyboard vacuum with a filter in front of the nozzle. The vacuum generates enough suction to allow the user to hover over the debris fragment without applying pressure on the surface. The fragment can be lifted and then placed on the weighing plate of the microbalance without putting unnecessary pressure on the plate that could result in the need to recalibrate the microbalance.

IV.II Size Measurement

The fragment size is defined by the *characteristic length* which is the average of the fragment's largest three orthogonal dimensions. A graphic representation of these measurements for a cylindrical prism is provided in Fig. 25.

Fig. 24: Bagged debris with label of identification number.

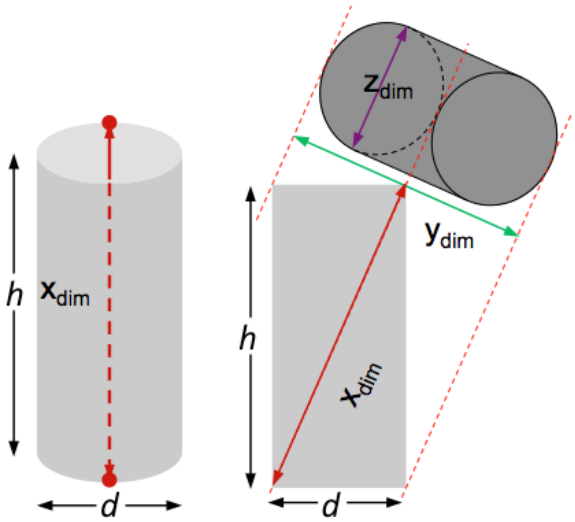

Fig. 25: Cylindrical prism with largest dimensions (X, Y and Z) superimposed.

Table 2: Data stored in the DCS for debris fragments

Data Type	Description/Example
Debris Type	ID number given to the panels at the impact chamber
Related Foam ID	The foam panels were organized by color in the impact chamber: green, tan, terra cotta, gray, natural
Grid Coordinate	If the debris fragment was found embedded in a foam panel, the grid location (e.g. C3) is specified
Box Number	The boxes used to pack the panels and debris were numbered chronologically for tracking (e.g. X-23, Y-11)
Section	The chamber was divided into sections to narrow the location information for where the debris were found post impact (e.g. the soft-catch arena was Section 5
Row	The soft-catch arena was divided into five rows (1-5) extending along the length of the arena
Area	The soft-catch arena was divided into three areas (Left, Middle, Right) along the diameter of the chamber
Shape	The Hypervelocity Test group at NASA has defined shape groups for aid in use of radar detection of debris in orbit
Material	Possibilities include all of the materials used in fabrication of DebriSat (e.g. aluminum, carbon fiber)
Mass	The mass of the debris fragment in grams
Size	Characteristic length (average of three maximum orthogonal dimensions
Special Notes	Comments describing any particular circumstance of the debris fragment
Debris ID	A number assigned in order of entry by the database

Measuring these three dimensions of the debris presented a challenge due to the fragility and randomness in shape of the fragments. Previous methods of measuring the debris involved the use of calipers and graph paper[2]. These methods require the debris to be handled and the measurements are entirely based on the judgement of the operator. Additionally, in most cases the debris fragments are either too fragile for the extensive manipulation needed to determine the correct orientations for measurement or the physical contact points required for the use of calipers typically do not exist beyond the X measurement (i.e., no physical contacts exist for Y and Z measurements). To overcome these problems, imaging technologies have been explored. For example, existing commercial three-dimensional scanners were considered but proved to be either cost prohibitive[3] or lacked accuracy[4] to measure the smaller debris fragments.

Another image-based solution was found in a technique known as space carving[5], which reconstructs a 3D image from multiple 2D images. This approach has proven to be viable and a testbed for image capture is been developed. The testbed consist of six point and shoot cameras and a green screen turntable. The six cameras are distributed along a vertical arch providing varied elevations to the image and the turntable rotates the object relative to the cameras for multiple azimuths and provide a full 360 deg. view of the test item. The space carving technique uses these 2D images to generate a 3D model of the object.

However, since the interest is the determination of the three largest orthogonal dimensions, the space carving algorithm has been modified to generate only a 3D point cloud of the object (rather than a full 3D rendering). To expedite the length determination process, a convex hull[6] algorithm is developed to process the 3D point cloud, significantly reducing the processing time. Details of the use of the space carving and convex hull algorithms determine the size of debris fragments are provided in Ref. 7.

V. CURRENT PROCESSING STATUS

The characterization phase of the DebriSat project has been active for a little more than one year and Table 3 shows the current count of items processed.

Table 3: Current count of items processed during first year of characterization phase.

Panels pre-imaging processed	304 of 564*
Panels X-rayed	148
Debris Collected (estimate)	90 000

Collecting debris fragments as small as 2 mm and processing the foam panels has proven to be time intensive work. While some of the panels have very few debris fragments others have hundreds and thousands resulting in many hours of pre-imaging processing work. The breakdown of time requirements for processing the foam panels is shown in Table 4.

* The original number of panels installed in the soft-catch arena totaled 564. Not all 564 panels remained intact post-impact but total number of intact panels will be unknown until all are processed.

Table 4: Average times for pre-imaging processing and x-ray imaging of foam panels. Post-imaging processing not included due to lack of data points at time of writing.

	Average Time (min)
All densities	149
Low-density	330
Mid-density	82
High-density	63
X-ray imaging	20

While there is currently insufficient data to report average post-imaging processing times, a high-density panel with eleven embedded debris required one hour and a low-density panel with more than 1,500 debris detected has required more than twenty hours of extraction work.

VI. CONCLUSION

The University of Florida is working on the collection, cataloguing and characterization of the debris generated in the DebriSat hypervelocity test performed in the spring of 2014. The results of this work will provide needed insight into the break-up properties of modern materials used in low-Earth orbit satellites and advance efforts to update existing standard break-up model for in-orbit collisions.

At the beginning of this characterization phase of the DebriSat project, it was estimated with the current standard breakup model that 85,000 debris fragments would be collected from the hypervelocity test. Based on initial panel processing data it was determined that the characterization phase of the project would take three years to complete from collection through measurement of the all of the debris. After one year of work, the University of Florida team has collected approximately 90,000 debris fragments while only having performed the pre-imaging processing of 50% of the foam panels and the post imaging processing of less than 10% of the foam panels. The magnitude of the debris field from the hypervelocity test was greatly underestimated and adjustments in the processing plan and schedule are being considered.

VII. REFERENCES

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