IAC-15-A6.1.30288

AN IMAGING SYSTEM FOR AUTOMATED CHARACTERISTIC LENGTH MEASUREMENT OF DEBRISAT FRAGMENTS

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The debris fragments generated by DebriSat's hypervelocity impact test are currently being processed and characterized through an effort of NASA and USAF. The debris characteristics will be used to update satellite breakup models. In particular, the physical dimensions of the debris fragments must be measured to provide characteristic lengths for use in these models. Calipers and commercial 3D scanners were considered as measurement options, but an automated imaging system was ultimately developed to measure debris fragments. By automating the entire process, the measurement results are made repeatable and the human factor associated with calipers and 3D scanning is eliminated. Unlike using calipers to measure, the imaging system obtains non-contact measurements to avoid damaging delicate fragments. Furthermore, this fully automated measurement system minimizes fragment handling, which reduces the potential for fragment damage during the characterization process. In addition, the imaging system reduces the time required to determine the characteristic length of the debris fragment. In this way, the imaging system can measure the tens of thousands of DebriSat fragments at a rate of about six minutes per fragment, compared to hours per fragment in NASA's current 3D scanning measurement approach. The imaging system utilizes a space carving algorithm to generate a 3D point cloud of the article being measured and a custom developed algorithm then extracts the characteristic length from the point cloud. This paper describes the measurement process, results, challenges, and future work of the imaging system used for automated characteristic length measurement of DebriSat fragments.

I. INTRODUCTION

Space debris poses a significant risk to the success of current and future space missions. In fact, a collision with a fragment as small as 1 cm in diameter can cause catastrophic damage. The rapidly increasing number of objects in Earth orbit adds to this potential risk. Fragmentation debris is of particular importance because it makes up over forty percent of the catalogued objects orbiting the Earth[1]. Although debris can be tracked from the ground, satellite breakup models are needed to provide predictions regarding fragments that are too small to be tracked, yet are large enough to pose a risk to satellites[2]. Thus, a method to accurately predict the debris resulting from an orbital collision is essential for effective space situational awareness.

In 2009, the collision of Iridium-33 and Cosmos-2251 made it clear that current satellite breakup model required updating. The current model is based on data from the 1992 Satellite Orbital Debris Characterization Impact Test (SOCIT) with a 1960s Navy satellite. The model predictions accurately matched the measured debris field for the older Cosmos satellite. However, the number of fragments produced by the Iridium satellite was underestimated by the model. This was due to new materials and construction techniques that are not captured by the current satellite breakup model[3].

In order to update satellite breakup models, the DebriSat project was conceived. A representative, 50-kg LEO satellite was designed and constructed using the materials and procedures utilized in the fabrication of modern satellites. DebriSat was then subjected to a hypervelocity impact test at Arnold Engineering Development Complex (AEDC), where the resulting fragments were collected[4].

The debris is currently being processed and characterized. As part of the characterization, each fragment's characteristic length will be recorded for use in the breakup models. Characteristic length is the standard parameter used by NASA to quantify a fragment's size. Characteristic length, L_c, is defined as the average of the object's three maximum orthogonal projected dimensions: X, Y, and Z. The X dimension is defined as the maximum dimension of the object. Then, Y is defined as the maximum dimension in the shadow of the object projected onto a plane whose normal is X. Finally, Z is the maximum projected dimension orthogonal to both X and Y[5].

Originally, characteristic length was measured using callipers, rulers, and graph paper. To limit human error, NASA began using 3D scanners and computer software to measure the debris fragments. While this was an important step toward removing the human factor from the measurements, the objects were still manually measured in the software by sizing a bounding box to the object[5]. As an improvement to the measurement process, an algorithm has been developed for extracting the characteristic length from point cloud data of a fragment. The point cloud consists of a set of data points with coordinates used to produce a 3D approximation of a real-world object. The algorithm is accurate and repeatable for a given point cloud[6].

The development of an imaging system for automated characteristic length measurement was driven by the need to quickly and accurately measure the tens of thousands of debris fragments produced in DebriSat's hypervelocity impact test. The imaging system was developed to acquire images of the object, create a representative point cloud, determine the characteristic length, and populate the data into a database. With this system, human error has been completely removed from fragment characteristic length measurement.

II. IMAGING SYSTEM DESCRIPTION

II.I Automated Image Acquisition

The imaging system obtains fully automated measurements using a series of calibrated cameras. Images are acquired from various azimuth and elevation angles around the object. These images provide 3D information about the shape of the fragment that is used to create a point cloud representation. The characteristic length algorithm is only as accurate as the point cloud it processes. Thus, the quality of the images and the resulting point cloud is essential for accurate characteristic length measurement. A thorough description of the image acquisition system is presented in Ref. 7.

The image acquisition process has been found to provide quicker and better quality results than commercial 3D scanners. The imaging system only takes about four minutes to acquire images compared to about an hour for 3D scanners. This is because the system only acquires the information needed for characteristic length measurement. The system does not detect concave features in the face of the fragment because these features do not contribute to the maximum dimensions used to compute characteristic length.

The non-contact measurement approach minimizes the possibility of fragment damage during characterization. It also reduces fragment handling, which could contaminate or alter the shape of the object. The automation of the image acquisition removes the possibility of operator error and improves the speed with which objects can be processed. In addition, the resulting push-button operations, as seen in the graphical user interface (GUI) in Fig. I, require minimal operator training.

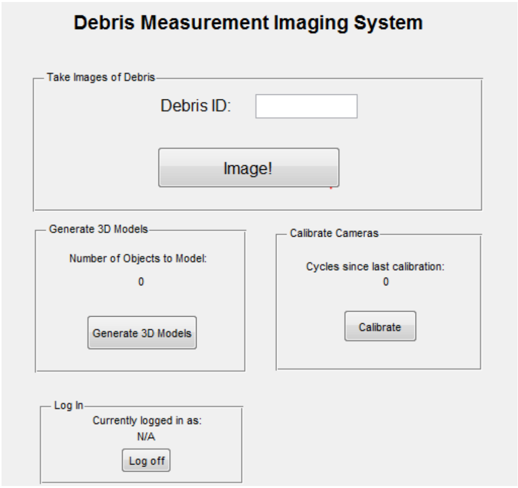

Fig. I: The imaging system GUI is shown above. Automated image acquisition can be completed by simply clicking the "Image!" button. System calibration and 3D model generation can also be completed from this window. All data is tagged with the operator's username for traceability.

II.II Object Detection

Once images are acquired, the debris fragment must be extracted from the background in each of the images. Effective object detection is achieved by using diffuse lighting and a green screen background. If the quality of object detection is poor, the resulting point cloud will not be accurate. An image processing script is used to detect the object in each image. This process takes about one minute for eighty images. A masked image is then produced where the background is converted to black.

The object detection is an automated process with operator oversight to ensure accurate detection. In the GUI, a slider can be adjusted to correct a false or inaccurate detection. As seen in Fig. II, even objects with partially reflective surfaces can be detected using the algorithm. In addition, objects as small as 2 mm (see Fig. III) have been effectively detected with this image processing approach.

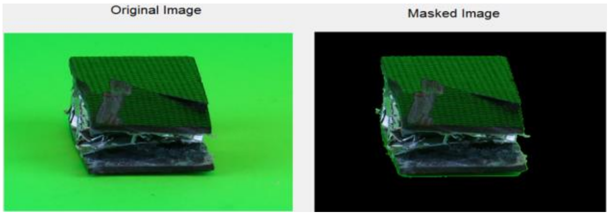

Fig. II: This section of composite panel was used as a test sample to assess the effectiveness of object detection for the types of fragments expected from DebriSat. The object has a significant amount of green reflection and yet is still effectively detected by the algorithm.

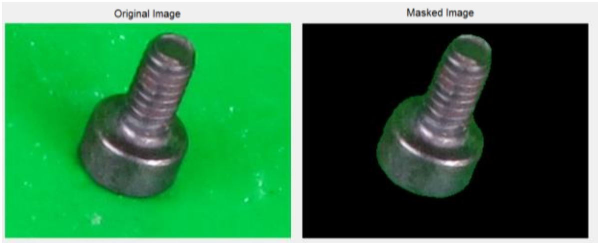

Fig. III: Fragments as small as this M2 socket head cap screw can be detected. This meets the research objective of characterizing fragments with characteristic lengths as small as 2 mm.

II.III Space Carving Algorithm

A space carving algorithm is implemented to create a 3D point cloud representation of the object from the masked images. The algorithm begins with a voxel cube enclosing the volume of the object. Calibration information provides data about the position and orientation from which each image was taken. Then, any voxel that is outside the silhouette of the object seen in any image is discarded[6]. The result is a 3D point cloud representation of the object as seen in Fig. IV. The run time for this portion of the algorithm is about thirty seconds.

The space carving algorithm cannot detect concave features in the face of the object. However, these features are irrelevant for characteristic length measurement and do not impact measurement accuracy. Because of the 3D reconstruction methodology of the space carving algorithm, the resulting point clouds are very clean and do not have extraneous points. These points often appear in 3D scanning systems and must be eliminated with post processing. However, the space carving approach only keeps points that are in the intersection of the silhouettes seen in all images. Thus, if a point is seen by all images, it is highly likely that it is indeed a part of the actual object.

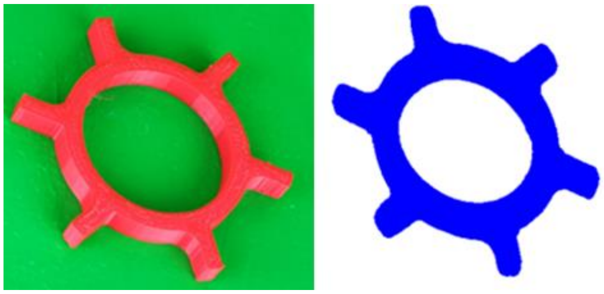

Fig. IV: A test sample image is shown (left) alongside the point cloud produced by the space carving algorithm (right).

II.IV Characteristic Length Algorithm

The point cloud of the object is then processed using an algorithm that returns the characteristic length measurement. A detailed explanation of the algorithm developed can be found in Ref. 8.

The algorithm uses a convex hull approach, which was developed to solve the computational geometry problem of finding the diameter of a point set. The convex hull reduces the number of points whose pairwise distances must be computed. This is because the points that give the diameter of the set are known to be vertices on the convex hull[9]. This improves the algorithm's computational speed so that it can measure a point cloud in less than one second. Coordinate transformations are achieved using direction cosine matrices to obtain the orthogonal projections needed for characteristic length measurement[6].

The automated measurement process produces three images of the point cloud, like the one shown in Fig. V, that show the maximum orthogonal dimensions used to calculate the characteristic length. This provides an opportunity for operator oversight of the object size characterization. The operator can judge the quality of the point cloud and the accuracy of the characteristic length measurement. In addition, this data can be stored for documentation of the measurements taken.

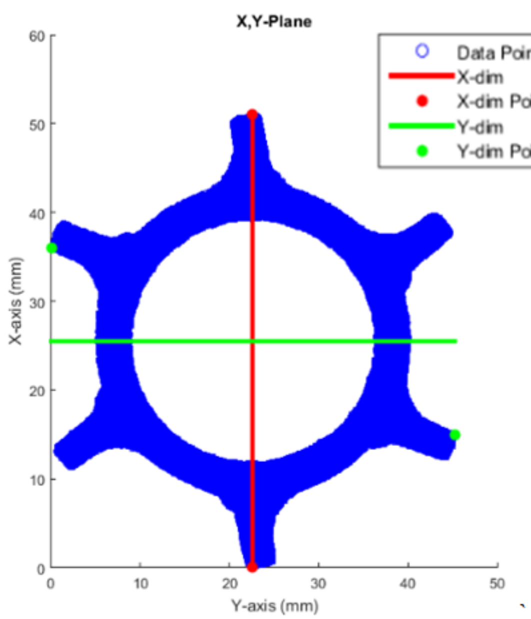

Fig. V: A 3D printed test object was processed and the algorithm returned the above plot that shows two of the three orthogonal maximum dimensions. The good quality of the point cloud, with distinct edges, is critical for accurate length measurement.

II.V Database Updating

The final step of the imaging system is to record the measurements in the project's mySQL database. The imaging system records the object's characteristic length, and X-, Y-, and Z-dimensions. As shown in Fig. VI, these measurements are automatically written to the database entry for that particular object's debris ID, which is inputted using a barcode scanner. In addition, pictures showing three orthogonal views of the object are added to the database. Furthermore, all of the raw images and the point cloud are stored to the server. Storing this data to the database helps with the data collection objectives of the project and provides documentation and traceability of the measurements conducted.

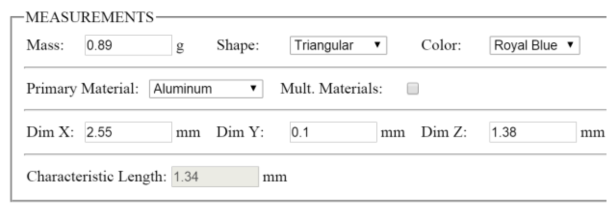

Fig. VI: The database entry for an object's X-, Y-, and Z-dim is shown above. The characteristic length is also reported. These fields are automatically populated into the database by the imaging system. Other characteristics of the debris fragment are manually inputted.

III. SYSTEM RESULTS AND VALIDATION

III.I Test Samples

The imaging system was tested using a variety of test samples. These samples included fragments representative of those collected from the hypervelocity impact test of DebriSat. However, they also included test objects intended to test the system's ability to measure reflective objects such as MLI, objects as small as 2 mm in length, and irregularly shaped objects.

III.II Measurement Results

Preliminary measurement results indicate that the characteristic length measurement accuracy is on the order of 2%. This accuracy is expected to improve as the system is further developed.

Preliminary testing also indicates the repeatability is on the order of 1.5%. Because the automated imaging system removes the human factor from measurements, random error in measurements can be mitigated. This merely leaves systemic error which can be accounted for in measurements.

While the results are promising, the imaging system was unsuccessful at generating point clouds for several test samples. These samples were typically either too small or too reflective to be effectively converted into a point cloud. The focus of future development of the imaging system will be to effectively process these test samples.

III.III Measurement Verification

Verification of measurements was performed through comparison to existing characteristic length measurement approaches, including NASA 3D scanner measurements and hand measurements with callipers. NASA provided point clouds of thirteen debris fragments that had been previously 3D scanned and measured. These point clouds were measured with the characteristic length algorithm to within about 1%, on average, of the NASA measurements. In addition, point clouds with known dimensions were generated using computer-aided design software. These point clouds were accurately measured to machine precision. With the new imaging system, accuracy has been retained while the time required for measurement has been reduced from over an hour for 3D scanned measurements to less than one second. Measurement results were also compared to hand measurements of the object using callipers. This approach validated the accuracy of the measurement system. However, it also served as a reminder of the benefits of the imaging system over hand measurements. Obtaining measurements with callipers proved to be difficult and time consuming. In addition, hand measurements require handling the fragment extensively, which increases the risk of contaminating or damaging the object. Future testing will involve measuring calibrated objects with the imaging system to have a precise comparison for measurement accuracy.

IV. CHALLENGES AND FUTURE WORK

IV.I Point Cloud Quality

The quality of the point cloud is a function of the number and orientation of images taken. Taking more images of the object from different angles increases the accuracy of the point cloud. However, this also increases the time required to image the object and generate a point cloud. Also, storage of the images becomes an issue. Because of the large number of fragments to be characterized, processing time and data storage are important considerations. By taking images from the optimal orientation angles around the object, the number of images can be minimized while still meeting the required 5% measurement accuracy.

One of the main issues with the point clouds is the convex features that result from the limited number of angles from which the object is imaged. In particular, imaging from lower elevation angles would be beneficial but poses difficulties with calibration. A new calibration procedure is being implemented to allow the use of images from lower elevation angles.

IV.II Detecting Reflective Objects

Effectively distinguishing the object from the background has been challenging with highly reflective objects, such as multi-layer insulation (MLI). This is because the object’s reflection is close enough to the background colour that the object detection algorithm cannot distinguish between them.

Several solutions to this challenge are possible. A polarizing filter has been used to eliminate reflections with limited success. Another option is to coat reflective objects in a material that will limit reflections. The issue with this approach is the contamination of the object in order to obtain a measurement.

IV.III Processing Small Objects

Although objects as small as 2 mm in length can be detected in the images, issues have arisen when trying to create a point cloud of small objects using the space carving algorithm. When the algorithm is run on small objects the result is an empty point cloud where all voxels have been carved away. Camera calibration and the space carving code are two potential causes that are currently being investigated.

Issues with camera calibration could be the cause. With small objects, small errors in calibration can have major impacts on the quality of the point cloud and the resulting measurement accuracy. A more precise checkerboard calibration pattern will be used to improve accuracy. In addition, a more rigid setup will be used to preserve the calibration as images are acquired.

The space carving algorithm code could also contribute to this challenge. The algorithm is not optimized for small objects. Therefore, the voxel resolution may be too large for small objects.

As the imaging system is further developed, the smallest size object that can be accurately measured will be experimentally determined. This will involve optimizing the space carving algorithm voxel sizes for small objects. Research will also focus on using 2D imaging with a single picture for small, flat objects. For objects like this, a 2D approximation may result in a much quicker measurement with comparable accuracy to 3D imaging.

IV.IV Experimental Accuracy and Precision

One of the primary benefits of this imaging system is that the automation allows for the error and repeatability of measurements to be quantified. This will be achieved by continuing to process test samples. The accuracy will be determined by looking at the measurement error between hand measurements with callipers, 3D scanning, and the imaging system. The exact 3D model of the object imaged will also be measured for accuracy reference. The robustness of the imaging system will be tested by processing a variety of shapes and sizes of objects.

In order to quantify the repeatability of measurements, the same object will be processed with the algorithm numerous times. The object will be placed on the imaging platform in different orientations to account for the measurement differences that can result from how the operator places the object in the system.

IV.V Image Acquisition Speed

Turning to the next azimuth angle is the most time consuming part of image acquisition. This is because the maximum turntable angular acceleration and velocity are limited to prevent movement of the object during imaging. To ensure that the object has not moved during imaging, an automated check will be implemented by comparing the first and last image taken at the same location.

IV.VI General User Interface

Future work will also focus on completing the graphical user interface (GUI) for the imaging system. This system will allow the operator to input the fragments debris ID number by simply scanning a barcode on the debris bag. The operator can then click a button to process the fragment. This will begin an automated routine to acquire images of the object. The GUI will also feature the option to run camera calibration. The operator will be prompted when new calibration is required after a prescribed number of imaging cycles. To improve processing speed, the fragments will simply be imaged while the operator is present. Then, the processing can be completed in the downtime overnight. At that time, the system will generate a space carved point cloud, measure the characteristic length, and upload the information to the database. Since the operator will be required to log in to the system, all database entries will include the name of the operator that conducted the processing.

V. CONCLUSION

The imaging system presented in this paper provides a complete, end-to-end solution to debris size characterization through characteristic length measurement. The system is fully automated with image acquisition, image processing, 3D point cloud generation, point cloud measurement, and database entry. For quality control purposes, operator oversight of the process is incorporated.

This imaging system is a significant improvement over the current methods of debris size characterization. The measurement results are faster, more accurate, and more repeatable than existing measurement approaches. Because the human factor is removed from measurement, the system uncertainty can be quantified. In addition fragment handling is limited to prevent damaging the samples.

The size characterization process involves simply placing the object on the setup, pressing a button, and removing the object six minutes later once it has been characterized by length. The system developed will be used for size characterization of the tens of thousands of debris fragments generated by the DebriSat test. The results will be used to develop new satellite breakup models. The resulting improvement in space situational awareness will benefit current and future space missions.

[1] Osiander, R., and Ostdiek, P., "Introduction to Space Debris," *Handbook of Space Engineering, Archaeology, and Heritage*, CRC Press, Boca Raton, FL, 2009, pp. 363-379.

[2] Englert, C., et al., "Optical Orbital Debris Spotter," Acta Astronautica, Vol. 104 (2014), pp. 99-105.

[3] Werremeyer, M., et al., "Design and Fabrication of DebriSat – A Representative LEO Satellite for Improvements to Standard Satellite Breakup Models," 63rd IAC Congress, Naples, 2012, IAC-12,A6,3,7,x16098.

[4] Rivero, M., Edhlund, I., et al., "Hypervelocity Impact Testing of DebriSat to Improve Satellite Breakup Modeling," 65th IAC Congress, Toronto, 2014, IAC-14-A6.2.10x25834.

[5] Hill, N. M., and Stevens, A., "Measurement of Satellite Impact Fragments," NASA Orbital Debris Quarterly News, Vol. 12, No. 1, Jan. 2008, pp. 9-10.

[6] Kutulakos, K. N., and Seitz, S., "A Theory of Shape by Space Carving," International Journal of Computer Vision, Vol. 38, No. 3, 2000, pp. 199-218.

[7] Moraguez, M., and Patankar, K., et al., "An Imaging System for Satellite Hypervelocity Impact Debris Characterization," AMOS Conference, Maui, 2015.

[8] Moraguez, M., "An Algorithm for Characteristic Length Measurement from Point Cloud Data," AIAA Student Conference, Savannah, GA, 2015.

[9] Mount, D. M., "Computational Geometry," *CMSC 754, University of Maryland*, 2012, pp. 10-21.