Design of Quality Assessment System for On-Orbit 3D Printing Based on 3D Reconstruction Technology

Jianning Tang, Xiaofeng Wu

***Abstract*—**With the increasing demand for space use in multiple sectors (navigation, telecommunication, imagery, etc.), the deployment and maintenance demand of satellites are growing. Considering the high launching cost and the restrictions on weight and size of the payload when using launch vehicle, the technique of on-orbit manufacturing has obtained more attention because of its significant potential to support future space missions. 3D printing is the most promising manufacturing technology that could be applied in space. However, due to the lack of autonomous quality assessment, the operation of conventional 3D printers still relies on human presence to supervise the printing process. This paper is proposed to develop an automatic 3D reconstruction system aiming at detecting failures on the 3D printed objects through application of point cloud technology. Based on the data obtained from the point cloud, the 3D printer could locate the failure and repair the failure. The system will increase automation and provide 3D printing with more feasibilities for space use without human interference.

***Keywords*—**3D printing, quality assessment, point cloud, on-orbit manufacturing.

I. Introduction

ON-orbit manufacturing technology has obtained interests from multiple institutes and commercial companies because of its huge potential in supporting long-term space missions, as the long-term space mission can pose a heavy burden on multiple factors including design and manufacturing of space architectures and delivery of supplies [1]. The 3D printing technology was firstly introduced in 1987 as a fast-prototyping approach [2]. After years of development, the technology is widely used in various industries and is capable of operating with multiple categories of material (polymer, metal, ceramic and concrete) [3], [4]. Furthermore, several 3D printing techniques are developed, including Stereolithography (SLA), Selcetive Laser Sintering (SLS), Fused Deposition Modelling (FDM) and recently developed cold spray [5]. Amongst them, FDM with its multiple merits (all-around hardware, lower operation cost and flexible material choice) has shown its great potential for space use. Particularly, the 3D printing using FDM has no need to deploy laser generation system onboard the printer, which can simplify the printing structure and save energy. Both features are important factors that must be considered when designing the 3D printers for space use. In recent years, NASA, partnered with Made in Space, Inc., has successfully completed the 3D printing demonstration in the International Space Station (ISS) and the printed samples have been tested and compared with the counterparts printed on the ground. The result proved that the microgravity would not cause any significant effects on the 3D printed pieces [6]. Meanwhile, European Space Agency (ESA) has analyzed the feasibilities to build lunar base with moon regolith using 3D printing. A 3D printed 1.5-ton moon base model has been built up with moon regolith [7]. Chinese Academy of Space Technology (CAST) has also performed on-orbit 3D printing experiment in Chinese new-generation manned spacecraft in 2020 [8]. However, research on the quality assessment including failure detection and repairing on the space-based 3D printed objects is not adequate, which is important to ensure the reliability of the 3D printed objects. Some failure detection strategies which are developed previously are mainly applied in ground-based 3D printers but are not applicable to space use [9]-[12]. Some researches regarding the thermal control and the robotic arms for space-based 3D printer are the attempts to apply 3D printing technology in exposed space environment [13], [14]. The space-based quality assessment system must be able to detect the failures. More importantly, this technique should also be capable of obtaining the precise geometry features and then guiding the printer to fix. In this paper, a quality assessment strategy capable of both detecting and repairing failures on 3D printed objects will be developed using 3D reconstruction technology.

II. Methodology

The 3D reconstruction is achieved by 3D scanning in this paper. As the output of the 3D scanning, the point cloud is processed to obtain the geometry features of defects on the target sample (dents in this paper). The samples used in the experiment are 3D printed with FDM technique. The final repairing process on the target sample is achieved by FMD with same printer. Through the reconstructed of the digital model of the damaged 3D printed pieces with a 3D camera, the point cloud of the target is created. Then the point cloud needs to be carefully modified to remove the noise points and fill the holes on the surfaces. The process is performed in Meshlab in this study. The modification is key to ensure the results of repair in the next stages. The noise points on both edges and surfaces of the model are removed manually in this study. Meanwhile, the holes are filled by using the close hole function in Meshlab. The max size for the holes to be filled must be adjusted with caution

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to avoid any change on the shape features of the model.

The reference model of the target object built in SolidWoks will be imported to Meshlab to compare with the fatigue model obtained by meshing the point cloud. The Boolean difference algorithm is used to derive the difference between the two models. Before the execution of Boolean difference, it is important to align the models. Multiple approaches are available for aligning. In this study, point based methods are used. The alignment process can make both models glue together based on the points selected previously on the model.

With Boolean difference algorithm, the difference between the standard Solidworks sample and the model obtained by 3D scanning can be obtained. The difference reflects the potential fatigue on the target object. The common defects including cracks and dents can be detected in this way. Then the derived point cloud and the mesh of the detected defects can be further aligned with the target defective sample to obtain location information in the general coordination system. The information will be used to generate G-code used for 3D printer to fill the defects on the object.

III. Experiment

In the experiment, Creality Ender 3D Pro Fused Deposition (FDM) 3D printer is used to print the 3D pieces with proposed defects (dents in this study). The Meshlab, Solidworks and Creality Slicer are used to build the model, process the point cloud and slice, and generate G-Code for the 3D printer. The faulty sample printed and analyzed in this paper is 40 mm width, 100 mm length and 10 mm depth with 3 dents on the surface. The study uses Creaform 700 3D scanner to obtain the point cloud of the 3D printed pieces. The performance data of the 3D printer are shown in Table I. The original point cloud has 247 thousand points (ss shown in Figs. 1 (a) and (b)).

TABLE I
The Performance Parameters of the 3D Scanner Used in this Experiment

Accuracy	Up to 0.03 mm
Volumetric Accuracy	0.02 mm + 0.06 mm/m
Measurement Resolution	0.05 mm
Measurement Rate	480.000 measurements/s
Light Source	Laser
Scanning Area	275 mm x 250 mm
Depth of Field	250 mm

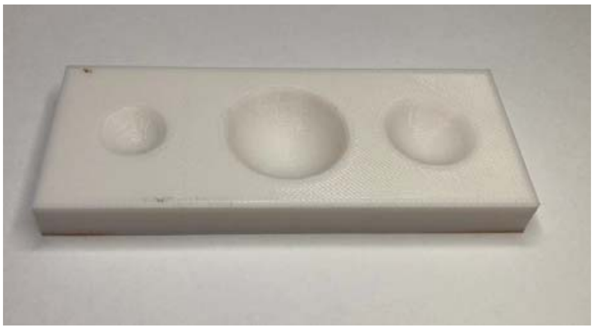


Fig. 1 (a) The 3D printed sample with proposed defects (dents)

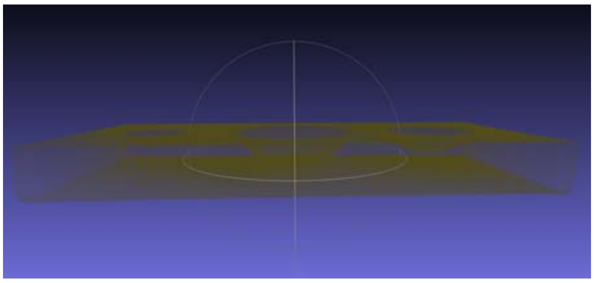


Fig. 1 (b) The original point cloud

The point cloud is simplified to reduce the number of points as the handling of a large amount of points in process can cost enormous computational resource and is time consuming. A variety of methods can be used to simplify the point cloud by reducing the number of points. The methods include cluster decimation, quadric edge collapse decimation using quadric based edge collapse strategy [15] and simplification method based on Poisson Disk strategy. In this study, Poisson Disk strategy is used to reduce the number of points. By setting the number of samples as 60.000, the Poisson Disk radius is derived automatically for down sampling. The resultant point cloud can be seen in Fig. 2 with approximately 115 thousand points, almost 50% of the total points have been simplified. The simplified model is then meshed by applying the Ball Pivoting Algorithm [16]. The meshed model can be seen in Fig. 3. The holes can be seen obviously on the model surface.

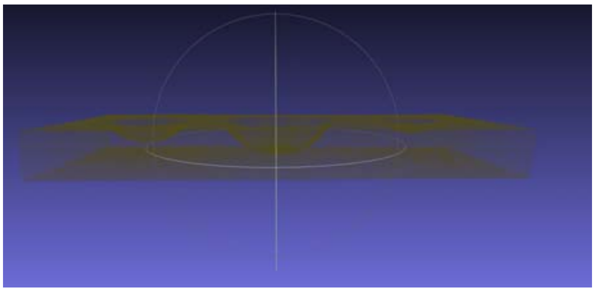


Fig. 2 Simplified model with approximate 115 thousand points by using Poisson Disk strategy

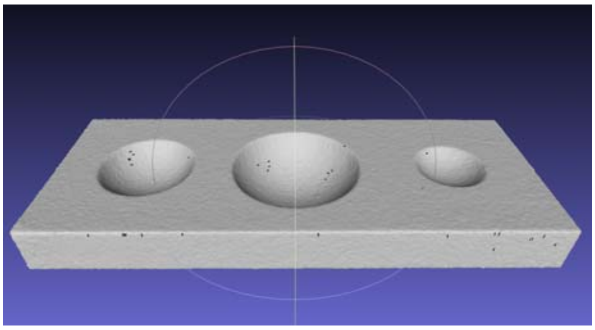


Fig. 3 The meshed model (the holes can be seen on the surface)

The use of the hole filling algorithm embedded in Meshlab can close the holes. However, the removal of the holes needs to be cautious to set the minimum hole size value to be filled up in this phase, as using too big value for the hole size may cause the defects to be filled on the sample and then miss the defects. By setting the minimum hole size value at 10 in this case, the holes are well filled. The meshed model with filled holes can is shown in Fig. 4. Keeping the model watertight with closed holes is essential to obtain correct result using Boolean difference algorithm.

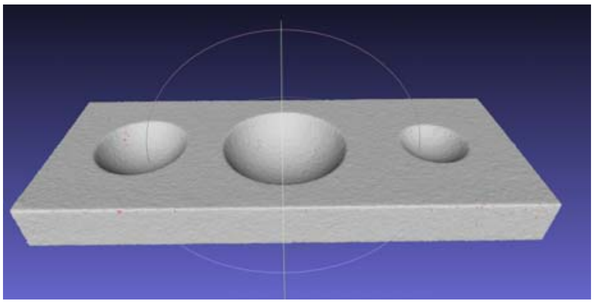


Fig. 4 The meshed model with filled holes (the filled holes are highlighted in pink in the figure)

The original reference sample built in SolidWorks is shown in Fig. 5. The reference model is the sample with desired geometry features. The reference model is used to compare with the target defective model in Boolean difference operation to extract the defective features on the target object model being scanned previously.

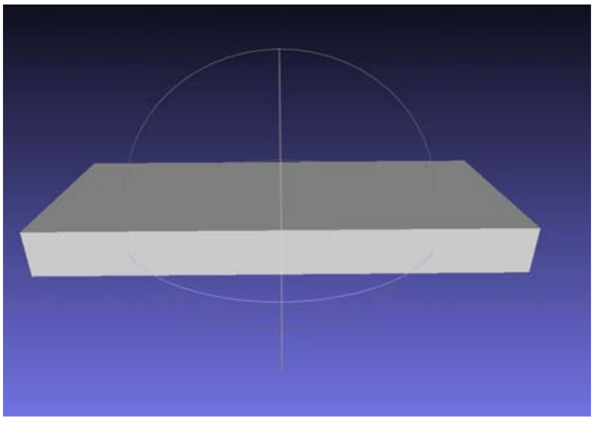


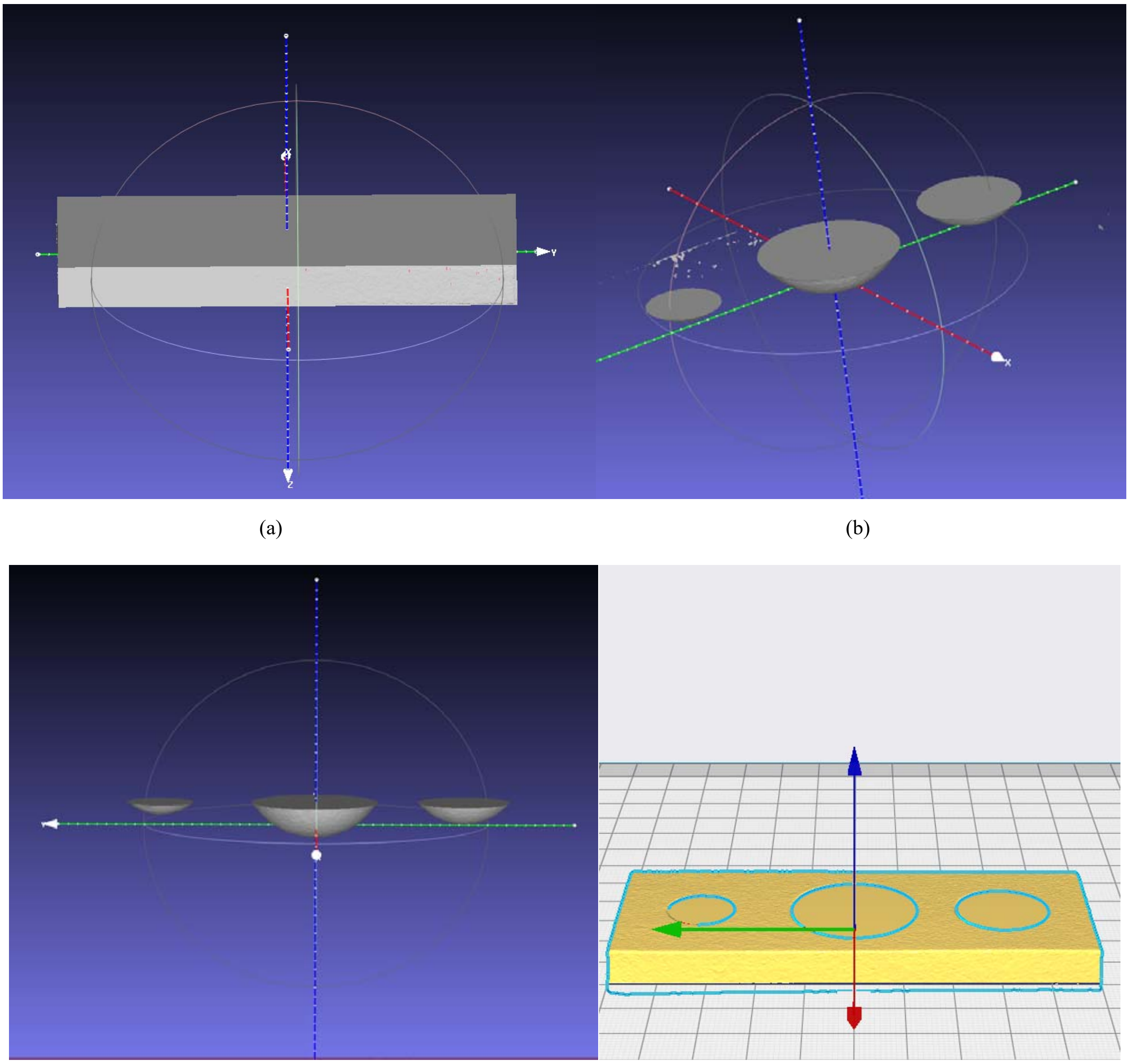
Fig. 5 The reference sample with 40 mm width, 100 mm length and 10 mm height

The alignment between the reference model and the model derived from scanning is accomplished via four points method. The Boolean Difference is applied to derive the defects based on the scanned sample and the reference model. The defects need to be further aligned with the scanned sample in Creality Slicer and sliced to generate G-Code for printer use (as shown in Fig. 6). The alignment involves the position adjustment of the derived defects on X axis, Y axis and Z axis, which is critical to achieve the desired repairing result, all the dents fully filled. More importantly, the adjustment process on the relative position between the scanned sample and the derived defects can optimize the printing route of the extruder for repairing. Following the optimized route to repair the defects can avoid the collision between the extruder and the surface of defective sample while repairing process. To be more exact, the collision of the extruder with the target objects surface may cause further damage on the object due to the high temperature on the extruder and may also result in the deformation on the printing beam. Both results are irreversible. The beam deformation on the printer will permanently affect the printing precision and cause scraps on the future printer results. Therefore, adjustment on the relative position to align the derived defect with the samples with failures is the essential process to repair the failures successfully.

Through importing the G-Code to the Ender 3D FDM printer, the dents on the scanned sample can be filled with newly printed fillers whose shape is the same as the dents on the scanned faulty sample. To avoid the potential risk on the extruder collision with the sample, in the experiment, an additional 0.2 mm offset is added on the Z axis of the defects as shown in Fig. 7. As a result, the printed filler in the dent is a little higher than the original sample surface. The offset can be lower with the use of 3D printer and 3D scanner with higher precision. Although the use of offset on Z axis is a feasible approach to further lower the collision risk based on the adjustment of relative position, it is not recommended to apply an overly high value on the offset. The bonding force between the newly deployed layers and the original layers on the sample will be affected significantly as the use of overly high offset. The repairing result on the sample used in the experiment is shown in Fig. 8.

IV. Discussion and Conclusion

The use of 3D scanning technology can generate the point cloud of the object geometry features. The failures on the object can be detected by comparing with the reference sample. However, the precision of the geometry features largely depends on the accuracy of the 3D scanner being used. As the features of the defects will be further used by the 3D printer with the diameter of the extruder being 0.4 mm, and printing precision being ± 0.1 mm, to avoid any detachment between the newly extruded layers and the original object surface, the precision of the 3D scanner needs to be less than ± 0.1 mm. In addition, with the adjustment on the focal area of scanning, the scanning speed can be changeable by trading off the accuracy, which is applicable to single defection tasks without the need to engage the printer for repairing. The printing technique used in this paper is FDM printing with PLA. The printing temperature for the new layers used to repair the defects must be higher than the melting temperature of the printing material to guarantee enough bonding force between the newly deployed layers and the original surface on the object. The use of the quality assessment (QA) system has the potential to resolve the concerns on failure defection and maintenance for the space architectures in space environment. The development of the system can extend the service life of the architectures in space and improve the safety of space missions to support the more sustainable and earth-independent long-term missions. This paper can be the preliminary research on the application of QA system in space. Further studies on the feasibilities of the failure detection and repairing with other kinds of material like PEEK, moon regolith and metal material are necessary, as these materials would be also commonly used in further space missions. Furthermore, the bonding force between different printing materials with different printing temperature while repairing is also worthy of further research.



(a) (b) (c) (d)

Fig. 6 (a) The alignment of the scanned model and the reference model; (b) The derived results by applying Boolean difference; (c) The defects (dents) derived after removal of noise points; (d) The alignment between the defect models and the scanned sample

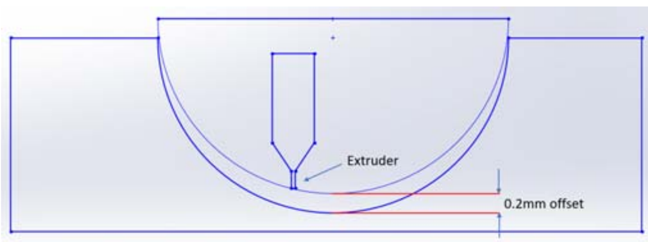


Fig. 7 The addition of offset on Z axis to avoid the extrusion collision with existing sample surface

Fig. 8 The repaired faulty sample with the dents filled

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