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Three Dimension Scanning using Infrared Coded Light

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Abstract: In this competitive market, reverse engineering is introduced to shorten a new product development time by digitizing an existing product for rapid redesign. In this project, a low cost and standalone 3D scanner is being developed to achieve this purpose. Research is done comparing advantages and limitation of different hardware and method for 3D scanning. Scanner is assisted by automated rotating and illumination scanning platform to improve its performance. Software is developed for scanning of object using a Red-Green-Blue-Depth (RGBD) camera. The scanned result is processed and refined using global and local registration method. Poisson surface reconstruction is performed on the processed point clouds for generating triangular mesh. This scanner able to scan the object with the accuracy up to 5mm with computational time around 25 minutes.

Keywords: 3D Scanning; Infrared Coded Light; Random Sample Consensus(RANSAC); Iterative closest point(ICP); Poisson Reconstruction.

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1. INTRODUCTION

Conception and manufacture of discrete products has been an important part in civilization. Up to 21th century, product enterprises still seeking for various ways shorten the lead time of product development to meet customer expectation. Product enterprise has invested in rapid prototyping, Computer Aided Design/ Computer Aided Manufacturing (CADCAM), Reverse Engineering and other new technologies to be more competitive which could provide business benefits. Rapid Prototyping and Reverse Engineering refers to the reproduction and duplication of physical object or existing part without drawing, documentation and computer model data [1] and understanding the principle behind of an object through analysis of its structure [2].

Increasing complexity in design have been a great challenge for all industry. For example, engineer and designers uses clay and plaster to present their ideas during automotive styling. However, a CAD model would be required for the idea to be manufacture. As the idea become more complex in shape, designing in CAD become more difficult because there is no guarantee that the CAD model could duplicate the sculpted produced [1].

A three-dimensional (3D) scanner is used as a device to assist in reverse engineering process. It has the capability of analyzing an object and convert the object surface to points coordinates. The point coordinate is then collected to set into a 3D model. The main difference between an ordinary scanner and a 3D scanner is 3D scanner are capable to produce a 3D image by collection of points in 3D coordinates on the object surface [2].

Image of a scene on the left eye is different from the image on the right eye as stated by Leonardo da Vinci. Their "difference" is known as Da Vinci stereopsis which can be used to infer the three-dimensional structure of the scene [3]. Vision has played an important role in the life of human allowing us to infer spatial properties of the environment that are necessary to perform crucial tasks towards survival [4].

The role of vision is implemented in a system transforming measurements of light intensity into estimating the geometric characteristics of the environment. Similar with human visual system where it produces an estimation of 3D layout of the scene by measuring the intensity of light incident the retinas and processes the measurements, artificial vision system developed could process light intensity measured by a camera and produce a 3D layout of the scene being viewed [4].

2. LITERATURE REVIEW

3D reconstruction of an object stands for the representation of the object spatial geometry in form of point cloud. This point cloud can be either sparse or dense, which is highly depend on the sensor's scanning rate. The information sense by the sensor is the relative x (width), y (height) and z (depth) distance between every point and the sensor in the sensor local coordinate system [5]. The structure of an object which include its spatial coordinates can be sensed based on the adoption of optical technology [6], shows in

Figure 1 and can be subdivided into either direct approach using active sensors or indirect approach using passive sensors [5], [6].

2.1 Passive Sensor

Example of passive sensor include normal Red-Green-Blue (RGB) camera. Single (monoscopic) or dual (stereoscopic) RGB camera with the help of photogrammetry software can be used for 3D reconstruction of an object [5]. The correspondences between each feature in different images is established manually to estimate the 3D coordinates through triangulation. The availability of high-resolution cameras has advanced for 3D reconstructions [7].

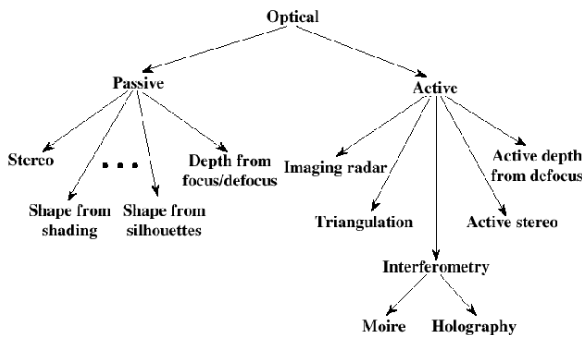

Figure 1. Texonomy of systems for shape acquisition [8]

Method of triangulate the image captured by passive monoscopic camera is known as photogrammetry [7]. The core principle of photogrammetry is triangulation, where the spatial points or geometrical information is reconstructed from mathematically converging lines from 2D locations of target point in multiple images taken from different positions and angles [5], [7].

Advantage of photo imaging using monoscopic camera with photogrammetry technique is that it the process of image does not need to be in real-time and can be later used to extract information pertinent to object colour and texture, makes it highly versatile [7]. Lower equipment cost is needed for this application where even using a digital RGB camera of a mobile phone can perform this task.

However, photogrammetric approach require high volume of images taken from different angle to generate sufficient information on object spatial coordinates [5]. Besides that, this method is time tedious and human intervention might affects the resolution of the scanned object [7]. The error in depth measurement is proportional to the square of depth. The occlusions are also often difficult to handle since the camera the camera need to be recalibrate if moved from one location to a new location [5].

2.2 Active Sensors

Active sensors such Red-Green-Blue-Depth (RGBD) camera, Structured Light projection system and Time of Flight (ToF) sensor used direct approach for the calculation of spatial information. In RGBD camera, components such as structured or coded infrared (IR) projector, infrared (IR) camera and colour (RGB) camera are normally integrated into single piece. It can either use monoscopic IR camera or stereoscopic IR camera with increase accuracy for 3D geometry acquisition [8].

Structured light projection scanning system has been designed with two common electronic devices including Digital Light Processing (DLP) projector and a digital RGB camera [6]. DLP projector is used to project light source with a known pattern or structure on the object to be scanned [6], [8]. The 3D scanning process involves series projection of light patterns onto the object that being scanned while single or multiple digital RGB camera is used for the acquisition of images of the object under structured lighting [3].

For RGBD camera and structured light scanning system, the projected light pattern (structured infrared or light) on the object will distorted based the geometry properties of an object and this information can be used to computed the depth or spatial properties of an object [3] by identify the similarities between the every pixels in images captured by camera(s) [8]. For the reconstruction of point cloud, triangulation is used [6], [7], [9] in many industrial applications. Figure 2 shows the scheme of monoscopic sensor for point cloud reconstruction.

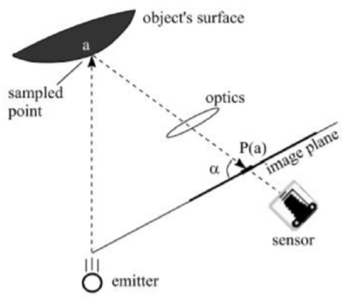

Figure 2. Scheme of typical active monoscopic sensor [6].

RGBD camera can be used for estimation of depth properties in areas with poor visual texture or illumination. This is due the infrared camera able to capture the infrared depth image at low light condition [10]. RGBD camera is highly portable due to its small form factor with satisfying accuracy which is suitable for scanning of complicated and textured surface [8]. However, depth images of RGBD camera might contain numerous 'holes' with no depth reading. This might be due to certain object surface structures does not reflect or over reflect the infrared light. Furthermore, even that the depth camera able to capture the depth image in low light condition, there will be the loss in the colour information if the object is scan under low light condition [10].

The advantage of using structured light projector as emitter is that it has infinite number of different light patterns. The light pattern can be modified based on user applications. For example, depending on the surface reflectance of an object, the projected light can change its colour to enable the detection of constituent features which results in higher accuracy of scanning results [6]. However, light projectors which cannot focus at short distance will limits the sampling density of the object surface [6]. Besides, the size of the light projectors is usually too bulky to be portable [3].

Time of Flight (ToF) sensors such as Light Detection and Ranging (LIDAR) or Laser Detection and Ranging (LADAR) which is a remote sensing sensor is useful for making spatial measurement [7]. The sensors scanning will acquire data or geometry properties of a scanned object in form of 3D points which is known as point cloud. The point cloud will use for reconstruction of 3D models using specialized software systems. ToF based surface measurement is suitable for long range scanning application and has the advantages of high sensing speed [8].

ToF sensors used the principle of waves to perform distance measurement. Low amplitude waves are propagated from an emitter through an object to measure distance of an object. The reflected waves are detected by a receiver and processed mathematically with specified filter functions to produce a processed signal time function. The pulses of acoustic or light waves can be used for echo ranging of distances on an object by interval time measurement start from initiation of the pulse until the return of the echo [10].

ToF sensor can cover a long scanning range with less distortion. Therefore, they are very suitable to use for outdoor applications. It able to capture the infrared depth image at low light condition [10] and having a small form factor. However, ToF sensor is expensive in price and in order to obtain a densely 3D point cloud, additional components such as motors are needed which increase the size of the scanner [9]. Parallel ultrasonic beam emitted from the transmitting transducer has relatively poor resolution and need to be manually focus by lens [11].

3. PROJECT METHODOLOGY

Development of project can be categorized into three stages including hardware design, real-time scanning software development and post-process software development.

3.1 Hardware

Raspberry Pi 4 Model B with ARM v8 processor is chosen to act as the core controller for 3D scanner. Active stereo RGBD camera is chosen for the application of 3D scanner due to the low cost and small form factor of the sensors. It also provides the availability to work under low light condition, and suitable for short range complicated surface scanning. It has two cameras which include an RGB camera providing colour information and a monoscopic infrared camera providing the depth information of scanned scene.

A scanning platform is designed to assist the scanning. Solidworks 2018 is used as a Computer Aided Design (CAD) software for mechanical design and simulation. The frame of scanning platform having a dimension of 350 x 350 x 350 mm fabricated using 0.5″ square mild steel. Gears have been used to increase the rotating torque of stepper motor for the rotating platform which can rotate the scanning object with weight up to 2kg. The dimension of motorize rotating platform is sized at 200mm diameter. WiFi ESP8266 Development Board WEMOS D1 is chosen as the main microcontroller to control the automated scanning station.

3.2 Real-time Scanning Software

Algorithm will be developed to complete the 3D scanning system. Software development could be separate into 3 parts including software for 3D scanner, graphical user interface (GUI) and software for automated scanning platform.

Software for 3D scanner will run on Raspberry Pi which installed with Robot Operating System (ROS) Melodic framework. ROS is a flexible framework for writing robot software. It is a collection of tools, libraries, and conventions that aim to simplify the task of creating complex and robust robot behavior across a wide variety of robotic platforms. In this application, ROS Real-Time Appearance-Based Mapping (RTAB-Map) package is used for RGBD Simultaneous Localization and Mapping (SLAM) approach with real-time constraints [12].

RTAB-Map is ROS wrapper of the RTAB-Map Core library and it subscribed to the camera colour and depth image topic and register the object depth information into the scan map. A software is developed using Python 2.7 to interact with the ROS RTAB-Map package from backend. RTAB-Map uses discrete Bayesian Filters to estimate the probability of forming a closed loop and compares the new point cloud with the point cloud stored in working memory. When it is found that there is a high probability of forming a closed loop between the new and old points cloud, a closed loop is detected, and the new and old points are linked together [12]. The colour and depth image of the scan is also stored in the project directories which will be used for refining purposes in post process.

Furthermore, Raspberry Pi is act as a server hosting the main webpage for 3D scanner. The webpage is developed using html and JavaScript with CSS styling to act as the GUI for the scanner. User will able to configure the settings and triggering scanning job from the Raspberry Pi through the webpage without accessing to the Raspberry Pi's backend. ROS3DJS and ROS Bridge library is used so that user will able to preview the real-time scanning results from the webpage.

Besides that, Raspberry Pi is also act as Message Queuing Telemetry Transport (MQTT) broker to allow the communication between the GUI, scanner and scanning platform. Once the scanning job is being trigged from GUI, a MQTT topic will be published and the scanner's controller which is Raspberry Pi that subscribing to that topic will triggering the backend scanning process. Another topic will also be published to start the rotation of the rotating platform to enable the 3D scanning of object from different angle.

The scanning platform consists of two features including a rotating platform and an illumination system which is controlled by WEMOS D1 controller. It is a WIFI development board based on ESP8266. Software development of WEMOS D1 is done through Arduino IDE using language C++. The controller is subscribing to MQTT topic for the controlling of illumination colour and intensity of the scanning platform from the main webpage as well as the rotation of the rotating platform.

3.3 Post-process Software

After completing the point cloud scanning, the scanned project will able to be download from the scanner webpage as a zipped file consisting the scanned point cloud, colour image and depth image for different angle. For the automating the post-processing of scanning results, a software is developed using Python 3.7. The post-process of point cloud is separated into 4 phase including formation of fragment, global and local registration of fragment, point normal estimation and surface reconstruction.

In order for the reconstruction of point cloud, we need to estimate the camera poses or trajectory of scanner from different angle. The scanned point cloud is sampled and subdivided into different fragment which consists of point cloud of different angle. Odometry is performed which mean estimating the relative pose between fragments.

After the point cloud fragment of different angle is formed, global registration on all the fragment is done to align them in a global space. Random sample consensus (RANSAC) algorithm is used for the global registration of all the fragments based on the distance and edge length between points. In each RANSAC iteration, random points are picked from source point cloud. Their corresponding points in the target point cloud are detected by querying the nearest neighbor in the 33-dimensional Fast Point Feature Histograms (FPFH) feature space. A pruning step takes fast pruning algorithms to quickly reject false matches early. Only matches that pass the pruning step are used to compute a transformation, which is validated on the entire point cloud [13].

For performance reason, the global registration is only performed on a heavily down-sampled point cloud. The result is not tight. Therefore, point-to-plane Iterative closest point (ICP) is used to further refine the alignment for local registration of fragments [14]. Point-to-plane ICP algorithm uses an objective equation (1),

$$E(T)=\sum(p,q)\in K((p-Tq)\cdot n_p)^2, \tag{1}$$

where n_p is the normal of point p. The purpose of ICP algorithm is to minimize the point-to-plane error between source and target point cloud based on the normal of each point in the point cloud.

When collecting data from the sensor, it happens that the point cloud contains noise that affecting the scanning outcome which would like to remove. Therefore, point cloud outlier removing needed to be done to removes the points that are further away from their neighbors compared to the average for the point cloud. In many scenarios we want to generate a dense 3D geometry or mesh. Therefore, to get a triangle mesh from this unstructured point cloud we need to perform surface reconstruction.

Before performing surface reconstruction, vertex normal estimation is needed to compute the normal of each point based on defined number of neighboring points. For each point in point cloud, adjacent points are found, and the principal axis of the adjacent points is calculated using covariance analysis.

After the computation of normal, Poisson surface reconstruction can be used for the reconstruction of triangular mesh from the point cloud. Poisson surface reconstruction will produce a smooth result as compared to other reconstruction method such as alpha shapes and ball pivoting as it solves a regularized optimization problem to obtain a smooth surface [15]. The surface reconstruction from oriented points can be cast as a spatial Poisson problem. Poisson formulation will consider all the points at once, without resorting to heuristic spatial partitioning or blending, and is therefore highly resilient to data noise.

4. RESULT AND ANALYSIS

The algorithm of 3D scanner is implemented and tested on real hardware. At first, a rough point cloud is generated. The point cloud is subdivided into fragments consists of point cloud of different angle and then registered into a global space using RANSAC algorithm. The results are further refined with ICP algorithm and noise is removed. For each point in point cloud, the normal is calculated based on its neighbouring points. Poisson surface reconstruction is then performed to form triangular mesh from the point cloud.

4.1 Hardware

A casing for portable 3D scanner which consists of Raspberry Pi and Intel Realsense RGBD camera is also 3D printed. The camera is equipped with aluminum heatsink as it released large amount of heat during scanning process. The design of the scanner is shown in Figure 3.

Figure 3. 3D scanner casing with heatsink installed on camera and Raspberry Pi

The illumination system of scanning platform is built with WS2812B led strips. Besides that, rotary station is designed from Lazy Susan bearing to ensure the smooth rotation of scanned object. The rotation of the rotary station is controlled by stepper motor. 3D printed gears are used in order to increase the torque of rotary station. The design of scanning platform and rotary turntable is shown in Figure 4 and Figure 5.

4.2 Real-time Software

The Graphical User Interface (GUI) allow users to interact with the 3D scanner easily on multiple platform and operating system such as on PC running Windows or Ubuntu and mobile devices running Android or IOS. User will able to configure the illumination of the scanning platform as well as triggering scanning job from the webpage. The GUI is shown in Figure 6 while the illumination control user interface of the scanning platform is shown in Figure 7.

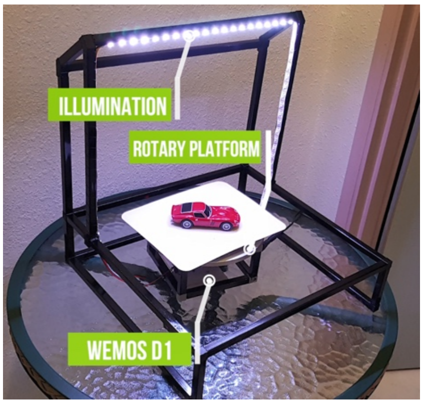

Figure 4. Rotating Scanning Platform with illumination

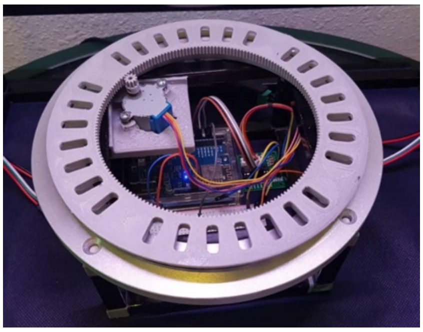

Figure 5. Rotating platform build from Lazy Susan bearing

Figure 6. GUI for 3D scanner which able to run on multiple platform

Figure 7. Colour and intensity control of 3D scanning platform.

ROS RTAB-Map package is running on backend registering the spatial information of the scanned object based on the colour and depth image of camera when the scanning job is trigged as shown in Figure 8. The frontend process of scanning on GUI is shown in Figure 9. The point cloud generated from real-time scanning could be downloaded from the GUI webpage as shown in Figure 10.

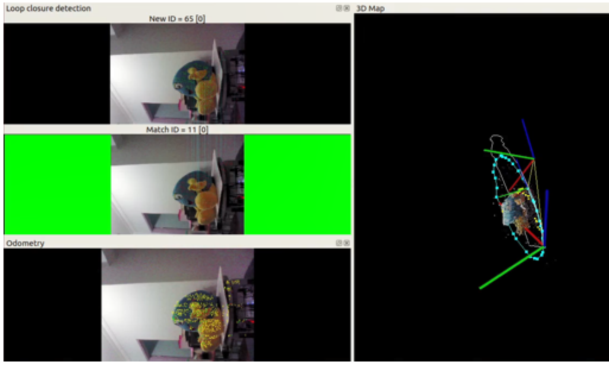

Figure 8. Backend process for 3D point cloud generation on Raspberry Pi

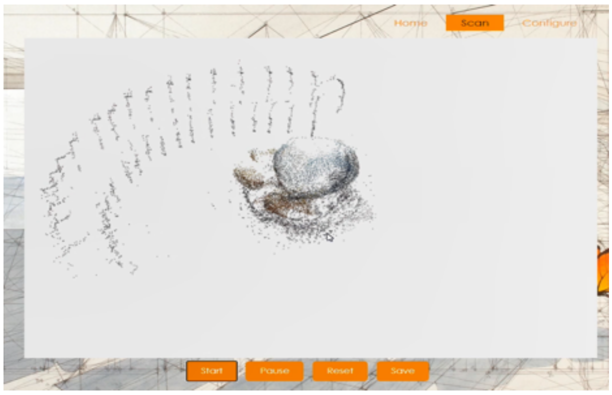

Figure 9. Frontend process of 3D scanning on GUI.

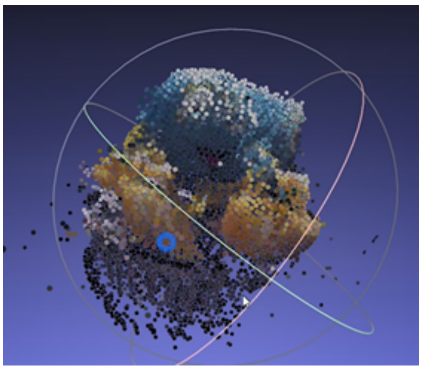

Figure 10. Pre-process point cloud

4.3 Post-process Software

In order to refine the point cloud, the generated point cloud is sampled and subdivided into different fragments which consist of point cloud of different angle. For instance, two fragments of point clouds shown in Figure 11 having different angles which marked orange and blue.

Global registration based on RANSAC algorithm is performed to align both point cloud fragments into a global space. In this example, orange fragment is set as the source point cloud and blue fragment is set as the target point cloud which will aligned into the global space of the source point cloud. The result is shown in Figure 12.

Figure 11. Two fragment of different angles. Orange (0 degree), Blue (5degree)

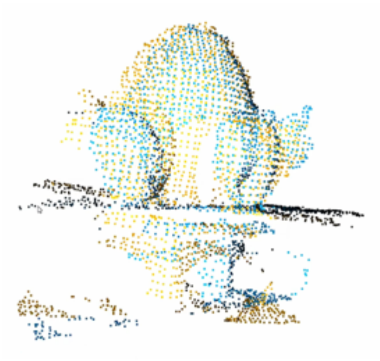

Figure 12. Global registration of two fragment based on RANSAC algorithm

A full iterative will done processing all the fragments based on RANSAC algorithm. The alignment of the point cloud is then further refined with local registration method which is point-to-plane ICP algorithm. The output of the point cloud of the same example after ICP algorithm is shown in Figure 13.

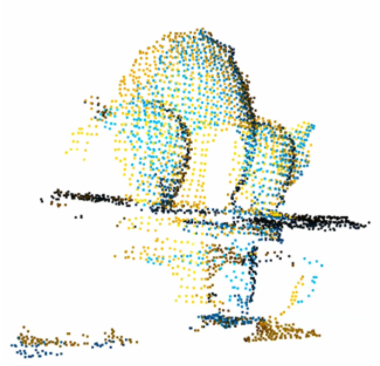

Figure 13. Local registration of two fragment based on ICP algorithm

Noise from the point cloud is removed by determining the outlier point which shown in Figure 14 and marked red. The output of point cloud after global and local registration of all the fragments with noise removal is shown in Figure 15.

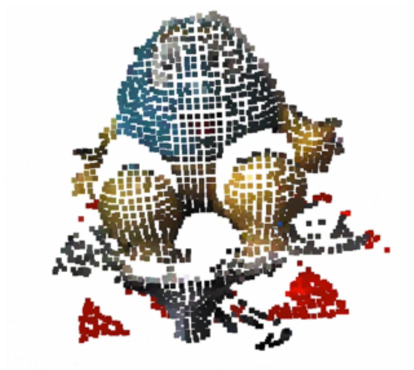

Figure 14. Outlier point (noise) which marked red will be removed.

Figure 15. Output of point cloud after fragments registration and noise removal

Next, normal of each point in point cloud is calculated and a line of normal is drawn for illustration purposes and shown in Figure 16. Surface reconstruction is done by creating triangular mesh from filtered point cloud and shown in Figure 17.

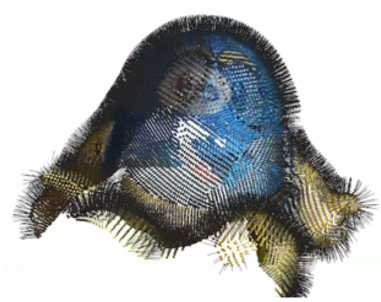

Figure 16. Point cloud's normal calculated and illustrated in lines.

Figure 17. Triagular mesh reconstructed from point cloud

5. CONCLUSION

Studies on 3D reconstruction of triangular mesh using infrared coded light technology is done in this project. The sampling of the 3D point cloud using RGBD camera is done and the post-processing of point cloud success to filter the point cloud to perform precise 3D reconstruction. This scanner able to scan the object with the accuracy up to 5mm with computational time around 25 minutes for highly dense point cloud. The illumination system of scanning platform able to improve the quality of scanning in term of colour texture and the rotary station designed enable the fully automated scanning of object with size less than 300X300X250mm and weight up to 2kg.

However, there are still some limitation on the 3D scanner. Raspberry Pi 4 will run overheated if performing multiple scans simultaneously due to its low processing power as it need to running ROS package from backend, hosting the webpage as well as act as MQTT broker. Therefore, upgrading controller for 3D scanner will improve the performance of 3D scanner. The exist of GPU is controller such as NVIDIA Jetson Nano will even accelerate the scanning speed of the 3D scanner.

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