Machine Vision-Based 3D Scanning for Upper Limb Prosthesis

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Abstract- The 3D reconstruction of upper limb anatomy plays a significant role in many biomedical fields such as ergonomics, motion rehabilitation, prosthesis design etc. Medical fields have extensive applications of various scanning, for instance, X-rays, Computer tomography, MRI and Ultrasound. These techniques provide information on internal organs, however, there is a gap in obtaining information on the outer body parts which could now be taken care of via 3D scanning technologies. The emergence of new RGB-D technology has allowed for a cost-effective approach to 3D scanning for various applications, including medical applications. In This study, a depth cameras ensure rapid acquisition times via capturing geometrical information at video frame rates. Intel RealSense cameras are among the best business options because they strike a solid balance between price, use, size, and accuracy, among other factors. Launched in January 2018, the Intel RealSense D415 offers a narrow field of view and a large acquisition range (about 160-10,000 mm) for capturing moving objects. In comparison, the RGB-D camera provides a cost-effective solution for obtaining 3D point clouds, its collection efficiency and data coverage are inferior to those of laser scanners due to its narrow field of view for indoor application.

Index Terms- Depth Camera, Intel RealSense D415, Scanning, Single Shot Data Acquisition.

I. INTRODUCTION

A person witnesses profound traumatic experiences upon the loss of a limb. The implications constitute psychological and physical trauma. It is critical to manage this issue promptly. The amputee has a livelong engagement with the prosthetic and its maintenance. In recent years, South Asia especially, Pakistan has experienced a significant increase in the incidence of traumatic amputations. Out of the traumatic episodes, more than 67% of amputations occurred as a result of events related to terrorism and counterterrorism, such as gunshot injuries, mine explosions, bomb detonations, shelling, and punitive actions [1]. The conventional approaches for rehabilitating individuals who have undergone such distressing encounters require modification. In certain communities, an individual who has undergone amputation is regarded as a burden to society. In addition to facing societal rejection, the amputee is prone to experiencing a state of helplessness, which exacerbates their situation. Hence, it is imperative to ensure the appropriate rehabilitation of individuals undergone amputation [2]. The amputee encounters challenges in recuperating, even after obtaining a prosthetic, primarily due to the design of the prosthetic, which requires an implementation of innovative approaches in the manufacturing of prosthetic and orthotic devices. The prosthetic design aims to accurately emulate and reproduce the appearance and adaptability of a natural limb while causing minimal discomfort to the amputee[3]. An increasingly prevalent method nowadays involves the utilization of RGB-D cameras for scanning. This study utilizes the Intel RealSense D415 camera to capture the depth profile of the specific limb being targeted. The objective was to recreate the limb to replace the missing limb of an individual who has had amputation.

Intel RealSense has been adopted in several fields since its release. Human interface design and systems with posture and gesture interaction are some of the many areas and applications. The core components of RealSense technology are depth cameras, tracking and depth modules, and vision processors. These components are facilitated by librealsense, a free and open-source software development kit (SDK) which may be used by developers and third-party system integrators to facilitate camera support. The D415 and D435 depth cameras were introduced by Intel in January 2018. The D435 depth camera's wider field of view (FOV) reduces blind spots, which makes it ideal for robotics applications. Its global shutter improves performance in low-light conditions, high-speed motion capture, and preventing blurring depth images. The D415 camera offers a better pixel density because of its reduced field of view, which translates into a higher resolution. Therefore, the Intel RealSense D415 claims to deliver improved results when accuracy is crucial (such as for 3D scanning applications), especially when employed at close range (i.e., <1 m). RGB-D cameras are becoming popular as low-cost 3D scanners; thus it is necessary to thoroughly characterize this new device in order to determine which device and its parameter settings work best.

Figure 1 Intel RealSense D415

The purpose of the Depth Camera was to offer respective projects or devices the capacity for observing view, comprehending, engaging with, and absorbing information from their surroundings. The D415 is equipped with the Intel RealSense Vision D4 processor, which offers a narrow field of view perfect for accurate measurements, rolling shutter technology, long-range capability up to about 10 m, and high-resolution depth up to 1280 × 720 pixels at 30 frames per second. The new D415 and the SR300 function differently because they use different depth measurement algorithms (e.g., structured light vs. active stereo). As the D415's rolling shutter sensors have a limited field of vision, fast-moving objects or rapid device movement (like rapid horizontal panning) may cause slightly distorted photos. The cross-platform, open-source Intel RealSense SDK 2.0 is compatible with the Intel RealSense D400 series. With a resolution reaching as high as 1920 x 1080 pixels, the colour camera on the D415 could gather texture information that could be superimposed over depth data. The Intel RealSense D415 boasts a working depth range of about 160-10,000mm. The depth and RGB cameras' declared horizontal field of view (FoV) is roughly 69°, while the vertical FoV is roughly 42°. The evaluation of point density variation is conducted for the FOV specified by Intel (69.4 x 42.5°), the two FOV extremes (i.e., obtained by subtracting and increasing 3°), and the actual FOV for the specific camera utilized for the performance investigation (67.24 x 41.01°).

The remainder of this article is organized as follows, Section II describes the literature review followed by Methodology in Section III. Experimentation is presented in Section VI. Results and Discussion are presented in Section V. Finally.

II. Literature Review

Numerous application domains, including mechanical engineering, robotics[4], industrial[5], automotive[6], biomedicine[7], cultural heritage, and have witnessed a rise in the use of 3D optical systems[8]. Their success is attributed primarily to recent advancements that have made it possible to create devices that are accurate, compact, and less expensive. A tiny depth sensor similar to Kinect was included in the iPhone X that Apple launched at the end of 2017[9]. The original Kinect tracked motion over a whole living room; this sensor, on the other hand, is just for detecting faces and is responsible for powering Apple's Face ID function. It is to be noted that the 3D scanning of upper limbs is a complex task as the involuntary movement of the patient is unavoidable and uncontrollable. Due to the non-stationary nature of the scanning target the scanning time must be reduced maximally to minimize the scanning artefacts. Paolo Neri et al discuss in detail that in the field of rehabilitation for amputees, 3D body scanning plays a pivotal role in the design and fabrication of customized medical devices, particularly for the upper limb. The process is initiated by acquiring data on the patient's anatomy which is vital for fabricating bespoke devices like prostheses. There have been advancements in consumer RGB-D sensors due to which the possibilities of virtual and augmented reality applications have expanded. There are various optical scanning methods through technologies like Time of Flight (ToF), Photogrammetry (PG), Moiré Profilometry, and advanced stationary scanners. It does not go without saying that there are challenges in upper limb scanning such as self-occlusions, the need for multiple scans, and artefacts caused by the slightest movement. These problems emphasize the need for rapid acquisition techniques. The Intel RealSense and Microsoft Kinect due to their accuracy and alignment are the high-end real time solutions for the problems stated. The field of 3D body scanning is evolving towards portable real-time scanning devices that overcome the limitations posed by traditional methods[9]. Chi Chen et al [10] conducted experiments for indoor scanning applications for which they concluded the observation that consumer RGB-D cameras present a cost-effective solution for collecting 3D point clouds, but they are limited by a narrower field of view compared to laser scanners. Depth information is extracted using an active stereo-vision technique that utilizes structured light range sensing. A camera records a series of recognized patterns that are successively projected onto the scene, and the distortion of the pattern is examined. They discuss the Time of Flight method which calculates how long it takes light to leave a source, travel to an object, and then return to the sensor array. Similarly, Giancola et al. [11]offered characterizations for the Intel D400 series, the Microsoft Kinect v2, and the Orbbec Astra S. Two separate sorts of studies were carried out for each of these devices: one for sensor-wise characterization and the other for pixel-wise characterization. Their experiments were designed to assess the quality of the reconstruction of known geometries and the accuracy of the cameras at various distances. Further testing is required to pave the way for global performance measurement standardization, thereby offering consumers a thorough study of camera limits and strengths in the best-case scenario of a close-range 3D scanner application scenario. Unfortunately, a widely accepted standard for depth camera systems and other non-contact 3D imaging systems has not yet been released by the worldwide community. A matter highlighted by Rocco Furferi et al is that despite the lack of a global standard for non-contact 3D imaging systems, the German standard VDI/VDE 2634 Part 2 offers some guidelines. Performance evaluations, considering point density variation and maximum IR camera resolution, highlight the need for industry-standard benchmarks, particularly in close-range applications, underscoring each model's unique strengths and suitability for specific use cases[7].

The Intel RealSense D415 and other depth cameras alike have revolutionized the field of 3D scanning by rapidly capturing geometrical information. This process significantly reduces scanning time which improves accuracy. The method proposed to use an off-the-shelf depth camera offers an efficient, non-invasive, and cost-effective approach in counter to traditional methods where manual measurements were to be taken. It is preferable to use real-time single-shot techniques to minimize artefacts from involuntary movements. The removal of artefacts is important for creating detailed biomechanical profiles.

III. Methodology

The research employed a straightforward methodology for acquiring a 3D contour of the target. In this research, the focus was on the upper limb and in the upper limb, the focus was on the hand. The target was captured using the Intel RealSense D415 camera.

The procedure was implemented using the Python programming language and some of the computer vision libraries available in Python. 3D scanning provides a streamlined approach to prosthesis design. This introduces a non-contact method of acquiring measurements for the custom-tailored prosthetic for the patient. Some of the challenges encountered by 3D scanning revolve around the endurance of the patient to maintain immobility of their unaffected or affected arm. This implies whether the scanning target is the unaffected limb or the amputated limb. The purpose of scanning the unaffected limb is to replicate a prosthetic that is of similar shape and size to the existing limb, and for scanning the amputated part is to design the socket that is fitted onto the affected limb. Involuntary movement causes distortions in the final result of the scanning process. For this reason, a camera with quick data acquisition capabilities is preferred. An accurate scan of the target surface is required to effectively design the prosthetic. There are numerous RGB-D cameras available on the market, however, the selection of the Intel RealSense was based on a comparison with its competitors and the availability of the cameras[12]. The specifications of the competitors are listed in Table 1.

Table 1 Comparison of Different RGB-D Cameras

Depth Camera	**Intel Real Sense D415**	**Microsoft Kinect v2 3D camera**	**Sense Cubify**
Sensor Technology	Rolling Shutter	Time of flight	Structured Light
Depth frame rate	90fps	30fps	30fps
RGB frame resolution	1920 x 1080	1920 x 1080	320 x 240
Mounting mechanism	One thread mounting	N/A	Handheld
Connector	USB C 3.1	USB 3.0	USB
Weight	0.3kg	1.4kg	-
Depth resolution	1280 x 720	512 x 424	640 x 480
Min depth distance	~45cm	87cm	38cm

IV. Experimentation

The scanning operation was programmed in Python using version 3.6.8 and the Python IDE, JetBrains PyCharm Community Edition 2020. The Intel RealSense SDK documentation is accessible in various programming languages, mostly in C++ and Python. The python version was chosen for this project because of its up-to-date documentation and the availability of certain Python-specific libraries such as OpenCV, and NumPy, which were important in generating the scan. The simulation starts with importing all the four libraries of; pyrealsense2, NumPy, cv2, and DateTime. Next is the initialization of the RealSense library and its operations. It starts by enabling the advanced mode function in the RealSense documentation. This function allows the user to be able to use further advanced functionalities of RealSense, such as setting a specific distance for the depth scanning, which is set to 400mm in this system. Afterwards is the initialization of the dual streams of depth and RBG, where both of them are set to a resolution of 640x480. Following that, the pipeline and config are initialized. Subsequently, after resolving any parameterization issues, the video streams are prepared for display. The target limb from the image's live feed is then cropped out. To do this, a binary mask would be built over the discovered portion of the scan and only the sections that were identified would be taken into consideration. Subsequently, a bounding rectangle would be made around the binary contour that had been drawn around the mask. As a result, the scanned portion of the stream would be surrounded by a rectangle. The parameters of the rectangle could then be used to construct a new output window. This would result in an entire window that is compactly binding just the scanned part of the video. The target's height and width would now match the height and width of this window. Next, using simple math, a ratio between the limb's actual height and pixel height could be calculated, and multiplying the limb's pixel parameters by this ratio would produce the targeted limb's actual parameters. Upon running, the code would then present a window displaying an RGB output of the camera in real time. The window displaying the output is shown in Figure 2.

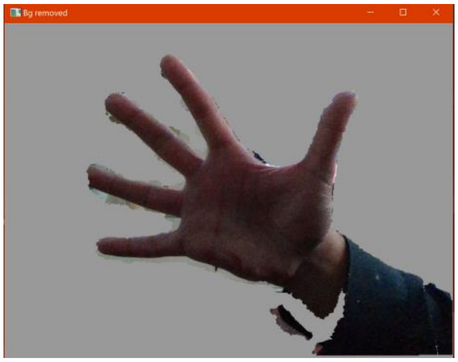

Figure 2 Video Stream Displaying Target Limb

When the window presents a satisfying output, the operator can then press the button on the keyboard, which is programmed to export the current RGB visual as a 3D STL file on the system. The following section will describe the results.

V. Results

After the process a depth profile was captured by the Intel RealSense. However, after the scan has been taken the 3D file needs some corrections. The manual measurement was a straightforward approach as shown in Figure 3. The readings were recorded and compared with that of the scan data. The hand's length is determined by measuring from the tip of the hand's tallest finger down to the crease below the palm.

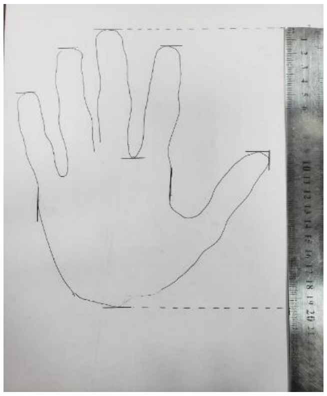

Figure 3 Methodology for Manual Measurements

The stl has irregularities in it, which are shown in Figure 4. These irregularities could be fixed by utilizing designing software or 3D manipulation software such as Blendr or Mesh mixer. Hundreds of images were taken to tally the accuracy of this method for acquiring a depth profile of the targeted limb.

Figure 4 Image capture through Intel Real sense D415

The captured images are uploaded to 3D viewing software to obtain the measurements of the person's hand through the scan data. The data displayed in Table 2 is represented in graphical form as well. This data incorporates a six random test values of the numerous captured data by the Intel RealSense D415 RGB-D camera. The data provides insight over the accuracy of the findings through this approach. Table 2 holds data for vertical measurement of a human's hand which is the upper limb selected in this research.

Table 2 Comparison of Manual vs Scan Measurement

Trial #	**Vertical Measurement (cm)(Manual)**	**Vertical Measurement (in cm) (via RGB-D)**	**Error (cm)**
1	19.3	19.01	0.29
2	20	20.23	0.23
3	18.1	18.53	0.42
4	19.4	19.11	0.29
5	19.4	19.35	0.05
6	18.1	17.98	0.12

The data captured shows little variation in manual measurement and in RGB-D camera data. The data is presented in graphical form as well in Figure *5*.

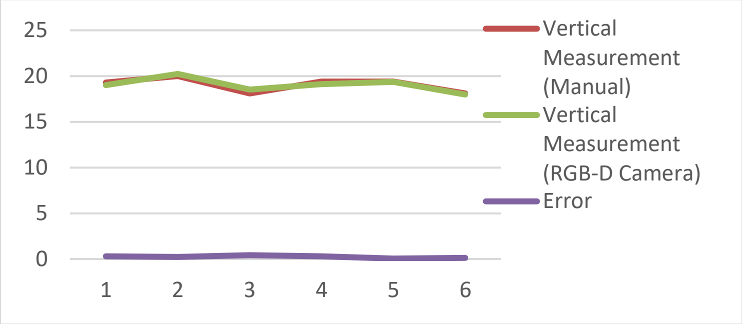

Figure 5 Graphical representation of data measurement

The intel RealSense D415-based developed scheme, with its sophisticated 3D scanning capabilities, offers numerous possibilities for various industries. In addition to its application in prosthetic design, this technology could also be applicable in augmented and virtual reality (VR), providing enhanced experiences by recognizing and mapping real-world objects. Additionally, it plays a pivotal function in the realm of 3D modelling and printing, facilitating its utilization in various fields such as product design, architecture, and art. This stimulates innovation and creativity by providing a framework for the development of visually appealing and practical designs. The D415's impact on the healthcare industry goes beyond the realm of prosthetic design. It provides healthcare practitioners with the capability to obtain high-resolution 3D images of patients, which is extremely helpful for medical diagnostics, treatment planning, and monitoring of wounds and surgical results. In the field of robotics and autonomous navigation, it could improve the understanding of space, helping to avoid obstacles and ensure safety. Retailers employ it for virtual try-on experiences, while archaeologists use it for documenting historical artefacts. Within the fields of building and design, it plays a crucial role in generating precise as-built models, while manufacturers reap the advantages of its accuracy in industrial quality control. With the advancement of technology, the D415's functions and responsibilities are continuously broadening. The entertainment sector utilizes its technological skills to create lifelike character animations, while education employs it to augment learning across many areas. The D415 is also utilized in the fields of security and biometrics, navigation, and mapping, as well as environmental monitoring. To summarize, the 3D scanning capabilities of the Intel RealSense D415 go beyond the limitations of a specific industry. The versatility and adaptability of this technology enable innovation and problem-solving in various domains, including healthcare, retail, robotics, and education.

VI. Conclusions

This study discusses employing a Machine vision tool for image capture, and data was subsequently fed to a system for modelling upper limb amputees. The device introduced here was originally intended for tracking, gaming, or gesture recognition. In this study, it was demonstrated that this device could also be effectively utilized as a low-cost 3D scanner in biomedical engineering. The scan data exhibits minimal deviation when compared to the manual measurement data. The findings of this study can aid in the design of upper limb prostheses by offering a cost-efficient alternative to current approaches that involve manual labor. While other methods may employ many cameras, the accuracy of measurements suggests that a single camera is sufficient for tasks that involve obtaining a depth profile of a specific item.

VII. References

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