Investigating the Use of Structured Light Imaging for 3-D Reconstruction of the Human Forearm for Automated Venipuncture.

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***Abstract*— Venipuncture is one of the most commonly performed medical procedures and is a key first step in a majority of diagnostic and interventional workflows. However, success rates are heavily dependent on clinician skill and patient physiology. Over the past decade, imaging technology has been developed to aid clinicians in visualizing hard-to-see veins, and more recently, robotic technology has been explored as a means of automating the needle insertion. Our group is developing a portable, autonomous venipuncture device that safely and efficiently cannulates the optimal peripheral blood vessel in the patient. Previously, the device utilized a near infrared imaging (NIR) approach based on passive stereo vision to reconstruct the patient's arm and vasculature in 3-D. However, passive stereo is prone to depth estimation errors and incomplete reconstruction, which may not be reliable enough venipuncture. In this paper, we investigated whether the use of active stereo based on 3-D structured light imaging would provide a more reliable and efficient method of 3-D reconstruction compared to the passive stereo approach.**

***Index Terms*— Medical robotics, passive stereo, robot vision systems, structured light, venipuncture.**

I. Introduction

VENIPUNCTURE is a standard clinical procedure for health care facilities with nearly 2.7 million procedures performed daily. In fact, venipuncture is the most common invasive medical procedure in the U.S. and is also the leading cause of clinical injury to both patients and practitioners [1]. Pediatric, geriatric, obese, and dark skin populations are the most prone to these venipuncture injuries because of their difficult to find veins, often termed difficult venous access (DVA).

A. Current Venipuncture Device

Over the past decade, DVA in patients has pressed the development of technologies to improve the success rate of venipuncture. However, these devices such as Accuvein or Vivolight [2] simply augment finding the vein, and do not enhance the needle insertion capabilities of the clinician; the ultimate determinate of a successful venipuncture. Our group is developing a portable, autonomous venipuncture device that safely and efficiently cannulates the optimal peripheral blood vessel (as seen in Fig. 1) [3] [4]. The optimal vein for cannulation is selected utilizing a near-infrared (NIR) and ultrasound imaging system that scans and selects the best cannulation site on the patient's forearm [3]. The current imaging system on the device utilizes passive stereo NIR imaging to reconstruct the patient's peripheral surface forearm in 3-D.

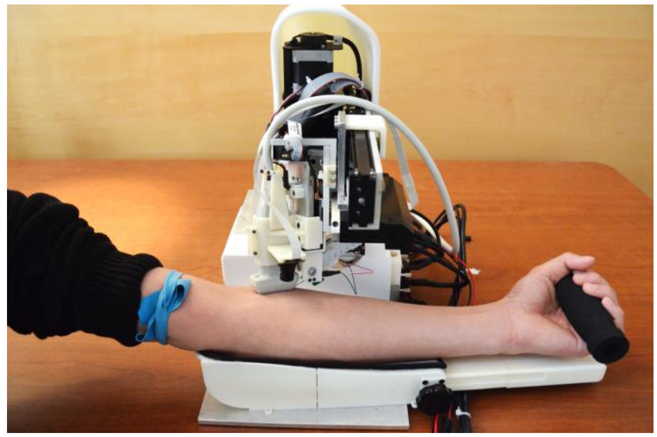


Fig. 1. The automated venipuncture device, which employs miniaturized robotics, NIR passive stereo imaging, and ultrasound imaging to safely and accurately perform venipuncture procedure (see Ref [4]).

The current passive stereo imaging method works well at identifying and reconstructing the forearm veins in 3-D. However, reconstruction of the entire forearm surface is prone to errors, including: incomplete image reconstruction, inaccurate depth estimation, and inconsistent results [3]. The objective of this paper is to investigate whether an alternative approach, structure light imaging, could provide a more accurate depth estimation of the forearm for the purposes of robotically lowering the ultrasound transducer safely onto the forearm. During the procedure, the transducer must make contact with the skin without causing too much pressure, while at the same time, leaving no air gaps in between the transducer and forearm. This requires that the active stereo approach be able to reconstruct the forearm to within less than a 2mm error.

II. Materials and Methods

Passive stereo imaging is a 3-D reconstruction method that utilizes the known distances between two cameras to calculate the depth from two images of the same scene [5]. Our passive stereo setup consisted of two Point Grey FireFly cameras placed horizontally and parallel to each other with a distance of 4.5 cm between each cameras lens center. The exact distances between the cameras and projectors during setup are not essential because the following calibration step calculates the intrinsic and extrinsic camera parameters needed for accurate 3D depth estimation.

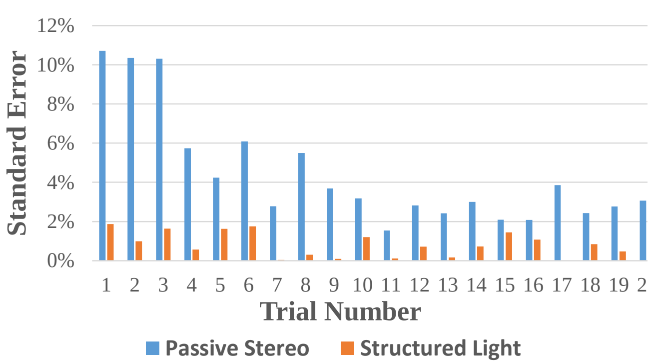
Active stereo imaging, conversely, is a more complex 3-D reconstruction method that introduces an active element, in this case light, onto the scene to attain 3-D information. Grey code structured light imaging, an active stereo method, is a 3-D reconstruction technique that works by projecting unique alternating columns of black and white light patterns onto the desired scene [5]. Our grey code structured light imaging setup consisted of a high frame rate camera, the Point Grey Grasshopper model, and the Lightcrafter 4500 Digital Micro-mirror device to project the patterns. The projector and camera were placed at 10 cm between each other. A standard checkerboard grid calibration method was used to calibrate both the active and passive system, as discussed in [5] and [6].

To compare depth accuracy between the passive and active systems, a 6x130x30 cm block was placed at various measured distances away from a background wall and was imaged using both the active and passive stereo systems. The block was placed at 20 different locations between the background and wall for a distance range between 1 to 20 cm. Differences in reconstructed distance between the block and wall and actual distances were recorded and standard error for each trial was calculated.

Disparity level resolution determines the ability of an imaging system to differentiate between two different levels of depth in a reconstructed image. In the case of forearm reconstruction, a high disparity level in an imaging system will be able to capture the detailed curvature of the human forearm. To validate this, 15 different forearms were imaged by both systems and forearms were reconstructed in 3-D point clouds.

III. Results and Discussion

Depth accuracy reconstruction (block to background depth estimation) results from each imaging method are shown in Fig. 2. Results showed that the active stereo structured light approach estimated the blocks distance from the background with an average depth estimation error of 0.81% while the passive stereo approach averaged an error of 4.39%. Standard deviation shows that the structured light imaging method



	Passive Stereo	Structured Light
Average Error per Trial	4.43%	0.81%
Standard Deviation (in mm)	+/- 3.5	+/- .93

Fig 2. Block depth error reconstruction results. Standard error is the percent difference between actual and reconstructed depth. Trial number also corresponds to measured distance between block and background (ex. Trial 12 is block placed 12 cm from background).

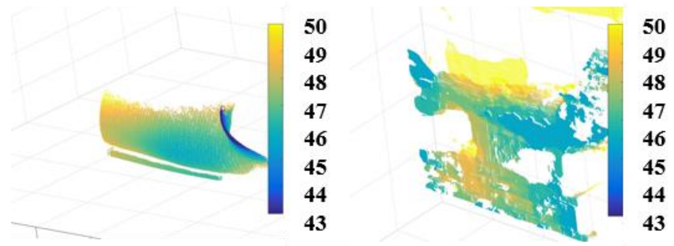


Fig. 3. 3-D reconstructed point clouds of upper forearms (in mm). [Left] Structured light result and [Right] passive stereo result. The structured light method (left) has a much higher disparity resolution, allowing it to capture the detailed curvature of the forearm.

estimated the blocks distance to within a +/- .93 mm tolerance. This is more than suitable for our target goal of <2mm standard deviation.

Figure 3 shows example results from each imaging system. From Fig. 3, difference in edge clarity and curvature when imaging the patients forearm is seen. The qualitative results from forearm reconstruction illustrate that structured light imaging provides a better reconstruction in both depth accuracy and disparity resolution. Active stereo provides a more accurate depth resolution and pixel capture consistency as can be seen from the detailed color blend in the curvature of the forearm (left image).

For computational time, passive stereo imaging was the faster method, with a mean time of 140 +/- 40ms. The structured light method, however, required a mean processing time of 5.0 +/- 0.6 sec. However, this time can be greatly reduced in the future by reducing the number of necessary images at the cost of reconstruction quality.

IV. Conclusion

In conclusion, it was found that the structured light imaging approach proved to be a superior method for 3-D image reconstruction of the forearm as compared to the passive stereo approach. Future work will involve investigating the optimal balance between computational time and image reconstruction quality in the structured light imaging system.

V. References

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