Projector Illuminated Precise Stencils on Surgical Sites

Muhammad Twaha Ibrahim* M. Gopi Raj Vyas Lohrasb R. Sayadi Aditi Majumder

University of California, Irvine

Abstract

We propose a system that provides realtime guidance to surgeons by illuminating salient markings on the physical surgical site using a projector. In addition to the projector, the system uses a RGB-D camera for feedback. This unit is called the projector-depth-camera or PDC unit. Using the PDC, we perform structured light scanning and generate a high resolution mesh of the surgical site. During planning or execution of the surgery, this digital model is marked by appropriate incision markings through a GUI. These markings are then illuminated at high precision via the PDC unit on the surgical site in realtime. If the surgical site moves during the process, the movement is tracked by the system and updated quickly on the moved surgical site.

Index Terms: Human-centered computing—Visualization—Visualization Systems and Tools—; Human-centered computing—Visualization—Visualization Application Domains—; Human-centered computing—Human Computer Interaction—Interaction Devices—

1 Introduction

In this paper we present a system that provides surgical guidance marks on the physical surgical site for training, consultation and skill transfer. We use a projector to directly illuminate a patient's surgical site with precise markings (e.g. points, lines and curves) for dynamic real-time surgical guidance visible to the entire operative team. We use a projector and an RGB-D camera to create a single Projector-Depth-Camera (PDC) unit. We first use the PDC for a structured light scan to create a high-resolution digital model of the surgical area in a pre-processing stage. This model is loaded in the GUI where it is marked by surgeons using a tablet or computer (Figure-1). The model is registered to the depth camera frame captured throughout the entire session of the interaction. Any markings made on the digital model is illuminated by the projector at a high precision at the surgical site in real time. Movement of the surgical site is common during the surgery. Therefore, we track the moving surgical area and update the projection quickly so that the digital overlay binds to the surgical site accurately even after movement.

Our method specifically overcomes the obtrusive, exclusive, and indirect attributes of headsets and displays by overlaying the projection directly on the surgical site, making information visible to everyone while maintaining high accuracy of registration with movements. Our projection conforms to the shape of the surgical site putting the digital data in physical alignment, and therefore in the best possible context, with the 3D shape of the surgical site, thereby improving surgical understanding.

2 Related Work

While many works exist that overlay information on a digital representation of the surgical site using a dedicated display [2], we will focus on works that aim to project information on the surgical site of a patient. Gavaghan et al. [4] design a handheld projector device called an Image Overlay Device (IOD) which they use to project onto a static surgical area with markers. Since the system is tightly calibrated apriori, they must recalibrate the system if the surgical site moves. Martischinke et al. [7] employ view-dependent rendering to project volumetric data on a surgical site by tracking the viewer position and adapting the volumetric rendering accordingly. Hoppe et al. [6] use markers for tracking and registering the projection to the surgical site. Wen et al. [8] propose a projection-based visual guidance system to assist with radiofrequency (RF) ablation needle insertion. The surgical site is surrounded by a rig of pre-calibrated stereo cameras and a projector. In case of movement, the system must be recalibrated. Similarly, Fukuhara et al. [3] use a pre-calibrated projector-camera pair to project blood vessels on the abdomen. They compute the camera and projector pose by matching the outline of the abdomen model in the camera image to the CT scan of the abdomen. Edgecumbe et al. [1] develop a small device using a pico projector, called the PicoLantern, for use in laproscopic surgeries. Using the camera in an endoscope, they can perform structured light scanning of organs inside the body.

In contrast, our system does not require any markers or pre-calibration and can bind to the surgical site with movement. We achieve this by designing methods that can leverage the low-resolution depth information provided by consumer RGB-D camera in addition to high resolution color information at video rates.

*e-mail: muhammti@uci.edu

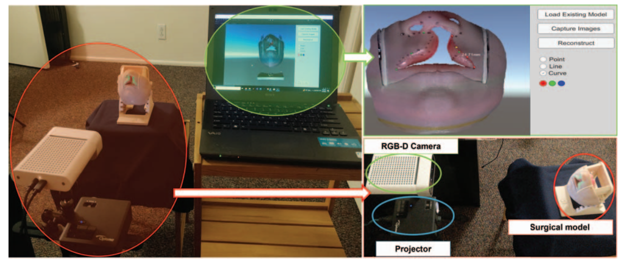

Figure 1: The setup comprising a RGB-D camera and a projector illuminating a model of the surgical area.

3 System Overview

Our setup (Figure-1) consists of a uncalibrated projector and a RGB-D camera (referred to as PDC unit) in a fixed configuration such that the surgical area is covered by the field of view of both devices. We assume that the camera provides registered color and depth images, as is available in most common devices. First, we reconstruct the shape of the surgical site and find the parameters of the uncalibrated PDC using structured light reconstruction. The GUI presents the reconstructed 3D model to the user, who annotates it with stencils. The marked stencils and calibration parameters are used to determine the projector pixels Ω which must be turned on to illuminate the physical surgical site at the intended regions. The surgical area is continuously tracked by the PDC unit and in case of movement, the marked stencils are transformed accordingly to generate Ω to bind the projection to its new location.

Structured light Reconstruction (SLR): We use SLR for shape reconstruction using micro-phase shift [5]. Known patterns are

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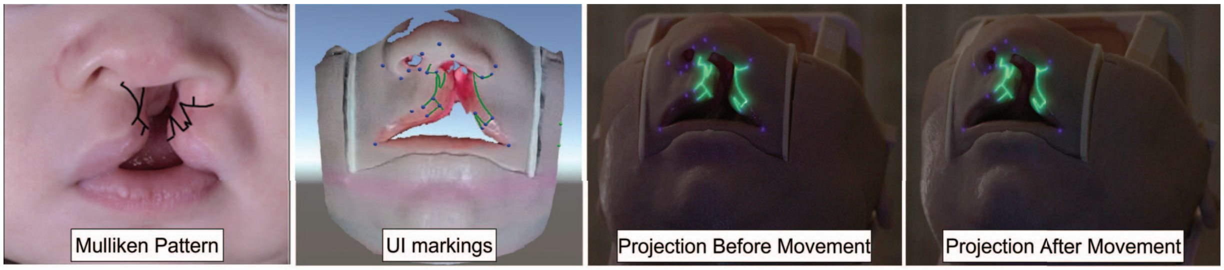

Figure 2: Projection of the Mulliken pattern marked by the user through the UI on a model of the cleft lip before and after movement.

Table 1: Projection accuracy evaluation of the anthropometric landmarks in mm. θ (in degrees) and δ (in mm) are the rotation and translation of the model from its original position.

Error	$\theta = 0$ $\delta = 0$	$\theta = 0$ $\delta = 30$	$\theta = 15$ $\delta = 50$	$\theta = 15$ $\delta = 100$	$\theta = 30$ $\delta = 200$
Mean	0	0.26	0.29	0.33	0.27
Std. Dev.	0	0.13	0.15	0.15	0.19

projected from a projector on the object of interest and captured by a camera to determine pixel correspondences between the two devices which are triangulated to generate an accurate 3D mesh model.

PDC calibration: The SLR step generates accurate pixel correspondences between the projector and RGB camera. Using the pixel correspondences generated from SLR, we calibrate the PDC unit. We use a standard reprojection solver to optimize the camera and projector parameters. This gives us a good set of calibration parameters which we use for triangulating the structured light scan and obtain an accurate 3D model of the surgical area.

User Interface: The high resolution precise 3D model of the surgical area is presented to the user through a UI, where they can inspect the model by zooming in and rotating it. Additionally, they can mark the model with points or curves. The UI sends the 3D coordinates corresponding to the marked points and curves to the projector.

Surgical Area Tracking: During surgical planning, it is possible that the surgical area may move with respect to the PDC unit. In discussion with our medical collaborators, we agreed that these movements can be modeled by a rigid transformation. Therefore, we track the surgical area in 3D space. We use the depth camera at this step to achieve this quickly. At each timestep k, we determine the rigid transformation S^k that minimizes the error between the current depth map from the depth camera and the depth map captured at the time of SLR using the Iterative Closest Point (ICP) algorithm.

Projection mapping: The 3D points W marked by the user, the projector parameters M^p and the rigid transform S^k are used to determine the final set of pixels Ω^k at time k that must be illuminated to project on the intended regions on the surgical area using $\Omega^k = \text{project}(S^k \cdot W; M^p)$. All pixels Ω^k are illuminated in the final image which is then projected onto the surgical area.

4 Results, Discussion and Future Work

In our setup, we used the Microsoft Azure Kinect RGB-D camera and an Optoma Technology ML750 DLP projector. Figure-2 shows the projection of the 21 anthropomorphic landmarks and the Mulliken pattern on the cleft model before and after the model is rotated and translated. Table-1 shows the mean and the standard deviation of the error between the projected points and their true positions for various positions and rotations of the surgical area. Note how the mean error is less than 0.5mm. This shows the accuracy of the entire system, including the PDC calibration, the SLR and surgical tracking. The one-time SLR and calibration took 5-6 minutes. The average time taken to compute a rigid transformation with movement each frame is 1.15 seconds.

Initial domain evaluation: We have been working closely with two reconstructive surgeons, Dr.A and Dr. B, who have many years of experience with craniofacial surgery. They provide feedback in every level of the development process. All the markings shown in the aforementioned images were performed by the doctors using the GUI. Initial response by the doctors are very positive as evident from some of the following comments. (a) *"The accuracy the PAR system achieves is phenomenal. Cleft lip surgery has perhaps the most rigorous surgical markings given the number of markings in such small anatomical confines. The demonstrated ability to achieve low error rates in cleft lip markings bodes well for the clinical translation of this technology to a wide variety of surgical procedures on the surface of the human body"*. (b) *"The fact that everyone in the operating room can see the projection allows for better communication between surgical team members. We look forward to testing this technology in the operating room."*

The proposed work is just the beginning of an effort to build a device that can be integrated in the OR to project surgical guidance directly on surgical sites. In the future, we plan to scale it to multiple superimposed PDC units to increase accuracy and provide high enough brightness to be visible under the bright OR light.

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