A Mixed Reality Guidance System for Robot Assisted Laparoscopic Radical Prostatectomy

Abhishek Kolagunda[1(✉)], Scott Sorensen[1], Sherif Mehralivand[2], Philip Saponaro[1], Wayne Treible[1], Baris Turkbey[2], Peter Pinto[2], Peter Choyke[2], and Chandra Kambhamettu[1]

[1] University of Delaware, Newark, USA
abhi@udel.edu
[2] National Institute of Health, Bethesda, USA

Abstract. Robotic surgery with preoperative imaging data for planning have become increasingly common for surgical treatment of patients. For surgeons using robotic surgical platforms, maintaining spatial awareness of the anatomical structures in the surgical area is key for good outcomes. We propose a Mixed Reality system which allows surgeons to visualize and interact with aligned anatomical models extracted from preoperative imagery as well as the in vivo imagery from the stereo laparoscope. To develop this system, we have employed techniques to 3D reconstruct stereo laparoscope images, model 3D shape of the anatomical structures from preoperative MRI stack and align the two 3D surfaces. The application we have developed allows surgeons to visualize occluded and obscured organ boundaries as well as other important anatomy that is not visible through the laparoscope alone, facilitating better spatial awareness during surgery. The system was deployed in 9 robot assisted laparoscopic prostatectomy procedures as part of a feasibility study.

Keywords: Mixed reality · AR · VR · Robot assisted prostatectomy

1 Introduction

Robotic assisted laparoscopic surgery carried out from platforms such as the da Vinci surgical system has been widely used to treat patients. This treatment approach uses preoperative imaging for diagnosis and planning purposes. Experts in [19] emphasize that surgery is spatial manipulation, and that a system which can combine information from multiple modalities and present it in way that gives surgeons the best spatial awareness possible would be very useful. Surgeons report using preoperative imaging for surgical planning, to build a mental map of the anatomical structures. They then constantly refer to it during surgery by merging, in their mind, the current laparoscopic view and the preoperative information to make critical decisions. Our interactions with the surgeons performing

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Robot Assisted Laparoscopic Prostatectomy (RALP) revealed that pinpointing the interface of the prostate with the neurovascular bundle can be very challenging. Recognizing the ideal point of incision in the prostate-vesical junction is a difficult but critical task especially in the presence of prostate cancer at the prostatic base, or a median prostatic lobe that is outside the direct field of view. During RALP procedure, a surgeon might have to periodically step away from the robot's console and consult the preoperative MRI data to plan their next course of actions. This involves the surgeons scrolling through MRI stacks on a 2D monitor provided by picture archiving and communication (PAC) system in order to spatially orient their current position with respect to the prostate, tumor and other critical anatomy. To expedite this process and present the pre-operative information to the surgeons in a more effective way, we have developed a Mixed Reality system for assisting laparoscopic radical prostatectomy.

Cohen et al. conducted a user study which indicated that augmenting pre-operative data onto the surgeon's view during RALP is useful [3] at key stages of the procedure. Augmented Reality (AR) systems that combine pre-operative and intra-operative information by overlaying virtual pre-operative objects on real intra-operative scenes have received significant attention from researchers as a tool to assist surgical procedures, specially robotic assisted procedures [5,10,20]. Alignment of pre-operative and intra-operative data which forms a very critical part of such AR systems are usually prone to errors and thus can be misleading or distracting. While augmenting surface features of the organ would still be useful, visualizing the features under the surface of the organ is still challenging, and with an augmented reality system the surgeon is still limited to only a few viewing angles (defined by the position of the laparoscope) of the aligned, augmented imagery. Virtual Reality (VR) systems have been typically used to run simulation for training surgeons for robotic surgery (MDVT-Mimic da Vinci Trainer) [12,15]. VR has also been used to spectate as well as for remote guidance (VIPAR) [17] during robotic surgical procedures for training and education purposes. It has also been used as a tool to view 3D pre-operative data for diagnosis and planning purposes. While VR provides an effective framework to view and explore pre-operative data, it does not fuse pre-operative and intra-operative data thus limiting its applicability during surgery. Keeping these limitations of AR and VR in mind we have developed a Mixed Reality (MR) system which is intended to be used during surgery to guide the procedure. It is designed to supplement or replace the 2D monitors used by the surgeons periodically during the procedure for consulting pre-operative data to asses their current state and plan future actions. Augmenting the intra-operative data into the virtual environment with pre-operative data presents all the required information is the same space. The system also provides enhanced visualization and interactive abilities.

2 System Components

The proposed MR system for RALP has the following modules: ***Shape Modeling***, ***Stereo Reconstruction***, ***Shape Registration*** and ***Interactive Visualization***.

Shape Modeling Module: 3D rendering and registration of the shape extracted from MRI data requires a dense and complete surface. Preoperative MRI image stacks are semi-automatically labeled by experts, giving us a series of 3D contours with low resolution in the Z-direction of the stack, but these are neither dense nor complete surfaces. To facilitate visualization and registration we model patient specific prostate shape using the hybrid shape model proposed in [13] which is a combination of Extended Superquadrics (ESQ) and Radial Basis interpolation Function (RBF). Fitting the model involves first estimating parameters of the ESQ and then using the residual error to solve for the RBF parameters. Once the model is fit, the points on the surface of the shape satisfy the equation

$$F(x,y,z)^{\frac{\epsilon_1}{2}} + G(x,y,z) = 1. \; Where, \tag{1}$$

$$F\left(x,y,z\right) = \left[\left(\frac{|x|}{a}\right)^{2/\epsilon_2} + \left(\frac{|y|}{b}\right)^{2/e2}\right]^{\epsilon_2/\epsilon_1} + \left(\frac{|z|}{c}\right)^{2/\epsilon_1} \; and \tag{2}$$

$$G(x,y,z) = \sum_{j=1}^{N} w_j \lambda(d_j). \tag{3}$$

$G(x,y,z)$ corresponds to the RBF where λ is a Gaussian with compact support, d_j is the cosine distance of (x,y,z) from the j^{th} RBF center, w_j is a weight associated with j^{th} RBF center. $F(x,y,z)$ corresponds to the ESQ and its parameters include size parameters (a, b, and c), and exponents (ϵ_1 and ϵ_2) which are cubic spline interpolation functions. To reconstruct the shape from the shape model parameters, we use geodesic domes based on an icosahedron that generate approximately uniformly spaced points on a sphere. These points are first projected onto the ESQ and then scaled using the RBF function. Given the points on a geodesic dome D, they are used to reconstruct the shape S as shown below.

$$S = \frac{D}{F(D)^{\frac{\epsilon_1}{2}}} \cdot (1 - G(D)). \tag{4}$$

The geodesic dome also gives us the triangular faces for constructing the mesh. The point resolution of the reconstructed shape is controlled by the dome frequency. This representation allows us to model the 3D shape of annotated MRI imagery, and quickly generate a meshed surface and point cloud of desired resolution for rendering and registration respectively.

The hybrid shape model was used to model the glands and organs but it was not best suited for vascular structures. For vascular structures like the Neuro-Vascular bundle we employ Iso-surface fitting and Poisson surface interpolation [11] to reconstruct the entire 3D surface from labeled contours. We construct a uniformly sampled 3D volume of size $L \times B \times D$ where L and B are the height and width of the MRI stack and D is the number of labeled 3D contours. The value at a voxel in the volume is set as 0 if it lies within the contour else set as the distance to the nearest in-plane contour point. An Isosurface is fit to this volume, normals are estimated at the contour points, the contour points along with their normals are transformed from image space to metric space and finally Poisson surface reconstruction is performed to recover the dense 3D surface mesh for visualization.

Stereo Reconstruction Module: The da Vinci surgical system uses a high resolution stereoscopic laparoscope which captures two images at 1280×1024 resolution. This allows for 3D reconstruction using stereo reconstruction methods. The stereo laparoscope is calibrated using Zhang's calibration method [22]. We follow the traditional shape from calibrated stereo pipeline [8], using semi-global block matching algorithm [9] for computing stereo disparity from rectified images. The reconstructed point cloud is noisy and has errors. We place a depth threshold to eliminate distant points reconstructed erroneously, then we use DBSCAN [6] to find dense clusters to remove noise and erroneous points. The processed point cloud is used as the target shape to register the preoperative shape. For visualization, we perform Delaunay triangulation of the reconstructed points in the image space to define a triangular mesh. The dense reconstructed points from stereo are connected using the computed triangular mesh, triangles that are too large or are too narrow and elongated are removed as these might correspond to discontinuities in depth. This allows us to render the stereo model as mesh with texture corresponding to the input image frames.

Shape Registration Module: To help surgeons spatially orient themselves to the surgical area, we align the shape from MRI to the surface of the prostate as seen through the laparoscope. This allows surgeons to visualize the position of the tumor and the spatial relation to other critical organs around the prostate. There have been different approaches to align preoperative data to laparoscopic data. The imaging modalities are pre-calibrated and the laparoscopic camera tracked to initially align and maintain alignment [7,21]. In these approaches, tracking can be error prone due to large camera motion and deformations of the organs. Point correspondences between preoperative and live images are used to find the transformation for alignment [16]. The lack of correspondences, occlusions and noise affects the robustness of such methods. Fiducial markers can be used for correspondences [18]. In [21], multi-modal registration technique is used. Imaging modality such as the 3D ultrasound is used in which identifying the prostate boundary is relatively easy. The two modalities are calibrated with each other, and the live camera is tracked to maintain alignment. Using fiducial markers and imaging modalities such as the 3D ultrasound might not be preferred during the surgery as they are intrusive. Su et al. [20] use manual initial alignment followed by ICP [1,2] based refinement using manually marked or automatically detected key points on the surface of the organ. This approach requires identifying key points used for alignment. In our case, when the surgeon is using the system, the anatomical structures are no longer being manipulated, and there are no active deformations of the organ that needs to be tracked. So we use the landmark free registration approach proposed in [14], which we found to work better than ICP for our data. This method requires no additional equipments, no known correspondences, and is robust to outliers and small scale non-rigid deformations. The method uses fuzzy correspondences to solve for the transformation that maximizes the overlap between the two shapes. Since the method is designed to work for point clouds, the implicit form of the shape from MRI is used to generate uniformly spaced points on the surface of the prostate. The transformation is initialized using prior knowledge of the scene; the surgeon's view of the prostate, using the standard laparoscope placement for RALP, has the apex at the top, the bladder at the bottom and the rectum behind the prostate. Once registered, the shape from MRI and the shape from stereo can be visualized in the interactive mixed reality system.

Visualization Module: We have used the Unreal Engine 4 to develop an interactive application. Within the application surgeons can view the current reconstructed stereo view, the MRI shape, and stereo shape registered to the MRI shape. Meshes are rendered using different material properties to emphasize organ differences. The prostate is rendered as a wire-frame, giving it a readily identifiable 3D shape, but also to create a form of transparency that allows the surgeon to see occluded surfaces of other organs. Other organs are rendered in contrasting colors, with specular and diffuse components to allow users to intuitively understand the 3D shape. The textured stereo model is rendered using purely emissive color so artificial shadows and shading are not a problem. The Unreal engine supports a wide variety of hardware including major head mounted device (HMD) for visualization, and supports motion controls. This means our application allows the surgeon to hold the models and manipulate it using intuitive motion controls for grabbing and manipulating. If the surgeons think that the shape alignment is incorrect they can also manually align them in the mixed reality application. The application supports standing and room scale interface, allowing surgeons to lean, physically walk around, or virtually teleport using motion controls. This allows for novel viewing points that can help the surgeons to visualize patient specific anatomy better.

3 System Evaluation

In this section we will discuss our evaluation approach for the proposed system. This includes performance evaluation, user evaluation, and a feasibility test performed by deploying the system during 9 RALP procedures. A recording system was developed that can connect to the stereo DVI output ports of the da Vinci surgical system. We have selected individual stereo pairs of key portions of the 9 procedures for our evaluation.

Shape Representation Module: The shape model is fit to MRI data offline before the procedure begins. We fit the shape model to points extracted from MRI data. A model with 294 parameters took, on average, 7.5 s to fit to the 3D points with an average error of 0.36 mm.

Stereo Reconstruction Module: We evaluated the stereo reconstruction module by reconstructing 24 video sequences of 12 frames each. The disparity range for semi global block matching algorithm was set to $[-160, 160]$. Stereo reconstruction of the laparoscope image pair, meshing of the reconstructed point cloud and noise removal takes, on average, took 10.6 s to run per frame. An image pair produces approximately 10000 to 20000 points with about 20000 to 40000 triangular faces. We only reconstruct every 5^{th} pixel in the image which still gives us a dense enough mesh for visualization.

Shape Registration Module: We evaluated the registration scheme on data from total 9 patients. The shape registration module takes, on average, 21.5 s to align the stereo reconstructed model to the shape model from MRI. The registration process is a hierarchical approach which starts with a low resolution model of the point clouds and moves to progressively higher resolutions. We run the registration method with 2 levels of hierarchy. This was sufficient since the initialization, based on the prior knowledge of the scene, leads to good registration. For registration we used points on the stereo shape that were reconstructed from the central 40% of the image as these points mostly corresponded to the prostate. To measure the accuracy of the registration scheme, we use the cloud compare utility [4] to measure distances between the reconstructed prostate points and the aligned prostate surface from MRI. The mean error of registration was 1.45 mm. Figure 1 shows sample histogram of registration errors for one of the patients data.

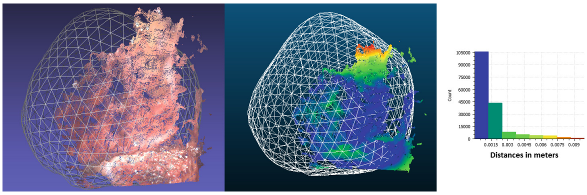

Fig. 1. Shape registration accuracy: shown from left to right are, aligned prostate regions from stereo and MRI, points from stereo prostate shape color-mapped based on the distance to the prostate surface from MRI, and histogram showing the distribution of distances.

Visualization Module: Performance in mixed reality is critical as drops in frame rate can lead to nausea, and user discomfort. The shape model and stereo reconstruction can both be tuned to modify the density of the models allowing us to choose for higher quality or less computational load. We have settled on $125,000$ polygons for our application, as this allows us consistent frame rate with dense looking models. Our application supports both the Oculus Rift CV1 with touch controls and the HTC Vive, and allows for standing and room-scale on both platforms. The application maintains a consistent 90 frames per second on the visualization platform, which is the maximum supported frame rate for both the Oculus Rift and the Vive. This frame rate maximizes user comfort and none of the experts reported motion sickness or any other discomfort.

User Evaluation: We presented the application to a group of 7 experts which included surgeons and radiologists. Each user was given a few minutes to move around and explore the mixed reality space and interact with the models. After having an opportunity to experiment and view the application, they were given a survey asking about their experience and preferences. After experiencing our system, every expert who was polled liked the application and felt that they could better orient themselves spatially. Many pointed out anatomical features unique to the patient that would influence how they proceed. While the system automatically aligned pre-operative and intra-operative shapes, the ability to manually align the models quickly using intuitive motion controls was also deemed useful (Fig. 2).

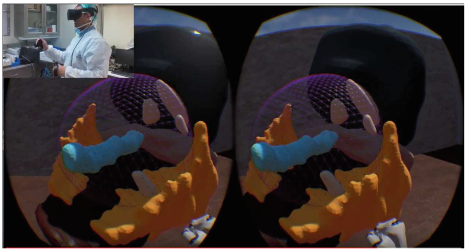

Fig. 2. A screen shot showing a surgeon interacting with the system.

Feasibility Test: The system described above was deployed during 9 RALP procedures. To our knowledge this was the first time ever such a system was used during the procedure. The imaging platform was connected to the da Vinci surgical robot through the passive DVI output ports to collect and process stereo images from the laparoscope. The Visualization platform was set up in one of the corners, away from the surgical table and close to the robot's console. The setup did not interfere with the procedure or the functioning of the robot. The stereo laparoscopes were calibrated prior to being used in the surgery. Pre-operative, segmented MRI (axial with resolution of $0.23 \times 0.23 \times 3$ mm) data was provided to us 1–5 days prior to the procedure. 3D shape of the anatomical structures were reconstructed from the labeled contours and were available for visualization before the surgery. During surgery, when the surgeon found the need to consult pre-operative data, he requested for it. Our system, then captured the current view of the surgery, performed stereo reconstruction, ran shape alignment, and then loaded the models into the mixed reality application. Once ready the surgeon interacted with the models in the virtual space to plan his/her next course of actions. During the course of a procedure, a surgeon typically used our system 4 times: (*i*) Before the surgery, he/she interacted with the 3D anatomical models extracted from pre-operative MRI to build a plan for the surgery. (*ii*) When the prostate was first visible, to re-confirm the spatial relation between critical anatomical structures. (*iii*) Prior to bladder neck sparing, to visualize the interface between the prostate and the bladder before separating the bladder from the prostate. (*iv*) Prior to apical dissection, which involves separating the prostate from the urethra. Our system took approximately 3 minutes from the time of initiating stereo image capture to being able to view the models in virtual space. This includes the time spent verifying the outputs of each module before visualizing them. The system, when run end-to-end takes less than a minute from capture to visualization. The surgeons spent approximately a minute using the application each time, during the surgery. They stated that it was easy for them to use the system and the turnaround time was quicker than anticipated. The surgeons stated that, the tool helped visualize the spatial relation between anatomical structures and orient better during the surgery.

4 Results and Discussion

Procedures in all 9 deployments of the system were successfully completed without any complications. Our system integrated into the current work-flow of the surgery by replacing/augmenting the 2D monitors and mouse interface of the PAC system with a full immersive and interactive 3D visualization that assists surgeons during surgery. The alignment of the 3D models lets them quickly localize spatially within the surgical area seen through the laparoscope and strategize on how to move forward with the procedure. The alignment proposed by our system was deemed correct for 7 patients, one of them was slightly mis-aligned which they had to correct manually and one of them had failed alignment due to inaccuracy in stereo reconstruction caused by blood/fat lodging on one of the camera's lens. During the feasibility study, on multiple occasions, the surgeon explained how the system helped him make a quick decision on the approach to take, which would not have been possible for him to do without our system. For example, in one of the cases the surgeon conducted a wider excision of the Neuro-Vascular bundles (NVB) based on the information he saw using our system that the lesion had invaded the NVB (see Fig. 3). Similarly, in another case, based on the information the surgeon saw in our system he conducted wider excision of the bladder neck (see Fig. 4). Both these pieces of information were not clear when looking at the MRI stack and the laparoscopic images separately.

One of the major criticisms of the system was that it required an external HMD and motion controllers to visualize and interact with the models. The surgeons stated that it would be more convenient if the visualization and the interaction can be done at the robot's console.

We see the advantages of using our system being two-fold. One, it helps improve patient health and two, it is a convenience for the surgeons performing the procedure. While a broader randomized study is required to evaluate the effectiveness of the system in improving patient health, the results from the feasibility study indicate that such a system would help surgeons make decisions during the procedure thus being a convenience tool. This is encouraging to continue developing and improving the system.

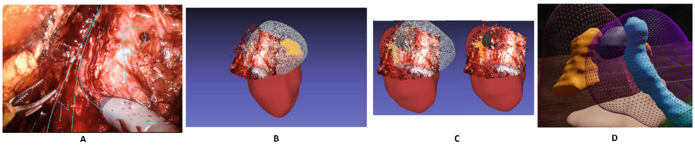

Fig. 3. (A): Surgeon's view before nerve sparing. Marked by letter N is the NVB and by letter P is the prostate gland. (B): Intra-operative and Pre-operative models aligned (White mesh: prostate, Pink: rectum). (C): Different view of the aligned models (Yellow: NVB Black: tumor). It can be seen that the tumor is extending into the NVB. (D): A close up of the model as seen in the HMD by the surgeon (Blue: urethra, Magenta: prostate, Yellow: NVB, Black: Tumor, Beige: seminal vesicle and in Pink: rectum). (Color figure online)

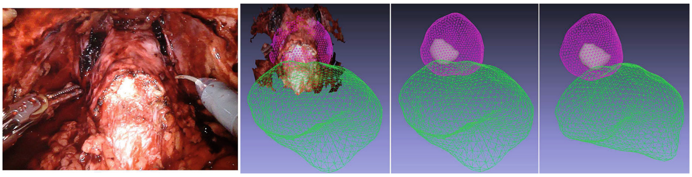

Fig. 4. From left to right: (1) Surgeon's view before bladder neck sparing. (2) aligned pre-operative and intra-operative models. (Magenta: prostate, Green: bladder). (3–4) Different views of pre-operative models showing tumor extending into bladder (Gray: Tumor). (Color figure online)

5 Conclusion and Future Work

We have developed a system which fuses pre-operative and intra-operative image data and presents it in a virtual 3D space for visualization and interaction using HMD and motion controllers to surgeons performing RALP. Through a feasibility study we have shown that the system could help improve spatial awareness during surgery and also help in making decisions at key stages of the procedure. To our knowledge this was the first time that such a system was deployed during RALP. Moving forward we are working towards developing a system that can integrate the visualization and interaction module into the surgical robot's console. We also wish to study the effectiveness of the system in long term patient outcome.

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