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Ultrasound Image-based Endoscope Localization for Minimally Invasive Fetoscopic Surgery

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Abstract— **The purpose of this work is to introduce an ultrasound image-based intraoperative scheme for rigid endoscope localization during minimally invasive fetoscopic surgery. Positional information of surgical instruments with respect to anatomical features is important for the development of computer-aided surgery applications. While most surgical navigation systems use optical tracking systems with satisfactory accuracy, there are several operation limitations in such systems. We propose an elegant framework for intraoperative instrument localization that does not require any external tracking system but uses an ultrasound imaging system and a computation scheme based on constrained kinematics of minimally invasive fetoscopic surgery. Our proposed algorithm simultaneously estimates endoscope and port positions in an online sequential fashion with standard deviation of 1.28 mm for port estimation. Robustness of the port estimation algorithm against external disturbance was demonstrated by intentionally introducing artificial errors to measurement data. The estimation converges within eight iterations under disturbance magnitude of 30 mm.**

I. Introduction

A. *Background and Motivation*

Positional information of surgical instruments is essential for surgical navigation and many other computer-aided surgery (CAS) applications. Therefore, accurate automatic localization of surgical instrument is required to provide intraoperative feedbacks in a CAS system. A typical surgical navigation system relies on an external tracking system to localize instruments. Optical tracking systems are especially popular due to their high accuracy. There are however shortcomings in the use of such systems. Line -of-sight between an optical tracker and markers has to be maintained [1]. In addition, bulky sensors have to be attached to surgical tools compromising usability. To address these shortcomings, we propose ultrasound image-based endoscope localization in minimally invasive fetal surgery.

Minimally invasive fetoscopic surgery provides a suitable condition to exploit ultrasound imaging as amniotic fluid medium favors ultrasound scanning. In addition, ultrasound scanning is considered an appropriate option with no known harm to the fetus unlike many other imaging modalities.

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Ultrasound image-based tracking of surgical tools has been explored in several works [2, 3]. Recent work by Stoll *et al*. [3] features passive markers and tracking algorithms designed for surgical instrument tracking. Real-time instrument tracking was also discussed in a work by Novotny *et al* [2] featuring a GPU-based approach.

Our work introduces a new approach for endoscope localization during minimally invasive fetoscopic surgery. Unlike previous works that use sophisticated marker configuration, fiducial marker design is kept simple so as to facilitate ease of implementation and minimize tedious calibration processes. To automatically compute instrument position relative to anatomical features based on information from 3D ultrasound images, we adopt an approach that combines kinematic analysis and image processing for estimation of endoscope poses. An algorithm for outlier rejection and automatic online updating of the estimation to increase its likelihood is designed to enhance the efficacy of the proposed localization scheme.

B. *Scope and Organization*

The contribution of this paper includes a novel ultrasound image-based endoscope localization method capable of simultaneous endoscope and port position estimation. Discussion will be specific to fetal surgery.

The next section presents the method starting with an overview followed by explanations of the various procedures that constitute the framework for intraoperative fetoscope localization. An experiment designed to evaluate the effectiveness of the method is featured in Section III. This is followed by a discussion of the experimental result in Section IV. Finally, Section V concludes this paper by stating its significances and potential development.

II. Methods

A. *Overview*

The proposed method comprises three main operations. First, an anatomical model of the placenta is constructed using 3D ultrasound images. Second, the endoscope that is introduced to the operation site is imaged in the same reference frame of the ultrasound imaging device. Since both models are constructed under the same reference frame, cross-domain registration is not required. Automatic computation of the endoscope position is performed by localization of the decoupled kinematic Degree of Freedoms (DoF) based on geometric eccentricity presented in the 3D image featuring the endoscope. Lastly, port position is concurrently estimated and updated sequentially with higher confidence after every iterative attempt. Fig. 1 is an illustration of the main operations in our proposed method.

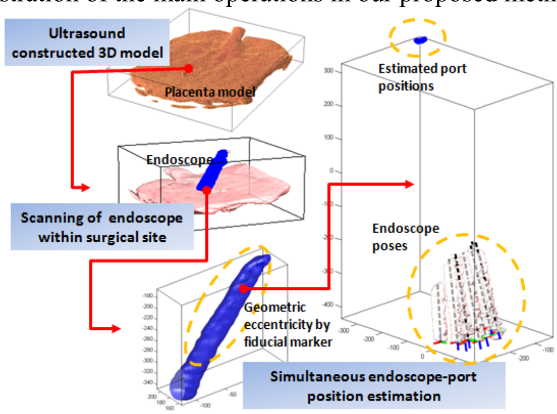

Figure 1. Pose and port estimation

B. *Construction of 3D Anatomical Model*

A three-dimensional model of the placenta is constructed by extracting an isosurface of the volumetric data of ultrasound 3D images. Polygonal surfaces are assigned to mesh surface boundaries. The vertices and indexed faces of the polygons are referenced with respect to the coordinate system centered at the apex of a stationary ultrasound probe.

C. *Fetoscope Localization*

The ultrasound image-based fetoscope localization involves three essential aspects: 1) task-specific kinematic model, 2) image processing method, and 3) pose estimation framework.

1) *Task-specific Kinematic Model*

The fetoscope's kinematics is modeled as a decoupled locomotion pivoted at the incision site i.e. the port or trocar position. This constrained kinematic model [4, 5] allows us to design a computation scheme that localizes each DoF almost independently. The task-space configuration of a fetoscope pose is defined by Euler angles roll, pitch, yaw, and an axial translation denoted by *r, p, y,* and *d* respectively. Hence, the expression

$$\boldsymbol{x}=[r, p, y, d]^{\mathrm{T}} \qquad (1)$$

denotes the state representation of the fetoscope pose in a camera-centric coordinate system.

2) *Image Processing*

A series of operations is carried out to process image data acquired from 3D ultrasound scanning device to useful information that exhibits geometric variants associated with the relevant DoFs. The selected techniques are generic image processing operations that can be implemented with little difficulties. These include noise reduction, artifact removal, automatic segmentation, and rejection of outliers. First, a 2D adaptive filtering is used to reduce noise. Artifacts like air bubble are removed using image morphology. Larger static artifacts can be removed by subtraction of a background image. The isosurface of volumetric data of the fetoscope is extracted by assigning an appropriate isovalue hence obtaining vertices of the fetoscope 3D geometry. Finally, outliers are reduced by iteratively rejecting data of high variance until a strong consensus is achieved.

3) *Pose Estimation Framework*

A statistical approach is adopted to decode geometric variants into their associated kinematic variables. Principal Component Analysis (PCA) is applied to compute the orientation of the fetoscope [6]. The shaft of the fetoscope provides natural geometric variance in the pitch and yaw direction that can be identified by the first principal axis. A cylindrical fiducial marker is designed to constrain kinematic variable *r* by introducing radial eccentricity to the featured endoscope in 3D position as illustrated in Fig. 2. Fig. 3 features ultrasound 3D images of the endoscope attached with a marker.

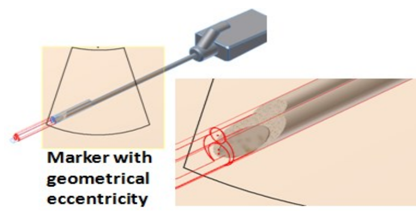

Figure 2. Marker design

This asymmetrical geometry about the axial direction results in a second principal axis pointing away from the direction of eccentricity. Therefore, *r* can be computed with the second principal component. To ensure robustness against artifact and segmentation errors, pose estimation is iterated each time rejecting outliers until a preset threshold of the component score is achieved.

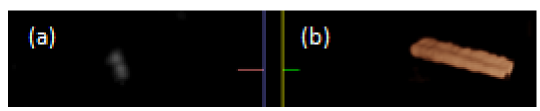

Figure 3. Geometrical eccentricity produced by marker in ultrasound image: (a) top (b) 3D view

In addition, 3D linear regression can be used to first estimate the axial direction of the endoscope followed by obtaining major axis orthogonal to shaft axis. While the linear regression approach provides flexibility as it can estimate axis direction even with limited 2D slices in the case of 3D tilt-scanning ultrasound probe, it is less robust against poor images and artifacts. Both methods, however, yield similar outcome in most cases.

D. *Port Position Estimation*

Kinematic constraint of minimally invasive surgery can be exploited by computing the pivotal position of the surgical instrument motion. For 3D tilt-scanning ultrasound probe, intraoperative real-time 3D scanning may be challenging. Port position estimation enables coarse estimation of orientation information within a limited number of 2D image slices in order to meet intraoperative requirements. Since the fine estimation of the fetoscope is designed to be automatic, it can be scheduled at appropriate intervals. Port position estimations can also be used to update endoscope position with enhanced likelihood conditioned upon previous frames.

In this work, port position estimation is iteratively updated to compute kinematic variables *d*.

Minimum path between fetoscope axes in an initial frame and its subsequent frame is first computed. The midpoint of the path is assigned as an initial estimation of the port location. The equation of the line representing the fetoscope axis of the next frame is obtained. A new path between its previous minimum path and the immediate frame's fetoscope axis is constructed iteratively. The midpoint of this newly constructed path is assigned as the updated estimation of the port position at that instant. This will ensure that the estimated location lies in a most probable path conditioned upon its previous frame.

The shortest path between two skew lines, l_i and l_j is in fact a straight line S orthogonal to both lines with end points $\boldsymbol{p}_i$ and $\boldsymbol{p}_j$ lying on l_i and l_j respectively. An endpoint on a line can be represented by vector equation as

$$\boldsymbol{p}=\boldsymbol{k}+t\boldsymbol{v} \quad (2)$$

where $\boldsymbol{v}$ and $\boldsymbol{k}$ are the directional vector of and a point on the line respectively, and t is a scalar parameter constraining $\boldsymbol{p}$ to a specific point.

Hence a closed-form solution to $\boldsymbol{p}$ can be obtained by solving t as follows.

$$\begin{bmatrix} v_{ii} & v_{ij} \\ v_{ji} & v_{jj} \end{bmatrix} \begin{bmatrix} t_i \\ -t_j \end{bmatrix} = \begin{bmatrix} -\boldsymbol{v_i} \bullet k_i^j \\ -\boldsymbol{v_j} \bullet k_i^j \end{bmatrix} \quad (3)$$

where v_{ij} denotes $\boldsymbol{v_i} \bullet \boldsymbol{v_j}$ and k_i^j denotes $\boldsymbol{k_j} - \boldsymbol{k_i}$. Subscript i and j refer to variable's association with line l_i and l_j respectively.

III. Experiment

A. *Experimental Setup*

Fig. 4 illustrates an experimental setup and test environment for evaluating the proposed method.

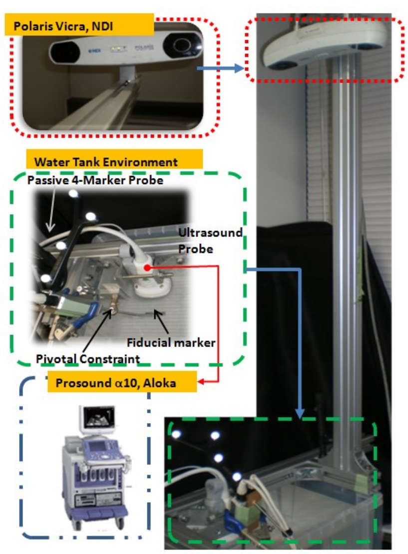

Figure 4. Experiment setup for evaluation

The experiment consists of a water tank environment with a constrained endoscope attached to a mechanical port, an optical tracking system, and an ultrasound imaging system.

B. *Procedure*

A ϕ5.4 mm endoscopic camera (LS501D, Shinko Optical) is used in the experiment. Accuracy of endoscope localization is benchmarked against commercial optical tracking system (POLARIS Vicra, NDI). Positional information of the endoscope is acquired by the optical tracking system and ultrasound imaging using our proposed framework. Ultrasound images are acquired using a Prosound α10, Aloka system with a stationary 3D tilt-scanning ultrasound probe attached as depicted in Fig. 4. Image slices are acquired at 1 degree angular step with (0.3x0.3) mm^2 pixel size. A mechanical port with a spherical joint is used to constrain endoscope motion, hence mimicking trocar constraint at the incision site.

IV. Results and Discussion

A. *Accuracy of Endoscope Localization*

Accuracy result of endoscope localization in a camera-centric coordinate system benchmarked against the optical tracking system is tabulated in Table 1.

TABLE I. ERROR IN POSITION ESTIMATION

Pose	Error				
	Δr (°)	*Δp (°)*	*Δy (°)*	*Δd₁ (mm)*	*Δd₂(mm)* [a]
1	0.28	3.53	0.65	2.26	2.89
2	0.34	0.78	0.99	0.76	1.24
3	0.94	4.00	1.80	5.74	6.29
4	3.63	2.30	1.86	9.39	10
5	1.10	2.12	0.93	9.58	9.65
6	7.57	3.48	0.76	7.67	7.46
7	0.96	0.34	2.27	11.90	10.84
8	2.21	3.17	0.99	9.10	9.49
Mean	2.13	2.46	1.28	7.05	7.23

a. Estimation without iterative port estimation

In general, estimation of *d* with iterative port estimation has better accuracy compared to that without iterative process as seen in the last two columns. Error in roll angle is larger than that of yaw angle because the artificial geometrical eccentricity created by the marker is not as distinctive as the shaft's axial length. It can be observed that pitch angle accounted for a significant proportion of the errors while yaw angle produces much lower error. This discrepancy can be explained by the uncertainty of the 3D tilt-scanning ultrasound probe in its slice-axis. The angular step resolution is 1^o which translate to a maximum uncertainty of approximately 2.3 mm for a scanning depth of 130 mm. Since pitch angle is a larger component of the angle of incident between the shaft and the slice plane, its accuracy is more significantly influenced by the device's measurement uncertainty. It can therefore be argued that much of the inaccuracy was caused by limitations in the acquisition device. However, it is possible to address this problem by incorporating effective calibration method and robust filtering that improves estimations in a stochastic system. It is therefore important to demonstrate consistency and robustness as presented in the following two sections.

B. *Precision in Port Position Estimation*

In an evaluation of 30 estimations, standard deviation of 1.28 mm is observed. Standard deviations in the x-, y-, and z-axis direction are 3.17 mm, 1.26 mm, and 1.84 mm respectively. Discrepancy in the precision between the orthogonal axes is once again observed. As expected, x-axis which is in the direction perpendicular to the slice plane registered the largest deviation. Uncertainty associated with the workspace of the experiment environment ranges from 0.8 mm to 2.3 mm in the x-axis direction. The precision in all three directions appears to be in agreement when this difference in uncertainties of axis achievable by the imaging device is factored in.

Fig. 5 features snapshots of the distribution of estimated port position along with endoscope pose in the workspace.

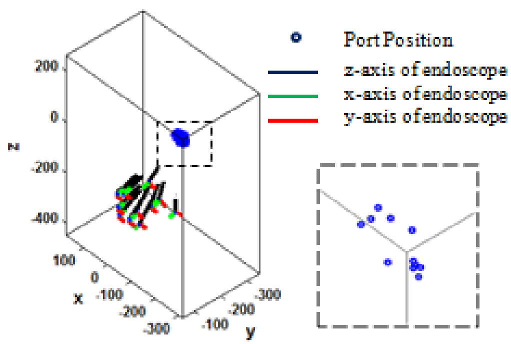

Figure 5. Simultaneous endoscope position computation and port estimation

C. *Robustness of Instrument-Port Position Estimation*

Robustness is reflected by a method's ability to adapt to unexpected disturbance. Our proposed method is assessed by intentionally leaving artifact untreated during upstream process and introducing artificial disturbance in measurement data.

The iterative PCA method for pose computation demonstrated robustness against artifact in the ultrasound image as shown in Fig. 6. It requires only two iterations to converge to a satisfactory solution. In most cases of the water tank experiment, consensus on estimation is reached in the first PCA operation.

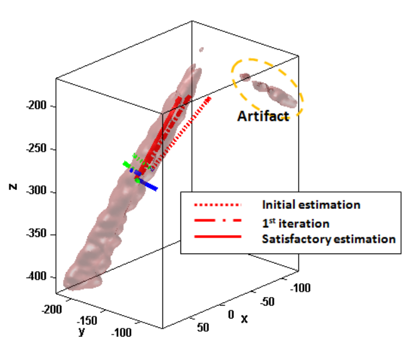

Figure 6. Iterative estimation of endoscope pose

Fig. 7 illustrates convergence of the port position estimation under various magnitudes of disturbance. Estimations regain consensus within the next three to five iterations even under disturbance of 30 mm in magnitude.

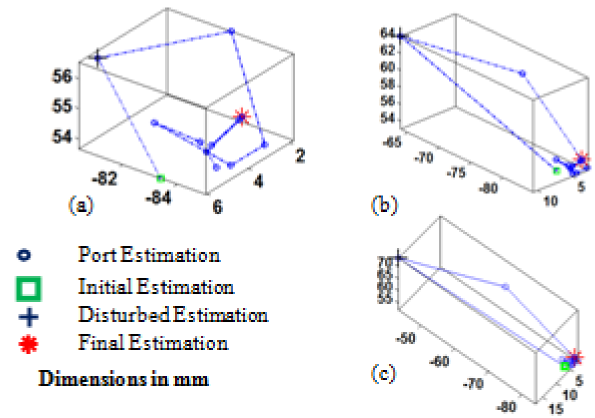

Figure 7. Convergence of port estimation under (a) 3 mm (b) 15 mm (c) 30 mm disturbance in x-y-z axis

V. CONCLUSION

This paper presented an approach for ultrasound image-based localization of an endoscope, and demonstrated the consistency and robustness of the method based on water tank results. More comprehensive studies on automatic model construction and the endoscope's position signal extraction using ultrasound data under more realistic clinical condition will be carried out. The focus of this paper is to demonstrate a novel method that can be implemented readily in the context of current technology. It is hoped that this work opens up new possibility in surgical navigation applications like data fusion with vision-based tracking as well as image mapping of 2D endoscopic views to a 3D ultrasound model for visualization.

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