CS 446 CIS II Paper Presentation Critical Summary

Project: Direct Photoacoustic Registration and Visualization

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Yip M. C., Adebar T. K., Rohling R. N., Salcudean S. E., Nguan C. Y., "3D Ultrasound to Stereoscopic Camera Registration through an Air-Tissue Boundary". MICCAI 2010, Part II, LNCS, vol. 6362, pp.626-634. Springer, Heidelberg (2010)

Paper Selection:

I selected this paper because it explores the same problem as my project. Both my project and this paper aim to display information from 3D ultrasound (US) in a stereo camera (SC) view during laparoscopic procedures. Although they propose a different method of registering US to SCvideo than the approach used in my project, the review of other registration techniques provides a good overview of the field that my project will affect. They also discuss possible practical issues with using this technology into the laparoscopic setting. Many of these issues are ones that I will also face when I likewise move my project from bench top into the laparoscopic setting. In addition, this paper is the state of the art in terms of registration accuracy that my project aims to improve.

My project is to directly register 3D US with SC with the photoacoustic (PA) effect. A laser is used to project spots onto the phantom or tissue surface, shown in the SC image as distinct points. These laser points cause the PA effect at the phantom or tissue surface generating an acoustic signal that can be seen in US images. This paper has the same goal but takes a different approach using a mechanical registration tool. Their method is based on a registration tool with optical markers on one side and US fiducials on the other. I will present their method in more detail in the technical summary. Although the methods differ, the statistical analysis and experimental considerations are very applicable to my project. They perform a one-way analysis of variance (ANOVA) to determine if different variables in their phantom have an effect on ultrasound fiducial localization. Likewise, it would be a very good idea to do a similar analysis on how different variables in the phantom affect the localization of the PA signal. They also present their registration errors based on sub-surface test points as opposed to test points on the surface. This is also something that I will keep in mind for my project when designing future experiments.

Technical Summary:

The authors propose a novel method for registering 3D US with SC video for the purposes of augmented reality and video fusion. They offer an overview of methods currently used to accomplish the stated goal such as ultrasound calibration and US transducer tracking and state some of their shortcomings. This paper's main innovation is a technique to acquire the 3D US to SC registration using a mechanical registration tool. This tool has optical markers attached on one face and US fiducials attached on the other face. It can be seen in figure 1b.

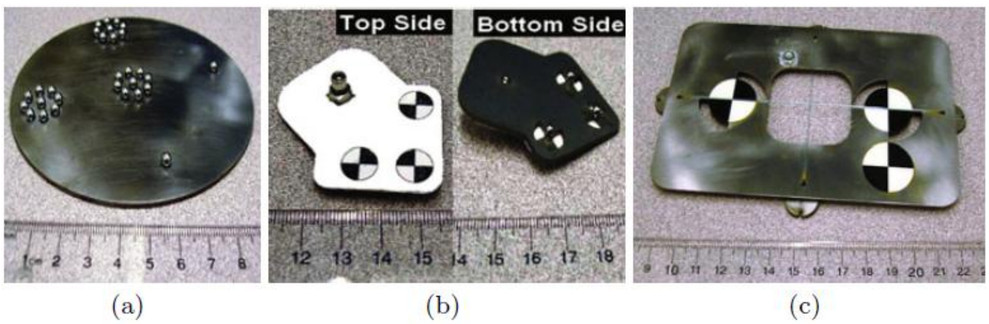

Figure 1. a) Fiducial Localization test plate, b) Registration tool, c) Registration Accuracy test tool [1]

Case	Fiducial Size	Lateral Position in US Image	Angle of Air-Tissue Boundary	Boundary Depth	Stiffness of Tissue
1	2mm	Offset (10cm)	0 degree	3cm	12 kPa
2	3mm	Central	20 degree	6cm	21 kPa
3	4mm	N/A	40 degree	9cm	56 kPa
Control	3mm	Central	0 degree	6cm	21 kPa

Table 1. Phantom Variables that may affect Fiducial Localization

Their study has two stated goals: "to determine the accuracy of locating US fiducials on an air-tissue boundary, and to determine the feasibility of using these fiducials to register 3D US to stereoscopic cameras." [1] For their first goal, they considered five variables in the phantom that may affect fiducial localization. Fiducial localization is their process of manually selecting where the fiducials are located in the US image. The five variables and how they were varied are described in table 1. The fiducial localization tool in figure 1a is used. It has "three sets of fiducials spaced 10 cm apart, with each set consisting of a center fiducial and eight surrounding fiducials at a radius of 10 mm." [1] The dimensional accuracy of the water jet cutter used to machine this and other tools is 0.13 mm.

Each variable was varied independently around the control case. The Euclidean distances between the localized outer and center fiducials are compared to the known tool geometry. This error is reported over 80 tests in table 2. They perform an ANOVA analysis to determine which variables are statistically significant. These are marked by a * in table 2.

Variable	Value	Mean ± Std Dev. (mm)	Median (mm)	RMS Error
Fiducial Size	2 mm	0.94 ± 0.34*	0.89	1.00
	3 mm	0.82 ± 0.28	0.78	0.87
	4 mm	0.70 ± 0.20	0.67	0.73
Boundary Depth	Long (9 cm)	0.54 ± 0.18*	0.55	0.57
	Med. (6 cm)	0.82 ± 0.28	0.78	0.87
	Short (3 cm)	0.66 ± 0.20*	0.64	0.69
Tissue Stiffness	High (12kPa)	0.81 ± 0.30	0.78	0.86
	Med. (21kPa)	0.82 ± 0.28	0.78	0.87
	Low (56kPa)	0.80 ± 0.19	0.80	0.82
Boundary Angle	0°	0.82 ± 0.28	0.78	0.87
	20°	0.78 ± 0.28	0.75	0.83
	40°	1.04 ± 0.35*	0.97	1.10
Lateral Position On Boundary	Center	0.82 ± 0.28*	0.78	0.87
	Offset (10 cm)	0.60 ± 0.28*	0.59	0.66

Table 2. Mean, standard deviation and median of errors associated with localizing bead fiducials at air-tissue boundaries. [1]

The authors give various reasons for the results in table 2. Small fiducials are more difficult to localize as they easily become lost in the air-tissue boundary reflection. They also state that fiducials were more difficult to localize when they are in the near field. From these results, they conclude that this technique will work on a variety of different tissues since the tissue stiffness had no effect. Fiducials offset from the center had lower errors because they were less obscured by specular reflection.

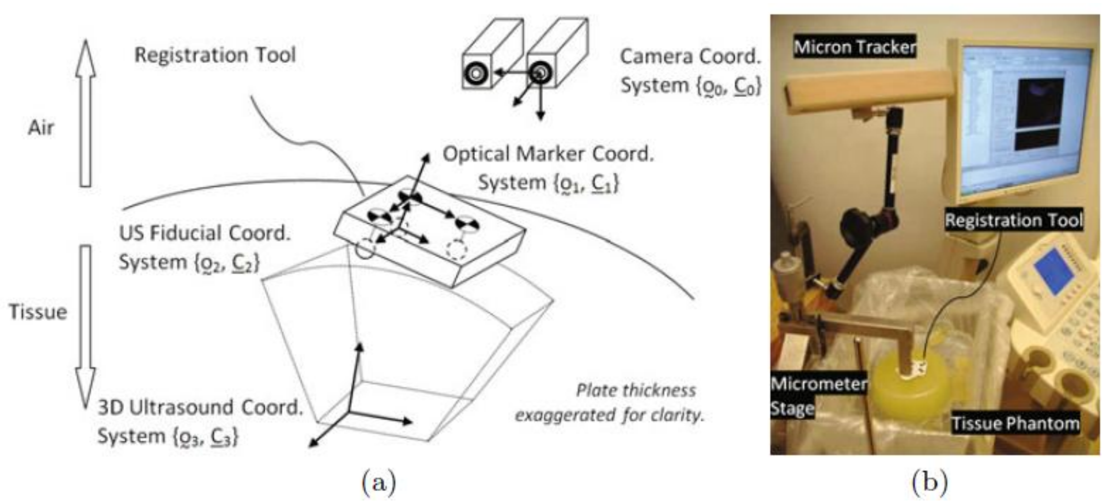

Figure 2. a) Schematic of the registration method, b) Experimental Setup [1]

For their second goal, they describe the chain of transformations to register 3D US to SC. Figure 2a shows the various coordinate frames. The transformation from $\{o_1, C_1\}$ to $\{o_0, C_0\}$, ${}^0T_1$, is given by triangulating the optical markers on the registration tool with the SC. The transformation from $\{o_2, C_2\}$ to $\{o_1, C_1\}$, ${}^1T_2$, is known from the tool geometry based on its mechanical design. The transformation from $\{o_3, C_3\}$ to $\{o_2, C_2\}$, ${}^2T_3$, is obtained by defining $\{o_2, C_2\}$ in $\{o_3, C_3\}$ based on the 3 localized fiducials. The fiducials are individually x_0, x_1, and x_2 localized in $\{o_3, C_3\}$. Equation 1 shows the process to obtain ${}^3T_2$. ${}^2T_3$ is then just the inverse of ${}^3T_2$. The overall transformation from 3D US to SC is thus ${}^0T_1{}^1T_2{}^2T_3$ or ${}^0T_3$.

$$
\begin{aligned}
{}^3v_1 &= {}^3x_1 - {}^3x_0 && (1)\\
{}^3v_2 &= {}^3x_2 - {}^3x_0 && (2)\\
{}^3i_2 &= \frac{{}^3v_1}{||{}^3v_1||} && (3)\\
{}^3k_2 &= \frac{{}^3v_1 \times {}^3v_2}{||{}^3v_1 \times {}^3v_2||} && (4)\\
{}^3j_2 &= {}^3k_2 \times {}^3i_2 && (5)\\
{}^3T_2 &= \begin{bmatrix} {}^3i_2 & {}^3j_2 & {}^3k_2 & {}^3x_0 \\ 0 & 0 & 0 & 1 \end{bmatrix} && (6)
\end{aligned}
$$

Equation 1. Definition of $\{o_3, C_3\}$ in $\{o_2, C_2\}$ [1]

They tested the registration accuracy by first determining the transformation from 3D US to SC with the registration tool in figure 1b. They then used the registration test tool in figure 1c to determine the subsurface accuracy. They achieve this by placing the test tool within a water bath and saving a 3D US volume. Then, they drain the water bath and track the optical markers on the tool with the SC. This process allows them to determine the crosswire of the test tool's pose in both the 3D US and SC space. The error is defined as the Euclidean distance between the crosswire pose in the SC space and the crosswire pose in the US space transformed to the SC space. The mean results of 12 points over 4 experiments are shown in table 3.

	$e_{Lateral}$ (mm)	$e_{Elevational}$ (mm)	e_{Axial} (mm)	e_{Total} (mm)
Registration 1	0.90 ± 0.44	0.77 ± 0.33	1.08 ± 0.75	1.75 ± 0.56
Registration 2	1.02 ± 0.45	0.60 ± 0.32	1.14 ± 0.99	1.83 ± 0.74
Registration 3	0.65 ± 0.43	0.76 ± 0.33	1.01 ± 0.63	1.55 ± 0.53
Registration 4	0.57 ± 0.40	0.82 ± 0.30	1.03 ± 0.79	1.60 ± 0.58
Average	0.78 ± 0.45 mm	0.74 ± 0.32 mm	1.07 ± 0.78 mm	1.69 ± 0.60 mm

Table 3. Mean errors (n = 12) between points in a registered 3DUS volume and its location in the stereo-camera frame. [1]

The main source of the error is in the axial direction. The authors reason that this is due to the tail artifact generated by the surface fiducials shown in figure 3. It is also stated that a model of the tail artifact could be used to further minimize the errors. They note that this method demonstrates lower errors than standard EM (3.07 +- 0.75mm) [2] or optical (2.83 +- 0.83mm) [3] tracking methods.

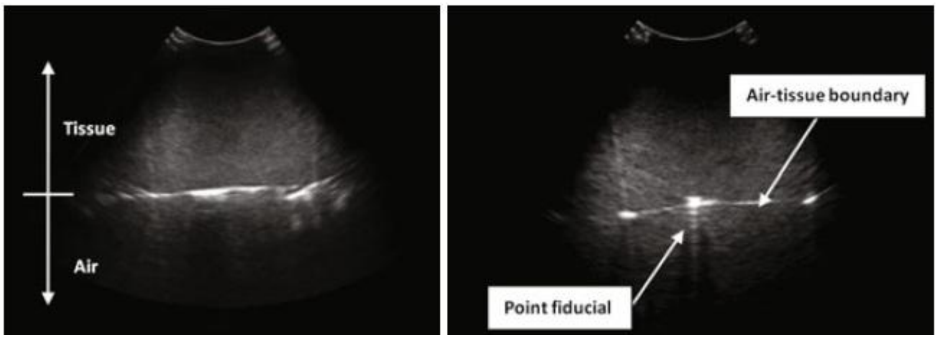

Figure 3. Example images of an air-tissue boundary (left) and a 3 mm fiducial pressed against an air-tissue boundary (right) [1]

The authors discuss several practical issues and possible remedies. First, this registration is most appropriate when the SC and the US transducer are fixed. If either moves, then a new registration must be reacquired. However, if there is robotic assistance, a new registration could be computed based on the robot kinematics. Another issue is the SC disparity. They show results based on a SC with large disparity and subsequently small errors. Laparoscopic SC's will have a much smaller disparity and consequently larger errors. They propose the solution of designing a larger registration tool that can be folded and fit through a trocar. They also note that these results were obtained using the minimum fiducials required to extract the six degrees of freedom in the transformation. More fiducials would allow the errors to be averaged, likely leading to smaller errors. Accuracy could also be increased by considering different registration tool poses.

Analysis:

The authors provided a novel method for registering 3D US and SC and showed promising results that are better than standard methods. This paper was well-written and provided a good overview of current methods being used to solve the problem.

For fiducial localization, they considered five different variables, which I thought were well-chosen. Another interesting variable would have been the level of scattering as this affects image quality. I also think this localization study would have been better if the fiducials were being automatically detected. In my opinion, manual localization makes it difficult to compare the results under different test conditions as manual localization is inconsistent. It may be the case that a semi-automatic method is used where the general area of the fiducial is manually localized, but the center of the fiducial is determined automatically. This approach would be more consistent and allow the variables to truly be isolated, but this is not stated in the paper. The ANOVA table is a great tool for demonstrating the significance of the considered variables.

For registration, they show the reader how they compute the series of transformations from the US frame to the SC frame. This is necessary for the reader to understand the method, so this level of detail was useful. I liked how they used a different test tool to test the registration error. In addition, they use it to determine the subsurface registration error as opposed to errors on the surface near the localized fiducials. This portion of the experiment was slightly confusing at first, so another figure would have been useful. They discuss the axial error and possible solutions, but do not mention the lateral or elevational errors even though they were not much smaller than the axial error. They suggest that a foldable registration tool could be used to compensate for smaller SC disparity, but this sounds like a terrible idea. Their method is based on the fact that the registration tool has known geometry, so anything that changes this geometry would seemingly create another source of error.

References:

[1] Yip M. C., Adebar T. K., Rohling R. N., Salcudean S. E., Nguan C. Y., "3D Ultrasound to Stereoscopic Camera Registration through an Air-Tissue Boundary". MICCAI 2010, Part II, LNCS, vol. 6362, pp.626-634. Springer, Heidelberg (2010)
[2] Cheung, C.L., et al.: Fusion of stereoscopic video and laparoscopic ultrasound for minimally invasive partial nephrectomy. In: Medical Imaging 2009: Visualization, Image-Guided Procedures, and Modeling. Proc. SPIE, vol. 7261, pp. 726109–726110 (2009)
[3] Leven, J., et al.: DaVinci canvas: a telerobotic surgical system with integrated, robot-assisted, laparoscopic ultrasound capability. In: Duncan, J.S., Gerig, G. (eds.) MICCAI 2005. LNCS, vol. 3749, pp. 811–818. Springer, Heidelberg (2005)