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Photoacoustic image guidance and robotic visual servoing to mitigate fluoroscopy during cardiac catheter interventions

Michelle T. Graham[a], Fabrizio Assis[b], Derek Allman[a], Alycen Wiacek[a], Eduardo Gonzalez[c], Mardava R. Gubbi[a], Jinxin Dong[a], Huayu Hou[a], Sarah Beck[d], Jonathan Chrispin[b], and Muyinatu A. Lediju Bell[a,c,e]

[a]Department of Electrical and Computer Engineering, Johns Hopkins University, Baltimore, MD, USA
[b]Division of Cardiology, Johns Hopkins Medical Institutions, Baltimore, MD, USA
[c]Department of Biomedical Engineering, Johns Hopkins University, Baltimore, MD, USA
[d]Department of Molecular and Comparative Pathobiology, Johns Hopkins Medical Institutions, Baltimore, MD, USA
[e]Department of Computer Science, Johns Hopkins University, Baltimore, MD, USA

ABSTRACT

Many cardiac interventional procedures (e.g., radiofrequency ablation) require fluoroscopy to navigate catheters in veins toward the heart. However, this image guidance method lacks depth information and increases the risks of radiation exposure for both patients and operators. To overcome these challenges, we developed a robotic visual servoing system that maintains visualization of segmented photoacoustic signals from a cardiac catheter tip. This system was tested in two *in vivo* swine cardiac catheterization procedures with ground truth position information provided by fluoroscopy and an electroanatomical mapping system. The 1D root mean square localization errors within the vein ranged $1.63 - 2.28$ mm for the first experiment and $0.25 - 1.18$ mm for the second experiment. The 3D root mean square localization error for the second experiment ranged $1.24 - 1.54$ mm. The mean contrast of photoacoustic signals from the catheter tip ranged $29.8 - 48.8$ dB when the catheter tip was visualized in the heart. Results indicate that robotic-photoacoustic imaging has promising potential as an alternative to fluoroscopic guidance in cardiac catheter interventions. This alternative is advantageous because it does not require the use of ionizing radiation, it provides depth information for cardiac interventions, and it enables enhanced visualization of the catheter tips within veins and within the beating heart.

1. INTRODUCTION

Cardiac arrhythmias (e.g., atrial fibrillation, ventricular tachycardia, supraventricular tachycardia) are characterized by irregular heartbeats, which increase the risk of stroke, heart failure, and other heart-related complications.[1] Over 2.7-6.1 million people in the United States suffer from atrial fibrillation alone.[2–4] Cardiac catheter interventional procedures are often performed to diagnose and treat cardiac arrhythmias. Treatment is often administered by inserting a catheter into the heart and ablating cardiac tissue with radiofrequency waves to restore the heart to its normal rhythm.[5]

The cardiac ablation procedure can be summarized by the four steps shown in Fig. 1, with each step employing a different guidance technique. First, a catheter is inserted into a peripheral vein and guided to the heart using fluoroscopy.[6,7] Next, a combination of fluoroscopy, intracardiac echocardiography, and electroanatomical mapping is utilized to navigate the catheter to regions of interest within the heart and confirm catheter-to-endocardium contact.[8] Lastly, ablation is performed, monitored, and assessed using biophysical models and impedance measurements.

Challenges with the current fluoroscopic image guidance approach during cardiac radiofrequency ablations include the lack of depth information and the risks associated with exposure to ionizing radiation. In addition, the current intracardiac echocardiography approach requires skilled operators and acquires images within a local reference frame.[9] Alternatively, transthoracic ultrasound can be used to achieve global localization. However, transthoracic images are limited by several artifacts including acoustic clutter[10] and shadowing from the ribs,[11]

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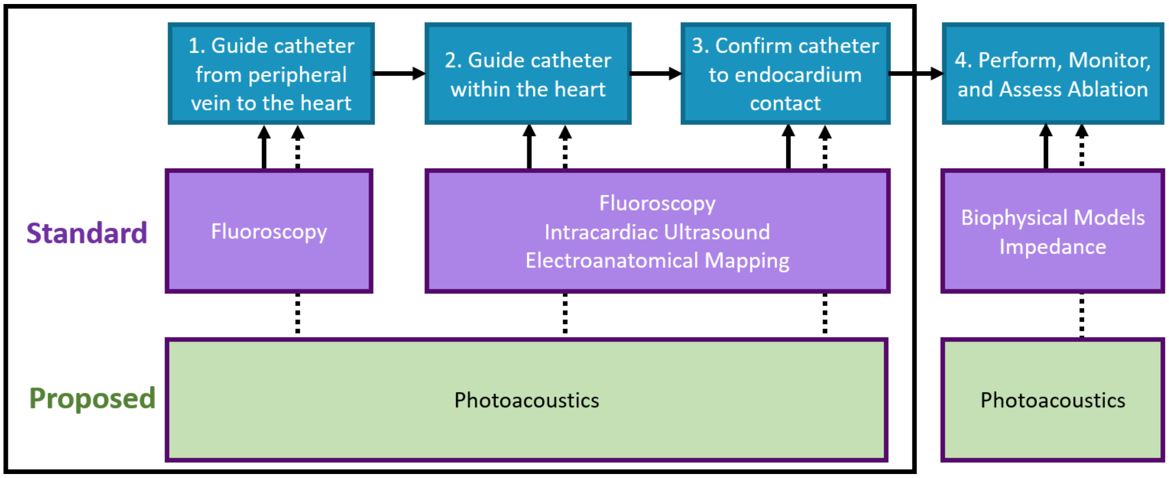

Figure 1: A standard cardiac catheter interventional procedure relies on fluoroscopy, electroanatomical mapping, intracardiac echocardiography, biophysical models, and impedance measurements for successful implementaion. We are proposing to replace (or significantly mitigate) fluoroscopy by introducing photoacoustic image guidance across each of the four stages of the standard procedure. The black box indicates the stages of the procedure addressed by our robotic-photoacoustic system.

which raises uncertainty about the catheter tip location. The catheter tip can also be difficult to differentiate from its shaft and surrounding tissue due to similar echogenicity.[12–15] Finally, biophysical models and impedance measurements are limited in their ability to provide direct visualization of the lesion as it is being formed.[16]

To overcome challenges associated with ablation monitoring, photoacoustic techniques are being investigated with promising results. Specifically, multiple *ex vivo* experiments have previously demonstrated the potential of photoacoustic imaging to identify cardiac radiofrequency ablation lesions with imaging depths up to 3 mm, with 6-10 dB of contrast between ablated regions and normal tissue, and with 97% diagnostic accuracy.[17–19] Given this promise of photoacoustic imaging with regard to lesion monitoring, we are exploring the potential of robot-assisted photoacoustic imaging to overcome the remaining challenges associated with guiding the catheter to and within the heart.[20] The bottom row of Fig. 1 demonstrates our proposed cardiac catheter ablation guidance system in which photoacoustic imaging is useful across each stage of the procedure.

During the first stage, a standard cardiac catheter can be modified to accommodate an optical fiber within its hollow core in order to generate photoacoustic signals from the catheter tip as it is guided toward the heart. These photoacoustic signals would be received by an external ultrasound probe. A robot arm attached to the ultrasound probe can be commanded to maintain the catheter tip at the center of the photoacoustic image with vision-based robotic control (i.e., visual servoing).[20] Toward this end, we developed a photoacoustic-based visual servoing system that commands a robot-held ultrasound probe to maintain visualization of segmented photoacoustic signals from the tip of the fiber-catheter pair.[20]

During the second stage of the procedure summarized in Fig. 1, the operator can continue using the described robotic-photoacoustic system to localize the catheter tip within the heart. During the third stage, the contrast differences between photoacoustic signals obtained with and without the catheter touching the endocardium can be used to confirm catheter-tissue contact prior to ablation. Finally, the extent of ablated tissue can be assessed using photoacoustic images.

This conference paper summarizes our success with the navigation and visualization components of utilizing photoacoustic imaging and robotic assistance during the first three stages summarized above and in Fig. 1. Our ultimate vision for cardiac catheter ablation guidance is a photoacoustic system which functions as the image guidance technique across all steps of the ablation procedure.

2. METHODS

Fig. 2 shows our robotic-photoacoustic imaging system which consists of a Phocus mobile laser (Opotek, Carlsbad, CA, USA) operating at 750 nm wavelength, an E-CUBE 12R ultrasound scanner (Alpinion Medical Systems, Seoul, South Korea), and a Sawyer robot (Rethink Robotics, Boston, MA). An Alpinion SP1-5 phased array ultrasound probe was attached to the end effector of the robot to acquire co-registered ultrasound and photoacoustic images during experiments. The laser was coupled to a 1 mm-core-diameter optical fiber inserted into a 5F inner diameter, 7F outer diameter cardiac catheter. The tips of the fiber and catheter were coincident, as shown in Fig. 2.

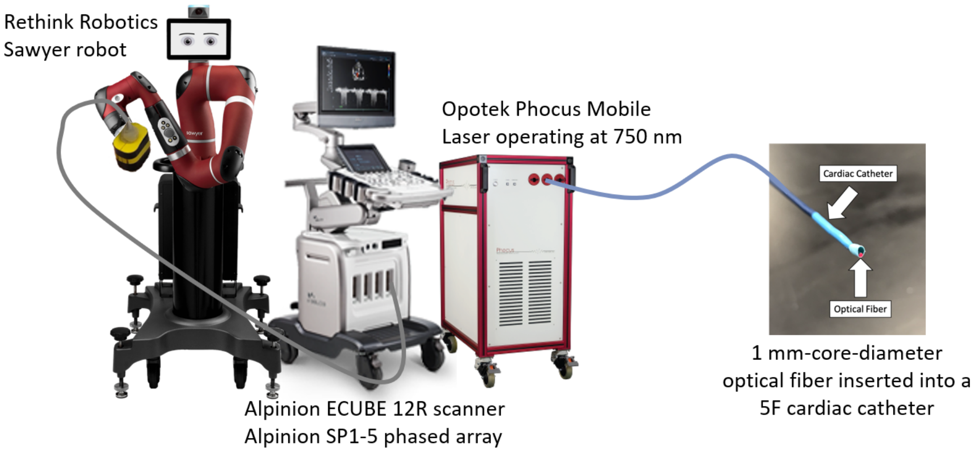

Figure 2: Robotic-photoacoustic imaging system equipment. The Alpinion SP1-5 phased array was held by the end effector of the robot with a custom 3D printed holder. A 1 mm-core-diameter optical fiber was coupled to the output port of the laser on one end with its other end inserted into, and coincident with the tip of, a 5F inner diameter (7F outer diameter) cardiac catheter to create a fiber-catheter pair.

In vivo experiments with two female swine were performed to evaluate the performance of the visual servoing component of our robotic-photoacoustic system and to assess photoacoustic signal visualization within the *in vivo* beating heart. During the first experiment, the tip of the fiber-catheter pair was navigated from the femoral vein toward the porcine heart and continuously visualized by the robot-held ultrasound probe during catheter navigation. The average laser energy per pulse was 2.67 mJ. During the second experiment, the fiber-catheter pair was navigated through the jugular vein, and the average laser energy per pulse was 0.75 mJ.

Fluoroscopic images were used to obtain 1D ground truth estimates of catheter tip locations during both swine experiments. In addition, an EnSite$^{\text{TM}}$Precision Cardiac electroanatomical mapping system (Abbott, Abbott Park, IL, USA) was used to obtain 3D ground truth location data during the second experiment. The catheter tip locations determined by our visual servoing system were compared to ground truth estimates provided by fluoroscopy and electroanatomical tracking in order to calculate 1D and 3D localization errors, respectively.

3. RESULTS

Table 1 summarizes the 1D and 3D root mean square errors (RMSEs) in catheter tip localization for the two *in vivo* swine experiments. For the first experiment, the 1D RMSEs were 1.63 - 2.28mm. For the second experiment, the 1D RMSEs were 1.13 - 1.35 mm during catheter insertion and 0.27 - 0.35 mm during catheter retraction. Larger RMSEs were measured during the first experiment, likely due to the ground truth fluoroscopic data acquisitions preceding the visual servoing data acquisitions, resulting in different trajectories. Therefore, fluoroscopy was performed simultaneously with the visual servoing experiments in the second experiment, resulting in more accurate ground truth measurements.

The 3D RMSEs were 1.54 mm for the insertion process and 1.24 mm for the retraction process during the second experiment. These 3D RMSEs were generally larger than the corresponding 1D RMSEs, as expected. In

Table 1: 1D and 3D RMSE Summary

Fluoroscopy	**1D RMSE (mm)**
Experiment 1	1.63 - 2.28
Experiment 2: Insertion	1.13 - 1.35
Experiment 2: Retraction	0.27 - 0.35
Electroanatomical tracking	**3D RMSE (mm)**
Experiment 2: Insertion	1.54
Experiment 2: Retraction	1.24

addition, larger RMSEs were obtained during fiber-catheter pair insertion when compared to RMSEs measured during retraction, likely because the retraction path was more well-defined than the insertion path.

Fig. 3 shows a posterior-anterior fluoroscopic image of the heart and a corresponding photoacoustic image overlaid on an ultrasound image acquired with a subcoastal acoustic window. The tip of the fiber-catheter pair is in contact with the right ventricular outflow tract. With the addition of the photoacoustic signal overlay, the catheter tip is more clearly identified and localized when compared to using ultrasound imaging alone. Photoacoustic signals from the tip of the fiber-catheter pair were acquired and photoacoustic signal contrast was calculated when the tip of the fiber-catheter pair was in contact with and not in contact with the endocardium, resulting in 48.8 dB and 29.8 dB mean contrast, respectively.

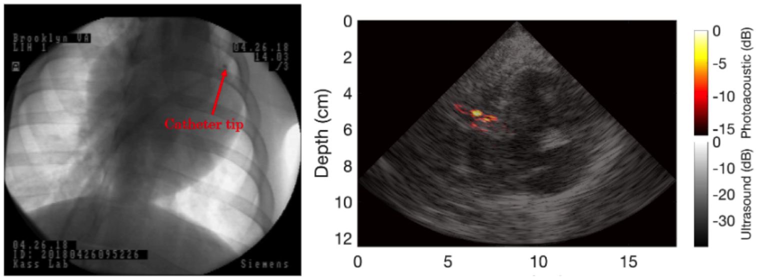

Figure 3: (left) Posterior-anterior fluoroscopic image acquired with the cardiac catheter tip in contact with the right ventricular outflow tract. (right) Corresponding subcostal photoacoustic image overlaid on co-registered ultrasound image.

4. DISCUSSION

The work summarized in this paper highlights the first use of a photoacoustic imaging system for *in vivo* guidance of a cardiac catheter within veins and a beating heart. Major benefits of our system include the addition of depth information and the absence of harmful ionizing radiation during the first two stages of the cardiac radiofrequency ablation procedure summarized in Fig. 1. The reported 1D localization errors summarized in Table 1 were larger during the first experiment (when compared to the second experiment) likely because of the serial acquisition of multiple ground truth fluoroscopy acquisitions followed by the visual servoing experiment. Fluoroscopy was performed simultaneously with visual servoing during the second experiment. Therefore, the localization errors obtained in the second experiments are more representative of the expected system accuracy.

It was generally difficult to differentiate the tip of the fiber-catheter pair in the ultrasound images, particularly when this tip was in contact with the endocardium. As shown in Fig. 3, with the introduction of photoacoustic imaging, the cardiac catheter tip was better visualized. This result highlights an additional benefit of photoacoustic images during the third stage shown in Fig. 1.

Several future modifications would be beneficial prior to clinical implementation of the proposed approach. For example, table- or body-mounted robots and wireless ultrasound probes would minimize the footprint of the system in the cardiac interventional suite. Reducing the diameter of the optical fiber would improve flexibility of the fiber-catheter pair. Customized patient draping to accommodate an external ultrasound probe would maintain sterility within the operating room. Finally, software and beamforming techniques can also be improved to enhance the system performance for clinical utility.

5. CONCLUSION

This paper highlights the feasibility of using a robotic-photoacoustic imaging system to provide guidance across multiple stages of cardiac radiofrequency ablation procedures. We successfully utilized this system to maintain visualization of a cardiac catheter tip as it traveled toward and within *in vivo* swine hearts. Overall, photoacoustic imaging is a promising technique for guidance of cardiac catheter-based interventions, providing excellent depth information and enhanced visualization of catheter tip locations within blood vessels and within the beating heart.

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