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# Design and in vitro evaluation of a real-time catheter localization system using time of flight measurements from seven 3.5 MHz single element ultrasound transducers towards abdominal aortic aneurysm procedures

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ABSTRACT

Interventional surgical instrument localization is a crucial component of minimally invasive surgery. Image guided surgery researchers are investigating devices broadly categorized as surgical localizers to provide real-time information on the instrument's 3D location and orientation only. This paper describes the implementation and in vitro evaluation of a prototype real-time nonimaging ultrasound-based catheter localizer system towards use in abdominal aortic aneurysm procedures. The catheter-tip is equipped with a single element ultrasound transducer which is tracked with an array of seven external single element transducers. The performance of the system was evaluated in a water tank and additionally in the presence of pork belly tissue and also a nitinol-dacron stent graft. The mean root mean square errors were respectively 1.94 ± 0.06, 2.54 ± 0.31 and 3.33 ± 0.06 mm. In addition, this paper illustrates errors induced by transducer aperture size and suggests a method for aperture error compensation. Aperture compensation applied to the same experimental data yielded mean root mean square errors of 1.05 ± 0.07, 2.42 ± 0.33 and 3.23 ± 0.07 mm respectively for water; water and pork; and water, pork and stent experiments. Lastly, this paper presents a video showing free-hand movement of the catheter within the water tank with data capture at 25 frames per second.

## 1. Introduction

Interventional surgical instrument localization is a crucial component of minimally invasive surgery. Fluoroscopy is currently the standard imaging modality for interventional procedures such as endovascular repair for abdominal aortic aneurysm (AAA) [1]. Fluoroscopy presents the user with real-time, two dimensional projection X-ray images of surgical instruments and the surrounding anatomy. Its limitations become apparent as minimally invasive procedures become more complex. It is difficult to appreciate three dimensional features from a 2D projection image. This leads to repeated fluoroscopy in order to obtain multiple projections, which results in increased operative time and exposure to contrast agent and radiation. Adverse outcomes ranging from erythema, "flushing, nausea, arm pain, pruritus, vomiting, headache and mild urticaria" to life-threatening reactions due to these factors have been documented [2,3]. These issues are particularly relevant as endovascular AAA procedures are performed in increasingly difficult cases [4].

Image guided surgery researchers are investigating other methods for instrument localization. In particular, devices broadly categorized as surgical localizers can be used to provide real-time information on the instrument's 3D location and orientation only. Localizers do not provide imaging information but rather are used in conjunction with image data to navigate surgical procedures [5]. Localizers can also provide feedback for surgical tool location during robotic surgery [6]. The two foremost surgical localization systems commercially available now are based on either optical or electromagnetic technology (Table 1). Optical localizers require a clear line of sight and therefore do not provide a viable solution for tracking catheters. Electromagnetic tracking systems on the other hand have demonstrated potential in preclinical abdominal procedures with errors <5 mm [7]. Further study is necessary to determine whether these errors are acceptable. Electromagnetic systems use a remote transmitter to create electromagnetic fields within the tracking volume. A receiver is mounted on the instrument and senses position based on the strength of the detected electromagnetic fields. However, past findings show that error increases in the presence of ferrous metals, which perturb the

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**Table 1**
Current localizer technology and how an ultrasound tracker might compare.

| Localizer technology | Optical | Electromagnetic | Ultrasound |
|---|---|---|---|
| Requirement | Unobstructed line of sight | Metal-free environment | Acoustic accessibility |
| Accuracy | RMSE < 0.5 mm | RMSE < 1 mm | Goal<br>RMSE < 2 mm |
| Applications | Spinal surgery | Neurosurgery | Abdominal |
| Reference | [10] | [11] | |

electromagnetic fields. This pitfall, along with the difficulties in image registration, have limited the advancement of electromagnetic localizer usage in clinical abdominal procedures [8,9].

This paper describes a prototype ultrasound localizer system much like an electromagnetic localizer. The catheter-tip is equipped with a single element ultrasound transducer. This transducer transmits an ultrasound pulse which is received by an array of seven external single element ultrasound receivers that are held in contact with the body. The received signals provide time of flight measurements which then provide the location estimate. These concepts are not novel in that time-based localization of gunshots have been documented around World War I and ultrasound imaging based methods for catheter localization have been documented since 1984 [12]. However, there has been little published work combining these two concepts.

The objective of this work is to demonstrate the feasibility of a 3D, real-time, low channel-count (<8) ultrasound based localization system. The initial design goals for this work are set with consideration to endovascular AAA procedures. The abdominal aorta lays along the top of the spine, at a depth of about 10–30 cm below the abdominal surface depending on patient body habitus. Therefore target penetration depth for this system is 10–30 cm. One possible cause of failure during endovascular AAA procedures is occlusion of the renal arteries [13]. Renal arteries generally have a radius of approximately 2.5 mm and therefore our target performance is to achieve root mean square error (RMSE) <2 mm.

A brief literature review on ultrasound imaging based approaches for catheter localization follows this introduction. Next, this paper details the system implementation in the methods section. Also in the methods are the experimental protocols and equation for calculating RMSE. Error quantification results and a video demonstrating real-time localization follow in the results section. This paper concludes with a discussion and considerations for future work.

## 2. Background: ultrasound imaging based catheter localization

This work does not use ultrasound imaging. However, researchers and clinicians alike have long used ultrasound imaging for locating interventional devices and much of the principles are the same. Breyer and Cikeš document the use of standard pulse-echo ultrasound imaging to visualize the catheter along with the rest of the anatomy [14]. This method was inadequate due to specular reflections that gave rise to spurious images, which motivated the use of a catheter-mounted monitoring transducer. One configuration was the transponder method, where the catheter-mounted transducer transmitted a pulse upon receiving an ultrasound signal from the imaging transducer, indicating catheter location as a strong signal on the ultrasound image. Vilkomerson and Lyons described in detail a similar arrangement where the catheter based transducer only received the ultrasound signal from the imaging transducer and then injected the signal into the ultrasound image to indicate catheter position [15]. Merdes and Wolf extended this method to provide 3D coordinate data using a 2D imaging array by comparing received signals to those from the expected imaging array beam profile and achieved 0.23 ± 0.11 mm resolution at a range of 75 mm and 0.47 ± 0.47 mm resolution at a range of 97 mm in vitro, showing a range-dependent resolution [16]. An alternative approach to visualizing interventional device tips has been to vibrate the device and image the tip with Doppler ultrasound. Armstrong et al. used the ColorMark device, which vibrated needles at 1–3 kHz for positive needle tip identification under Doppler ultrasound and demonstrated success in 18 of 25 clinical pericardiocentesis procedures [17]. Fronheiser and Idriss employed a similar approach for locating catheters and demonstrated success visualizing device tips in real time 3D in vivo [18].

## 3. Methods

### 3.1. Hardware system design

Fig. 1 shows a schematic of the ultrasound localizer system hardware. The catheter tip includes an ultrasound transducer. A pulser (Panametrics 5072PR) drives this transducer with a 5–10 ns, −360 V spike excitation to transmit an ultrasound pulse. The external transducer sensor array, held in acoustic contact with the patient's abdomen, receives the pulse. The Verasonics Ultrasound Engine (Redmond, WA) ties these pieces of hardware together [19]. It provides the trigger signal to the pulser and amplifies and digitizes the incoming radio frequency (RF) data from the transducer sensor array. This RF data is passed onto the host PC, which processes the data to estimate the catheter's coordinates.

### 3.1.1. Catheter transducer

The localizer system uses a custom catheter transducer (Fig. 2). It is made of a single element cylindrical tube of PZT 5H which resonates predominantly in the radial direction (Boston Piezooptics). It is mechanically and electrically connected to the end of a coaxial cable, which mimics a catheter. The transducer has a resonance frequency of about 3.5 MHz with 19% fractional bandwidth. The resonant frequency falls within the range of frequencies associated with abdominal ultrasound imaging, which requires sufficient penetration depth [20].

### 3.1.2. Transducer sensor array

Sensor count and placement influences localization performance and is an active area of research. At least three non-collinear sensors are required for time of flight 3D localization. More sensors deliver increased performance in the face of noisy measurements and can also provide redundancy in the event that a particular sensor measurement is invalid. This work uses seven sensors arranged in a uniform circular array (Fig. 3) as described by McKay and Patcher [21]. We have previously characterized the theoretical

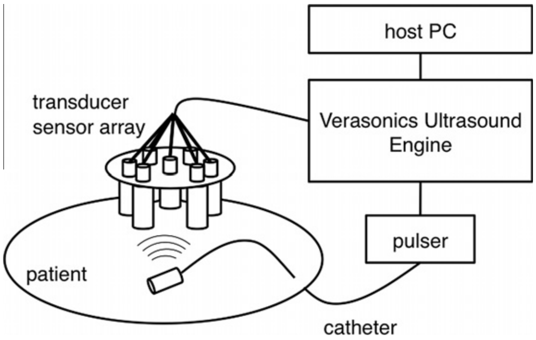

**Fig. 1.** Schematic of the hardware used for the ultrasound localization system.