# A System for 3D Ultrasound-Guided Robotic Retrieval of Foreign Bodies from a Beating Heart

Paul Thienphrapa, Bharat Ramachandran, Russell H. Taylor, and Aleksandra Popovic

*Abstract*—**By way of the venous system or direct penetration, particles such as thrombi, bullet fragments, and shrapnel can become trapped in the heart and disrupt cardiac function. The severity of disruption can range from asymptomatic to fatal. Injuries of this nature are common in both civilian and military populations. For symptomatic cases, the conventional approach is removal of the foreign body through open heart surgery, which comes with high perioperative risks and a long recovery period. To circumvent these disadvantages, we propose a minimally invasive surgical approach for retrieving foreign bodies from a beating heart.**

**This paper describes the first use of 3D transesophageal echocardiography (TEE) for steering a robot. Experiments demonstrate the feasibility of using 3D ultrasound to both guide and track a robot as it pursues a foreign body, with an RMS error of 1.6 mm in a laboratory setup. Results also support the hypothesis that direct pursuit of the foreign body may exceed the capabilities of conventional surgical robots, necessitating alternate retrieval strategies.**

## I. Introduction

Penetration of a foreign body into the heart is a common injury arising from both civilian accidents and military warfare [1], [2]. It can occur as a result of a direct penetrating injury through the chest and pericardium or as a result of embolization from the venous vasculature after a soft tissue injury in the chest, abdomen, or extremities. A perforating heart injury may cause irreparable damage to the muscle, which is often fatal, while a non-perforating direct injury usually results in a foreign body being lodged in the pericardial wall; however, small caliber bullets and small shell fragments with low velocity tend to circulate freely in the chambers [3], [4]. Embolized objects typically circulate in the right atrium and can become entrapped in the pericardial trabeculations and fatty tissue [4].

### A. Clinical Background

A direct injury is usually accompanied with severe life-threatening symptoms such as hemorrhage and cardiac tamponade requiring a fast response to stabilize the patient [1]. Once the patient is stabilized, cardiac surgery is performed to remove foreign objects and, if needed, repair the pericardium. Embolized foreign bodies can be symptomatic or asymptomatic [5]. Asymptomatic foreign bodies are entrapped in the pericardium and are treated conservatively with frequent follow-ups to evaluate if the foreign body has been released. Free-moving foreign bodies usually cause a series of cardiac symptoms, such as arrhythmia or neurotic manifestations and have to be removed surgically. Only a small fraction of patients can be treated percutaneously using catheters due to the difficulty of manipulating catheters to moving targets. The most frequent surgical approach to remove lodged or freely circulating foreign bodies from the heart is a median sternotomy followed by an incision in the pericardium to expose the heart chamber and the object [1], [5-7]. Localization of the foreign object is commonly performed using chest X-ray or ultrasound imaging to identify depth and amount of penetration and to detect foreign bodies [2]. An alternative approach is left/right thoracotomy. Median sternotomy is a risky, highly invasive procedure requiring a long recovery time. Potential risks related to sternotomy include bacterial mediastinitis, inflammation of the tissues in the mid-chest, and bone fracture. Moreover, patients with a history of sternotomy are at risk of a serious injury due to sternotomy wires and staples if undergoing cardiopulmonary resuscitation (CPR) in the future [8]. In a standard surgical setting, a cardiopulmonary bypass (CPB) may be used to stop the heart during surgery. The use of CPB is associated with serious risks of hemolysis, clotting, and air embolism.

### B. Objectives

This work represents the initial steps in addressing the problem of minimally invasive management of foreign bodies in the heart. By avoiding the perioperative and postoperative risks associated with sternotomy and CPB, a minimally invasive approach can significantly improve the management of cardiac foreign bodies by reducing risk and mortality, improving postoperative recovery, and potentially reducing operating room times.

The objectives of the present study are (1) to develop a framework for further investigation of the problem; (2) to present the behavior of a foreign body in a beating heart and study the ability of a robotic system to pursue it; and (3) to explore the use of 3D transesophageal echocardiography (TEE) for autonomous guidance and tracking of a robot towards a moving target. In preliminary experiments, the tracking and guidance tasks are decoupled to expose the robotic performance in the context of the application.

Manuscript received December 20, 2011.

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## II. Related Work

An early example of 3D transthoracic ultrasound for visual servoing involved an instrument equipped with markers visible in ultrasound images, as described in [9]. The instrument was driven to a series of image locations to measure the tracking error. With a robot speed of 3 mm/s, and an image processing algorithm updating the tool position at a rate of 2 Hz, an error of less than 1 mm was achieved. This work was furthered in [10] using the same ultrasound system and driving the tracked instrument towards tracked targets in the water tank; the experiments yielded an error of 1.2 mm with a maximum robot speed of 2 mm/s and maximum range of motion of 10 mm.

In another instance [11], autonomous ultrasound-guided robot experiments employing 3D catheter transducers found errors of approximately 3 mm. (It is noted that catheter transducers have low resolution.) In [12], the ultrasound targets were embedded in a tissue model (chicken breast) to mimic clinical conditions. Errors in a separate needle-touch experiment were found to be 1.15 mm.

The performance requirements for robotic tracking of a foreign body in the heart are more akin to the 1-degree-of-freedom (DOF) heartbeat compensation devices presented in [13], [14]. The motion of the heart wall was determined by manually segmenting 3D ultrasound images to acquire parameters such as speed, acceleration, range, and frequency. A handheld robotic device [13] was fabricated with these specifications to allow a surgeon to perform mitral valve repair on a beating heart. Water tank experiments showed errors on the order of 1 mm. Due to processing delays (8 Hz update) a computational model is introduced to predict the position of the valve.

The use of 3D US for autonomous robot guidance is in its infant stages, a claim supported by factors such as high cost, low voxel resolution, and inability to access real-time volumetric data streams [15]. While these factors continue to become decreasingly prohibitive, the body of work that has been done using 2D ultrasound probes and robot-controlled probes serves as inspiration for future work. For example, B-mode ultrasound images can be used to estimate the 6-DOF pose of a robotically-controlled probe by online reference to a model volume, and the pose can in turn be used to servo the probe to obtain a desired image slice [15], [16]. Many studies have performed 3D volume reconstruction from 2D slices acquired through robotic sweeping of the probe [17], [18]. Ideas presented in these works may be useful to overcome the limitations caused by a small field of view when using 3D US.

Tool tracking and target tracking are fundamental components of the proposed system, and the enhancement of tracked objects for visibility in ultrasound can help improve its efficacy. Ferrous shrapnel, which can be difficult to detect in ultrasound when adjacent to other hyperechoic surfaces, is illuminated under color flow Doppler in [19] using a variable magnetic field collinear with the transducer axis. Vibration of the target, 90–120 cm/s, is visible to the naked eye, and can be located within an RMS error of 1.06 mm. The approach is similar in spirit to [20], in which a surgical tool is vibrated using piezoelectric buzzers to improve visualization of the tool tip under color Doppler. Finally, though they use 2D B-mode ultrasound images, [21] and [22] leverage the known shapes of the surgical tool in order to determine its pose.

## III. Original Contributions

In much of the previous work using 3D US for robot guidance [9-12] the targets are static in a water tank. The tracking of a foreign body in a beating heart phantom represents a more complex scenario because the foreign body is in free motion within a moving organ.

While positive results were attained by employing predictive control to track heart structures in one dimension in [13], [14], the requirements for retrieving a foreign body differ from these in multiple ways. The foreign body moves in three dimensions, making the registration between the ultrasound and robot coordinate systems a nontrivial problem relative to the 1-DOF case. Another difference is that the motion of a beating heart is considerably more predictable than that of a foreign body moving freely within the heart. In addition to periodic heart motions, the foreign body is also subject to blood flow and interactions with the endocardium, septum, and other structures in the heart. Thus, the foreign body may at times appear to exhibit periodic motion in some or all dimensions, and at other times its motion can be arbitrary [23]. A predictive control scheme is likely to be less effective in this case.

To the best of our knowledge, the contributions of this paper not found in prior art include:

1. The first use of 3D TEE for robot steering.
2. The first use of 3D TEE for tracking a moving target (in a heart phantom).

## IV. System Description

A prototype system for minimally invasive evacuation of foreign bodies from a beating heart is illustrated in Fig. 1. Its primary components include an ultrasound system, a robot, a beating heart phantom, and a workstation computer. This setup is used to image the moving foreign body and conduct robot guidance experiments.

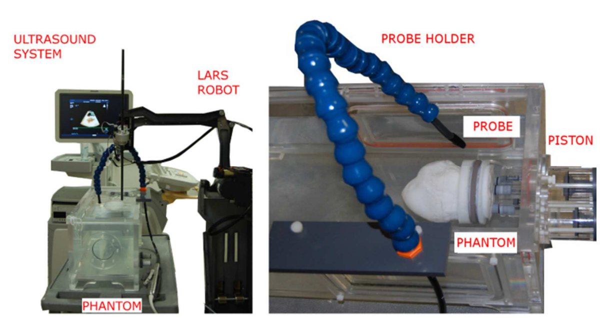


Fig. 1. (a) Experimental setup. (b) Arrangement of the TEE probe and heart phantom.

### A. Ultrasound System

The Philips iE33 xMATRIX Echocardiography System and Philips X7-2t 3D TEE probe are used. Image volumes have a resolution of 112×48×105 voxels of size 0.81, 0.96, and 0.98 mm, spanning a field of view of 60° azimuth, 30° elevation, and 12 cm depth. Gain is set at 47%, compression at 40 dB.

### B. Robot

The foreign body motion characteristics, detailed in [23] and reviewed in Section V, indicate that catching such an object is a demanding task that appears to warrant novel strategies and robot designs. Nevertheless, as an early approximation we use an existing surgical robot, the LARS Robot [24]. This 7-DOF robot (three translations, three rotations, and one insertion) was designed for laparoscopic surgery. It can reach speeds of 50 mm/s and accelerate at a rate of 375 mm/s$^2$ in the $x$- and $y$-directions. The $z$-axis is the limiting direction, with a maximum speed of 20 mm/s and acceleration of 90 mm/s$^2$. Implementations of the robot forward/inverse kinematics and operation modes are based on the *cisst* software package [25].

A 3.0-mm diameter rod held by the robot serves as a surrogate for a surgical tool, while a 3.2-mm diameter steel ball is attached to the rod tip to enhance tracking, thus decoupling the tracking problem from the visual servoing task; in future work we will address increasingly realistic scenarios, where the robot is equipped with a functional end effector.

### C. Beating Heart Phantom

The beating heart phantom, developed in-house, is a multimodality phantom compatible with X-ray, ultrasound, and MR imaging. The phantom heart, made of PVA (Polyvinyl Acetate), is a full replica of a human heart and is fixed inside a Plexiglas water tank during experiments. Two pneumatic pistons pump water into and out of the heart phantom to create the deformable effect of a heartbeat and blood flow. One of the pistons, 31.75 mm in diameter, pumps approximately 18 ml of water into and out of the right ventricle (the chamber of interest) per heartbeat; the piston motion is specified in Fig. 2. The stroke volume is chosen to be lower than that of healthy humans in order to mimic both surgical [26] and cardiovascular conditions following heart injury.

### D. Workstation Computer

A workstation computer with a dual core 2.33 GHz Intel Xeon processor and 4 GB of RAM is used for real-time image processing (including acquisition and tracking) and trajectory level robot control. The computer is connected to the ultrasound system and robot via TCP/IP network links.

## V. CHARACTERIZATION OF FOREIGN BODY MOTION

The movement of a foreign body in the heart is influenced by a complex combination of pulmonary motion, heartbeats, blood flow, and interactions with tissues. Whereas pulmonary and cardiac motion can be predicted using a computational model, interaction with heart structures and interruption of blood flow around the foreign body would require, if at all possible in real time, an extremely complex model involving a geometrical model of the heart and computational fluid dynamics. In order to design a system to retrieve cardiac projectiles, the motion of the foreign body must be understood. Pulmonary motion, which is slow and repeatable, is not considered for the time being as it does not add significant complexity to the foreign body tracking problem. The robot can compensate for breathing to keep the end effector steady relative to the insertion point.

In foreign body characterization experiments [23], a 3.2-mm steel ball was selected to act as a foreign body due to its likeness to the clinical case in terms of size (typically 2–5 mm) and material. The ball was inserted into the right ventricle of the heart phantom. Submerged in a water tank, the heart was activated with a preprogrammed heartbeat motion (Fig. 2). Five ($n$=5) 20-second-duration sets of 3D US images capturing the moving foreign body were acquired at a rate of approximately 20 Hz.

Tracking of the foreign body was performed using 3D normalized cross-correlation (NCC). The foreign body was selected interactively in the first ultrasound image frame as the region of interest (ROI), to provide a template for the algorithm to automatically track in subsequent frames. Fig. 3 shows the 3D motion traces of the foreign body in one data set; NCC was found to perform with 2.3 mm of error (RMS) when compared to manual tracking results. Fig. 4 displays an ultrasound image of the foreign body in the phantom at rest.

The motion traces of Fig. 3 show a rough correspondence between the foreign body motion and the 1-Hz heartbeats, but there is a large component of arbitrary motion as well. This observation is supported by the frequency spectrum of the motion [23]. Significant spectral power at both lower and higher frequencies suggest a more complex behavior overall.

A closer inspection of the motion traces reveals that the foreign body reaches speeds of approximately 343.5 mm/s and accelerations of about 7.8 m/s$^2$. Speeds have previously

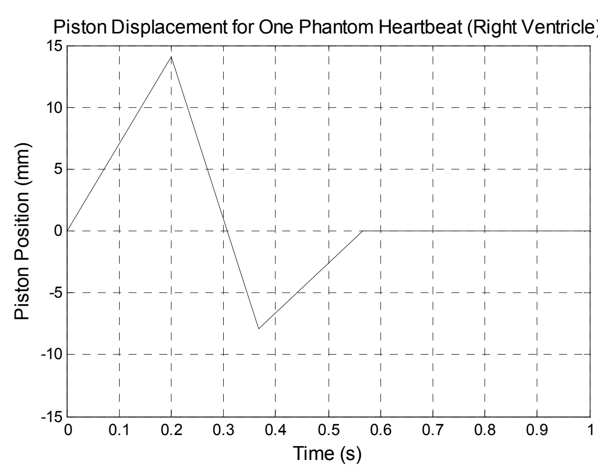


Fig. 2. Piston displacement in the beating heart phantom for one heartbeat in the right ventricle.

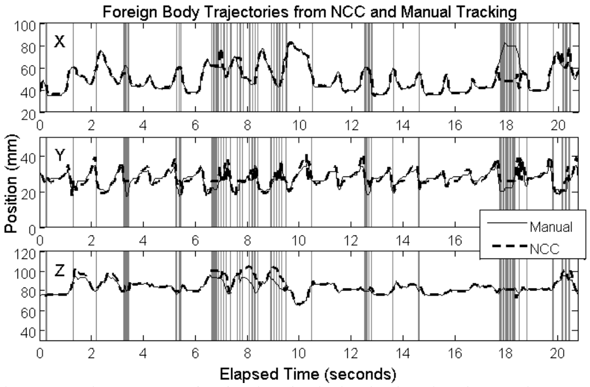

Fig. 3. Motion traces of a foreign body in the beating heart phantom. Performance of NCC was validated against manual tracking.

been reported for the heart wall (up to 300 mm/s [27]) and mitral valve (up to 200 mm/s [13]), with accelerations of 3.8 m/s$^2$ in the latter case. These are fairly challenging figures for existing surgical robots to achieve, particularly with paths less predictable, in three dimensions.

## VI. Experimental Results and Discussion

### A. Experimental Procedure

The tracked foreign body positions ${}^{u}p_{fb}$, obtained from characterization experiments, are used to guide the robot, effectively in pursuit of a virtual foreign body moving in the beating heart phantom. First, with the robot (tool tip) in the field of view of the ultrasound probe, the transformation ${}^{r}T_{u}$ between the robot and ultrasound coordinate systems ($r$ and $u$ respectively) is determined by moving the robot to several known positions and recording an image for each. The tip positions ${}^{u}p_{reg}$ in ultrasound image coordinates are extracted manually, and a transformation matrix is computed using standard approaches. The average target registration error (TRE) over the five data sets is 0.44 mm.

The transformation ${}^{r}T_{u}$ is then applied to the tracked foreign body positions ${}^{u}p_{fb}$ to place them into the robot frame. The robot is commanded via position control per ${}^{r}p_{fb}$, the foreign body positions in terms of robot coordinates. As the robot moves, ultrasound images of the tip are acquired at a rate of 20 fps for retrospective analysis. The steps described heretofore are summarized as follows:

$$Reg({}^{u}p,\ {}^{r}p) \tag{1}$$

$${}^{r}p_{fb} = {}^{r}T_{u} \cdot {}^{u}p_{fb},$$

where

$$Reg \Leftrightarrow {}^{r}T_{u}\colon {}^{u}p \longrightarrow {}^{r}p \tag{2}$$

is a paired-point registration.

Tracking of the robot tip in the ultrasound images is performed in an identical fashion to the tracking of the foreign body. The ROI (the tip in this case) is selected interactively in the first frame and tracked automatically in subsequent frames using NCC. The tracked tip positions in ultrasound space are transformed into robot space:

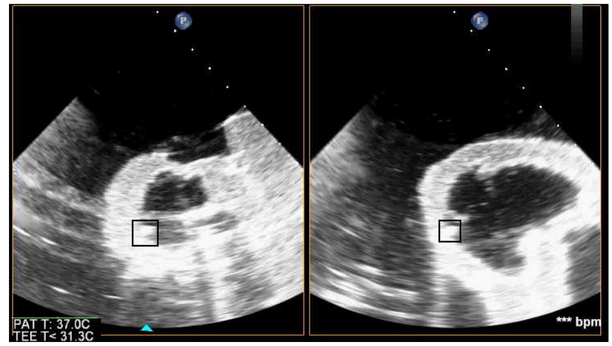

Fig. 4. Ultrasound image showing the foreign body (outlined) in the heart phantom in two orthogonal slices.

$${}^{r}p_{tip} = {}^{r}T_{u} \cdot {}^{u}p_{tip} \tag{3}$$

We compare the foreign body positions ${}^{u}p_{fb}$ with those of the tracked tip positions of the pursuing robot (${}^{u}p_{tip}$) in order to understand the feasibility of the proposed system—a close match would suggest that the robot can follow and thus capture the foreign body successfully.

### B. Results

While the foreign body can attain speeds of 343.5 mm/s, the robot prototype is only capable of 20 mm/s along its limiting axis. There is a mismatch in acceleration as well: 7800 mm/s$^2$ for the foreign body versus 90 mm/s$^2$ for the robot. The speed of the foreign body is thus reduced to account for the speed mismatch. Alternatively, a simulated robot at full speed could be used to gauge performance requirements from a dynamics viewpoint, but the former approach was chosen for this study because it enables us to (1) perform 3D US-based guidance on a real robot; (2) test the hypothesis that chasing the foreign body exceeds the ability of surgical robots; and (3) track the robot under 3D US. Two reduction factors are applied to highlight the influence of velocity in this application.

A sample foreign body trajectory and its robot counterpart are shown together below. The motion shown in Fig. 5 results from reducing the foreign body speed by a factor of 9.0, roughly related to the maximum speed of the robot. The RMS error over all data sets is 2.1 mm. Reduction of the speed by a factor of 20.0 (Fig. 6) yields a reduced error of

Table I
Robot RMS Position Error from Foreign Body Path

| (Units: mm) | | Speed Reduction 9x | 20x |
|---|---|---|---|
| Data Sets | A | 2.2 | 1.6 |
| | B | 2.5 | 1.9 |
| | C | 2.2 | 1.9 |
| | D | 1.8 | 1.2 |
| | E | 1.8 | 1.6 |
| Agg. | Min | 1.8 | 1.2 |
| | Mean | 2.1 | 1.6 |
| | Max | 2.5 | 1.9 |
| | SD | 0.3 | 0.3 |

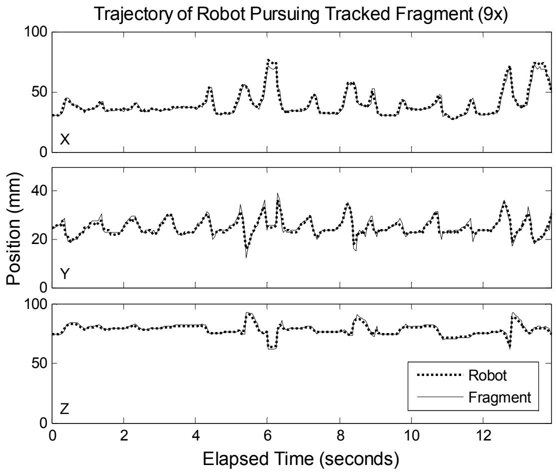


Fig. 5. Motion traces of a foreign body, and that of a robot in pursuit, with virtual target speed reduced by a factor of 9.0.

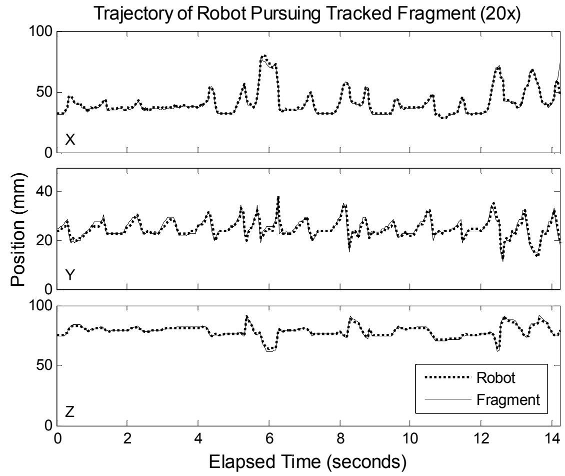


Fig. 6. Scenario of Fig. 5, but the virtual target speed is reduced by a factor of 20.0.

1.6 mm over all data sets. The foreign body in this case is virtually motionless, analogous to a near-continuum of static targets along a 3D path. Excerpts of these plots are shown together for comparison in Fig. 7. Table I lists results from all five data sets.

### C. Discussion

The 1.6 mm error in 3D US-based dynamic target tracking suggests the viability of the proposed system, in light of previous work reporting accuracies of 1–1.2 mm for static targets [9], [10], [12], [13]. The error increase from 1.6 to 2.1 mm in fastest case shed additional light on the inherent accuracy of the system. Comparison of these two accuracies suggests that the main contributor of errors in the dynamic task is the inability of the robot to change directions as abruptly as the foreign body does. Robot speeds of 17 mm/s (20x less than 343.5 mm/s) have been observed in the dynamic test cases, while [9] and [10] use robot speeds of 3 and 2 mm/s respectively, and the robot of [12] is jogged manually. The high-speed 1-DOF device (290 mm/s) of [13] achieves a 1.0 mm accuracy aided by a predictive model, which is appropriate for heart valve motion but less suitable for a foreign body, as shown in [23].

In contrast to the previous work in 3D US-based robot guidance reporting relatively low acquisition and processing frequency (e.g. 2 Hz [9] or offline servoing [12]), the 20 Hz frame rate achieved with our setup was sufficient to track a heart wall [28], a foreign body, and to steer a robot. Despite the limited field of view, particularly in comparison to a transthoracic probe, it appears feasible to use the 3D TEE probe for this application, as motion of the foreign body is limited to a single ventricle.

Insights gained from this study motivate the need for novel robot designs, in particular one with a flexible end effector with distal dexterity to navigate the heart chamber. The experiments show that millimeter-scale accuracy may be difficult to achieve at the speeds required to follow a foreign body, so careful retrieval planning will be preferred over direct pursuit.

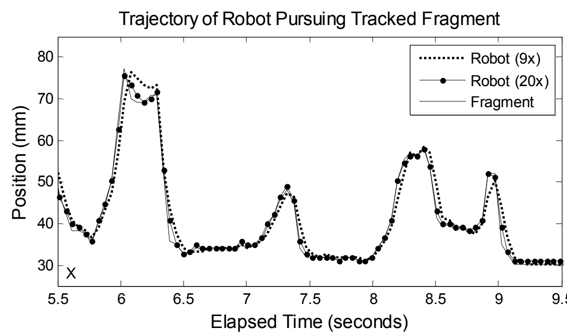


Fig. 7. Close-up view of Fig. 5 and Fig. 6 superimposed, illustrating the increased ability of the robot to follow a reduced speed target.

## VII. Conclusions and Future Work

The proposed minimally invasive robotic and imaging system to assist surgeons in detection and removal of foreign bodies from the heart is aimed at reducing risks and postoperative recovery time, and potentially perioperative time. Mortality rates would decrease, patients could return to normal activities sooner, and medical centers could treat more patients. The characterization of foreign body motion in a beating heart phantom shows that the motion is fast, abrupt, and often unpredictable, thus favoring the design of a dexterous robot and carefully planned capture approaches. Results show the viability of continued development in this direction. Future milestones will address increasingly realistic scenarios such as performing online registration and tracking, defining behaviors under error conditions, and devising virtual fixtures for protecting tissues from the robot. As an early approximation, symmetric objects were chosen for tracking; advanced algorithms will likely be necessary to handle irregularly-shaped targets.

## Acknowledgment

Authors thank Emil Radulescu for insights on ultrasound technology, and Douglas Stanton, Vijay Parthasarathy, Ameet Jain, and Andrew Lang (all of Philips Research North America) for their help with the ultrasound equipment/setup.

## REFERENCES


[1] United States Department of Defense, "Emergency War Surgery: Third United States Revision, s.l., 16: Thoracic Injuries," ed, 2004.

[2] J. C. Williams and W. C. Elkington, "Slow progressing cardiac complications—a case report," *J. Chiropr. Med.,* vol. 7, pp. 28–33, 2008.

[3] A. J. Marshall, N. J. Ring, and P. L. Newman, "An unexplained foreign body in the myocardium," *J. Royal Soc. Med.,* vol. 95, pp. 250–251, 2002.

[4] P. N. Symbas, A. L. Picone, C. R. Hatcher, and S. E. Vlasis-Hale, "Cardiac missiles. A review of the literature and personal experience," *Ann. Surg.,* vol. 211, pp. 639–648, 1990.

[5] G. M. Actis Dato, A. Arslanian, P. D. Marzio, P. L. Filosso, and E. Ruffini, "Posttraumatic and iatrogenic foreign bodies in the heart: report of fourteen cases and review of the literature," *J. Thorac. Cardiovasc. Surg.,* vol. 126, pp. 408–414, 2003.

[6] J. Evans, L. A. Gray, A. Rayner, and R. L. Fulton, "Principles for the management of penetrating cardiac wounds," *Ann. Surg.,* vol. 189, pp. 777–784, 1979.

[7] S. C. Nessen and D. E. Lounsbury, "War Surgery in Afghanistan and Iraq: A Series of Cases, 2003-2007, s.l. Department of the Army, Office of the Surgeon General and Borden Institute, 14: Thoracic Trauma," ed, 2008, pp. 118–156.

[8] J. P. Steinhoff, C. Pattavina, and R. Renzi, "Puncture wound during CPR from sternotomy wires: case report and discussion of periresuscitation infection risks," *Heart Lung,* vol. 30, pp. 159–160, 2001.

[9] J. A. Stoll, P. M. Novotny, R. D. Howe, and P. E. Dupont, "Real-time 3D ultrasound-based servoing of a surgical instrument," in *IEEE Int. Conf. on Robotics and Automation*, 2006, pp. 613–618.

[10] P. M. Novotny, J. A. Stoll, P. E. Dupont, and R. D. Howe, "Real-time visual servoing of a robot using three-dimensional ultrasound," in *IEEE Int. Conf. on Robotics and Automation*, 2007, pp. 2655–2660.

[11] J. Whitman, M. P. Fronheiser, and S. W. Smith, "3-D ultrasound guidance of surgical robotics using catheter transducers: feasibility study," *IEEE Trans.Ultrason., Ferroelectr.,* vol. 55, pp. 1143–1145, 2008.

[12] K. Liang, D. V. Allmen, A. J. Rogers, E. D. Light, and S. W. Smith, "Three-dimensional ultrasound guidance of autonomous robotic breast biopsy: feasibility study," *Ultrasound Med. Biol.,* vol. 36, pp. 173–177, 2010.

[13] S. G. Yuen, D. T. Kettler, P. M. Novotny, R. D. Plowes, and R. D. Howe, "Robotic motion compensation for beating heart intracardiac surgery," *Int. J. Robot. Res.,* vol. 28, pp. 1355–1372, 2009.

[14] S. B. Kesner, S. G. Yuen, and R. D. Howe, "Ultrasound servoing of catheters for beating heart valve repair," in *Int. Conf. on Info. Proc. in Computer-Assisted Interventions*, Berlin, Heidelberg, 2010, pp. 168–178.

[15] A. Krupa, G. Fichtinger, and G. D. Hager, "Real-time motion stabilization with B-mode ultrasound using image speckle information and visual servoing," *Int. J. Robot. Res.,* vol. 28, pp. 1334–1354, 2009.

[16] R. Mebarki, A. Krupa, and F. Chaumette, "Modeling and 3D local estimation for in-plane and out-of-plane motion guidance by 2D ultrasound-based visual servoing," in *IEEE Int. Conf. on Robotics and Automation*, 2009, pp. 319–325.

[17] P. Abolmaesumi, S. E. Salcudean, W. H. Zhu, M. R. Sirouspour, and S. P. DiMaio, "Image-guided control of a robot for medical ultrasound," *IEEE Trans. Robot. Autom.,* vol. 18, pp. 11–23, 2002.

[18] E. M. Boctor, G. Fischer, M. A. Choti, G. Fichtinger, and R. H. Taylor, "A dual-armed robotic system for intraoperative ultrasound guided hepatic ablative therapy: a prospective study," in *IEEE Int. Conf. on Robotics and Automation*, 2004, pp. 2517–2522.

[19] A. J. Rogers, E. D. Light, and S. W. Smith, "3-D ultrasound guidance of autonomous robot for location of ferrous shrapnel," *IEEE Trans.Ultrason., Ferroelectr.,* vol. 56, pp. 1301–1303, 2009.

[20] M. P. Fronheiser, S. F. Idriss, P. D. Wolf, and S. W. Smith, "Vibrating interventional device detection using real-time 3-D color Doppler," *IEEE Trans.Ultrason., Ferroelectr.,* vol. 55, pp. 1355–1362, 2008.

[21] M. A. Vitrani, H. Mitterhofer, N. Bonnet, and G. Morel, "Robust ultrasound-based visual servoing for beating heart intracardiac surgery," in *IEEE Int. Conf. on Robotics and Automation*, 2007, pp. 3021–3027.

[22] M. Sauvee, P. Poignet, and E. Dombre, "Ultrasound image-based visual servoing of a surgical instrument through nonlinear model predictive control," *Int. J. Robot. Res.,* vol. 27, pp. 25–40, 2008.

[23] P. Thienphrapa, H. Elhawary, B. Ramachandran, D. Stanton, and A. Popovic, "Tracking and characterization of fragments in a beating heart using 3D ultrasound for interventional guidance," in *Medical Image Computing and Computer-Assisted Intervention - MICCAI 2011*. vol. 6891, G. Fichtinger, A. Martel, and T. Peters, Eds., ed: Springer Berlin / Heidelberg, 2011, pp. 211–218.

[24] R. H. Taylor, J. Funda, B. Eldridge, S. Gomory, K. Gruben, D. LaRose, M. Talamini, L. Kavoussi, and J. Anderson, "A telerobotic assistant for laparoscopic surgery," *IEEE Eng. Med. Biol. Mag.,* vol. 14, pp. 279–288, 1995.

[25] *The cisst Libraries*. Available: https://trac.lcsr.jhu.edu/cisst/

[26] K. L. Ryan, W. H. Cooke, C. A. Rickards, K. G. Lurie, and V. A. Convertino, "Breathing through an inspiratory threshold device improves stroke volume during central hypovolemia in humans," *J. Appl. Physiol.,* vol. 104, pp. 1402–1409, 2008.

[27] J. B. Kostis, E. Mavrogeorgis, A. Slater, and S. Bellet, "Use of a range-gated, pulsed ultrasonic Doppler technique for continuous measurement of velocity of the posterior heart wall," *Chest,* vol. 62, p. 597, 1972.

[28] B. Ramachandran, P. Thienphrapa, A. Jain, and A. Popovic, "Tracking using 3D ultrasound for guiding cardiac interventions," in *Int. Conf. on Biomedical Engineering*, 2011.