Appeared in SPIE Medical Imaging, San Diego, USA, Feb. 2012

# A high accuracy multi-image registration method for tracking MRI-guided robots

Weijian Shang*[a], Gregory S. Fischer*[a]
[a]Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA, USA 01609;

## ABSTRACT

Recent studies have demonstrated several functional surgical robots and other devices operating in the Magnetic Resonance Imaging (MRI) environment. Calibration and tracking of the robotic device is essential during such MRI-guided procedures. A fiducial tracking module is placed on the base or the end effector of the robot to localize it within the scanner, and thus the patient coordinate system. The fiducial frame represents a Z shape and is made of seven tubes filled with high contrast fluid. The frame is highlighted in the MR images and is used in localization. Compared to the former single image registration method, multiple images are used in this algorithm to calculate the position and orientation of the frame, and thus the robot. By using of multiple images, measurement error is reduced and the rigid requirement of slow to acquire high quality of images is not required. Accuracy and performance were evaluated in experiments which were operated with a Philips 3T MRI scanner. Presented is an accuracy comparison of the new method with varied number of images, and a comparison to more traditional single image registration techniques.

**Keywords:** MRI, registration, multi-image, image-guided therapy, medical robot

## 1. INTRODUCTION

Taking advantages of the high soft-tissue contrast and multi-parametric imaging capabilities of the Magnetic Resonance Imaging (MRI), a variety of image-guided devices have been developed. Recent studies have demonstrated several functional surgical robots and other devices operating in the MRI environment. Examples of such systems include needle-based transperineal prostate interventions in MRI developed by Fischer[1], image-guided systems for placing deep brain stimulation electrodes developed by Cole[2]. Martin also developed a deep brain stimulator placement device[3]. Both Susil and Su have developed MRI-Guided needle insertion robots for prostate brachytherapy[4, 5]. Additional systems can be found in the paper written by Elhawary[6]. High accuracy calibration and tracking of the robotic device is essential during such MRI-guided procedures. In the following sections, we will present a novel high accuracy multi-image registration method for tracking MRI-guided robots.

A variety of active and passive registration and tracking have been done in prior work. Several active registration and tracking methods have been introduced Derbyshire, Claudia and Krieger[7, 8, 9]. Such as the scan plane tracking using active tracking method developed by Derbyshire[7]. Although high accuracy and high speed have been found in active tracking method, downsides like the requirement of special scanner programming, limitations of scanner channel and special design of electronic hardware should not be neglected.

Passive registration and tracking is an alternative method. Krieger developed a position and orientation tracking of robotic medical instruments within the imaging volume of a MRI system by using passive MRI fiducial markers. By using image-based passive tracking approach, expensive instrumentation such as coil is not required any more. Although it is said to be a compromise between imaging speed and quality that can degrade localization accuracy and reliability[10], several works on numerical algorithms have been done to improve the accuracy of passive tracking. Lee introduced two numerical algorithms for registration of rigid line fiducial objects[11]. Also in this paper, we introduce a new method which works well on the processing of low quality images to get high registration accuracy.

*[wshang, gfischer]@wpi.edu; phone 1-508-831-5261; fax:1-508-831-5680; aimlab.wpi.edu

Within the method of passive registration and tracking, prior works have shown several approaches on single-image robot registration and tracking in ether MRI or CT environment[10, 11, 12]. Although having high registration speed, single-image registration method requires high quality images to reach a relatively high accuracy. Also, it only uses the information in one image, but not the information between images which is another degree of information in the superior direction of a RAS patient coordinate system. By taking advantage of this one more degree of information, multi-image method could reach a higher accuracy. Even if the single slice registration technique averages results from multiple slices, each slice is still calculated independently and not taking advantage of all of the available information. Being used as the ground truth by Susil[12] also showed that it had a better accuracy than single-image registration method.

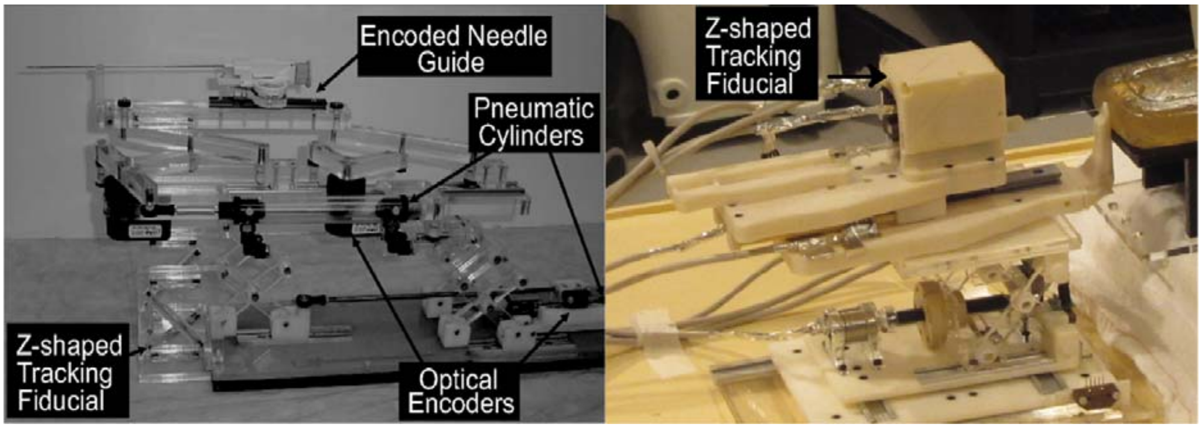


Figure 1 Passive fiducial modules mounted on the needle insertion robots. A system developed by Tokuda et al.(left) [13], Needle insertion robot developed by Su et al.(right) [5]

In this paper, we introduce a spatial localizing approach by using passive fiducial markers in MRI environment in order to get position and orientation of the MRI-guided robot. Also, to get higher accurate registration result, a new algorithm is used to calculate the centroid and equations of the fiducial bars.

## 2. METHODS

### 2.1 Experimental Setup

A plastic fiducial tracking module is placed on the base or the end effector of the robot to localize it within the scanner, and thus the patient coordinate system. The fiducial frame represents a Z shape made of 7 plastic tubes filled with MR-visible, high contrast fluid(Beekley, Bristol, CT, shown in Fig. 2(lower left)). The frame is highlighted in the MR images and is used in localization. Each of the seven tubes has a 30mm diameter. The Z-frame and its MR image are shown in Fig. 2. The whole size of fiducial module is 50mm×50mm×50mm.

The position and orientation of the Z-frame is computed from the intersecting lines by using the coordinates of seven points. The Z-frame was placed in a Philips 3T MRI scanner, on a platform manufactured by laser-cutter with pre-determined positions and orientations. Several sets of images were taken by using T2 protocol, flip angel=45°, matrix=256×256, slice thickness=3mm.

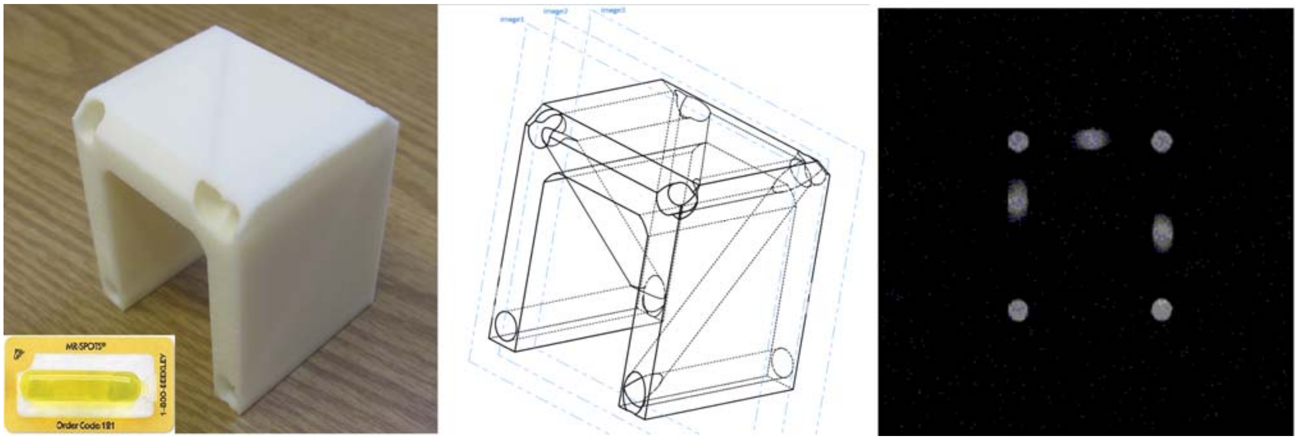

Figure 2 The fiducial tracking module Z-frame(left), CAD model of Z-frame(middle), Z-frame MR image(right) and Beekley fiducial tubes(lower left)

## 2.2 Fiducial Detection and Localization

The flow chart of the detection and localization algorithm is shown in Fig. 3. After being read in, the images were reconstructed, including threshold, binarize and denoise. Then only the information of seven fiducial points were left. In some of prior works, the center of each fiducial point was found directly by finding its centroid[11]. This may be effective on high quality images with no bubbles or other artifacts, but is not robust. Therefore, in our work, unlike getting the centroid directly, we use a flipping method with ellipse model to reconstruct every fiducial point on the image, then the centers of reconstructed points were calculated to be used in localization later. A fiducial pattern matching function was made to match the fiducial pattern by using the geometric character of Z-frame for seven points on each image. After getting the coordinate information for the points on every images we need, least square line fitting methods were used to fit the seven fiducial lines of the Z-frame. The algorithm was implemented in Matlab. The position and orientation of the Z-frame are given after the calculation by Matlab. Fig. 4 shows a 3D plot of fiducial points on each image and seven fitted fiducial lines in patient coordinate.

Registration accuracy was tested by both position and orientation.

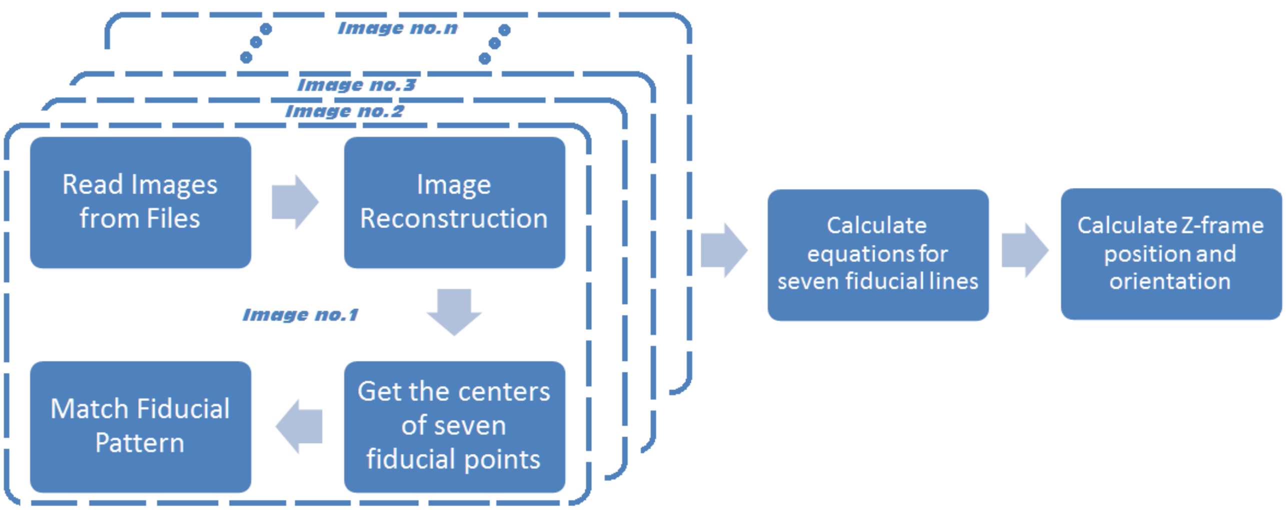


Figure 3 Fiducial Detection and Localization Algorithm

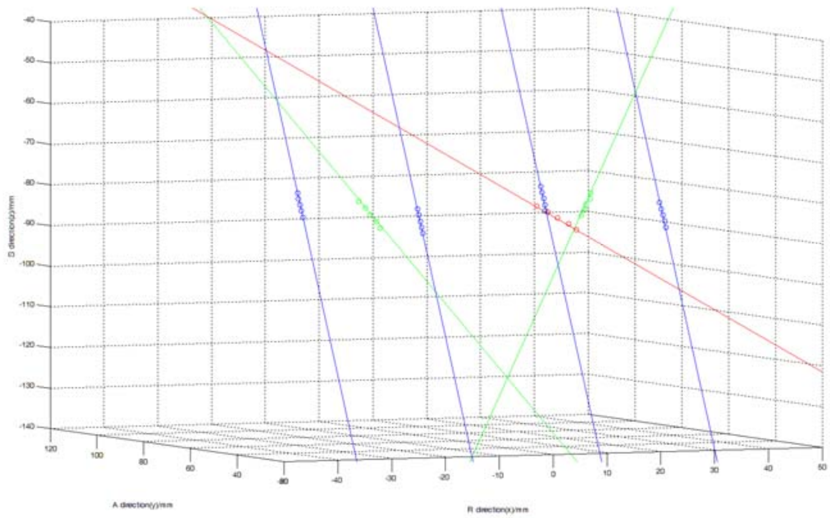

Figure 4 Matlab plot of the spacial pose of the Z-frame by using 5 images. The circle represent the located fiducial centroids in each image, the blue line represent the 4 horizontal fiducial tubes, the green lines represent the angles tubes on the sides, and the red line represents the angled tube on the top surface.

### 2.3 Accuracy Study

In order to determine the registration accuracy, we designed a testing platform which was manufactured by laser-cutter with pre-determined positions and orientations. As the ground truth, relative positions and orientations were tested in the experiment. Several groups of images were taken at each position and orientation. The relative changes were calculated after to test the registration accuracy. All images were obtained in pixel matrix of 256×256, image pixels were 0.5mm×0.5mm, slice thicknesses were 3mm.

## 3. RESULTS

Relative displacement of 85mm and rotation angles of 5°, 10°, 15° were tested during the experiment. The errors which include the displacement error and angular error are defined as the difference between the manufacturing parameters and the registration results. At each position and orientation, several groups of images were taken. Within each groups, different number of images were used to do a one-time-registration. Three, four, five, six and seven images were used separately. The average displacement error of all registrations by using different number of images was 0.27mm, the average angular error was 0.13deg. Since the pixel size was 0.5mm×0.5mm, this method was proved to have sub-pixel accuracy which is ideal for the registration and tracking of MRI-guided robots. The probability distribution of the displacement error is shown in Fig. 5. All of the displacement errors were below 0.8mm among 120 samples, 94.2% percent of the errors were below 0.6mm and the maximum error was 0.75mm. Both displacement and angular errors of the multi-image registration method are summarized in Table 1.

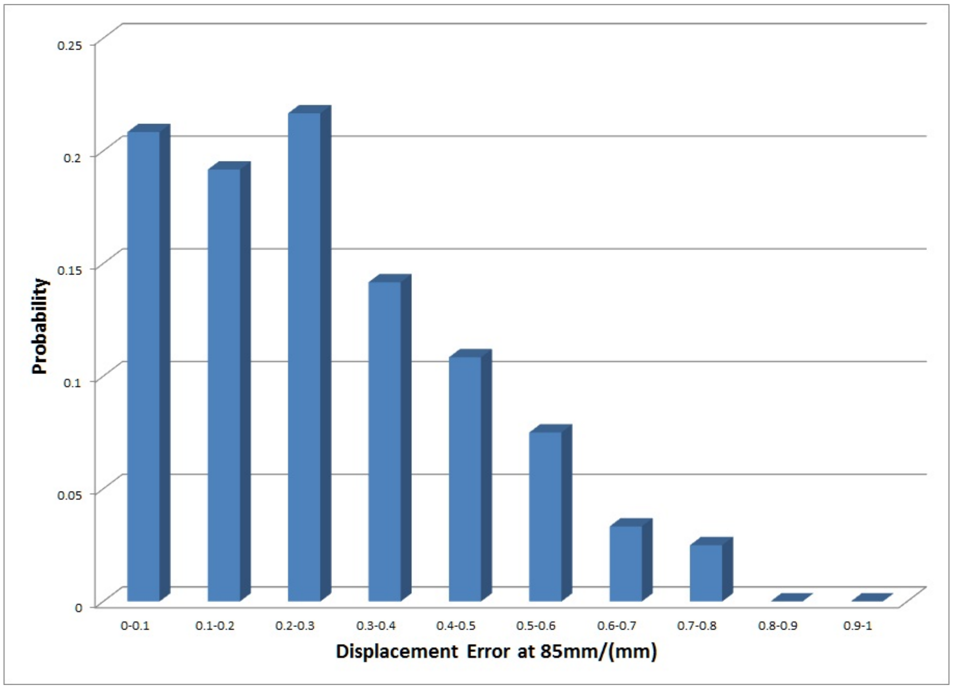


Figure 5 Probability distribution of displacement error. All of the errors are found below 0.8mm

Table 1Multi-image localization accuracy

| | Average Error | Standard Deviation | RMS Error | Data Points |
|---|---|---|---|---|
| Displacement | 0.27mm | 0.18mm | 0.33mm | 120 |
| Rotation | 0.16° | 0.46° | 0.46° | 248 |

## 4. DISCUSSION

In this paper, we achieved that using the multi-image registration method were found to have sub-pixel accuracy. The errors of both displacement and angle were well below 1mm and 1deg. The average displacement error was 0.27mm, maximum was 0.69mm. The average angular error was 0.16deg, maximum was 0.49deg. The average error was sub-pixel level. To prove the advantage of high accuracy of multi-image registration, a comparison was done between multi- and single-image registration methods. Table 2 shows the results of both multi- and single-image registration. Compared to the prior Susil's works and DiMaio's work[12, 10], the angular error when using the multi-image method decreased by 0.19deg and 0.15deg and the displacement error decreased by 0.11mm, 0.35mm and 0.08mm which shows a significant accuracy increase from single-to multi-image method. One exception we could see from the Table 2 is that the displacement error in DiMaio's work was 0.089mm which was smaller than any of other works including our multi-image method. That is because the displacement tested in our work was 85mm which was much longer than the displacement tested by DiMaio[10], only from 0 to 18mm.

To find how the number of images used to approach one-time-registration affects the accuracy, we compared the accuracy results from four groups, which are using three, four, five and seven images to approach one-time-registration. The comparison is shown in Fig. 6. We could see from the figure that the angular error has a relative significant drop of 0.03deg at the change of using of three to four images, and the displacement error has a relative significant drop of 0.1mm at the change of using of five to six images.

Table 2 Accuracy comparison between multi-and single-image methods. Susil's test1 was the offset error of holder pose[12]. Susil's test2 was the offset error of the needle tip[12]. Lee's test was the average displacement error of four algorithms[11]. DiMaio's displacement error was the average out-of-plane(z) error[10].

| | | Displacement error | Rotation error |
|---|---|---|---|
| Multi-image Method | Our work | 0.27mm | 0.13° |
| Single-image Method | Susil's test1 | 0.38mm | 0.32° |
| | Susil's test2 | 0.63mm | |
| | Lee's test | 0.35mm | |
| | DiMaio's test | 0.089mm | 0.28° |

A new centroid finding method-flipping method was implemented here to get the center of fiducial points more accurate. Another comparison between the results by using single-image with and without flipping method was done in the experiment. The result in Table 3 shows that using of flipping method improves the accuracy of the measurement by 0.03deg. More importantly, this provides added robustness to images where the fiducials do not show up completely, such as when a bubble is present in the fiducial tube or there is image noise.

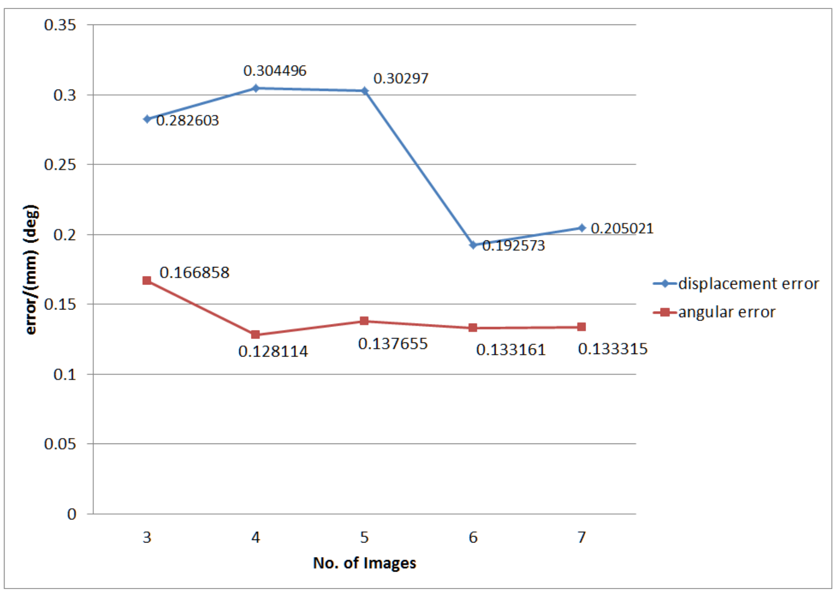


Figure 6 Accuracy comparison between different no. of images evenly distributed in the acquisition volume.

Table 3 Accuracy comparison between using and not using flipping methods

| | Average Error | Standard Deviation | RMS Error | Data Points |
|---|---|---|---|---|
| Using Flipping Method | | | | |
| Rotation | 0.48° | 0.56° | 0.75° | 102 |
| Not Using Flipping Method | | | | |
| Rotation | 0.51° | 0.59° | 0.78° | 102 |

The comparisons we have done above have proved that the advantage of high accuracy of multi-image registration method is significant. Although we got a good accuracy result of this method, there are several improvements we could apply in the future. In this study, we are using multiple images to approach a one-time-registration after initial setup of the robot. the technique may be utilized for interactive tracking as well, with the tradeoff being number of images acquired & acquisition speed vs. registration accuracy. It is possible that some of the images only contain part of fiducial information, for example, only six fiducial points were shown in one image. It is better in the future to make the fiducial pattern fitting function more robust to recognize partial fiducial information. Although having high accuracy, this method requires the acquisition of several images which take more time than single-image registration method. A compromise should be made between the sufficient accuracy and registration speed.

A new fiducial frame will be designed in the future to make it more compact with the robotic system. New fiducial tubes with thinner cross sections will be used to make the whole size smaller. Also, smaller cross section would decrease the error produced during finding of centroids of the fiducial points.

Finally, the performance of real-time registration, navigation and tracking will be tested in the near future by implementing this work into a MRI-guided surgical robot.

## REFERENCES


[1] Fischer, G. S., Iordachita, I., DiMaio, S. P. and Fichtinger, G., "Development of a Robotic Assistant for Needle-Based Transperineal Prostate Interventions in MRI," 10th International Conference on Medical Image Computing and Computer-Assisted Intervention – MICCAI 2007, Brisbane, Australia, Lecture Notes on Computer Science, Vol 4791, 425-433 (2007)

[2] Cole, G., Pilitsis, J. and Fischer, G. S., "Design of a Robotic System for MRI-Guided Deep Brain Stimulation Electrode Placement," International Conference on Robotics and Automation - ICRA 2009, Kobe, Japan, 4450-4456 (2009)

[3] Martin, A. J., Larson, P. S., Ostrem, J. L., Sootsman W. K., Talke, P., Weber, O. M., Levesque, N., Myers, J. and Starr, P. A.. "Placement of deep brain stimulator electrodes using real-time high-field interventional magnetic resonance imaging," Magn Reson Med, vol . 54, 1107–1114 (2005)

[4] Susil, R. C., Menard, C., Krieger, A., Coleman, A. J., Camphausen, K., Choyke, P., Fichtinger, G., Whitcomb, L.L., Coleman, C. N. and Atalar, E., "System for prostate brachytherapy and biopsy in a standard 1.5 T MRI scanner," Magn. Resonance Med., vol. 52, 683–6873 (2004)

[5] Su, H, Shang, W, Cole, G. A., Harrington, K. and Fischer, G. S., "Haptic System Design for MRI-Guided Needle Based Prostate Brachytherapy," Haptics Symposium - Haptics 2010, Waltham, Massachusetts (2010)

[6] Elhawary, H, Tse, ZTH, Hamed, A., Rea, M., Davies, B. L. and Lamperth, M. U., "The case for MR-compatible robotics: a review of the state of the art," Int J. Med. Rob. 4, 105–113 (2008)

[7] Derbyshire, J. A., Wright, G. A., Henkelmann, R. M. and Hinks, S., "Dynamic scan-plane tracking using MR positioning monitoring," J. Magn. Reson. Imaging, 8, 924 –932 (1998)

[8] Hillenbrand, C. M., Elgort, D. R., Wong, E. D., Reykowski, A., Wacker, F. K., Lewin, J. S. and Duerk, J. L., "Active device tracking and high-resolution intravascular MRI using a novel catheter-based, opposed-solenoid phased array coil," Magn. Reson. Med., 51, 668– 75 (2004)

[9] Krieger, A., Fichtinger, G., Metzger, G., Atalar, E. and Whitcomb, L.L., "A hybrid method for 6-dof tracking of mri-compatible robotic interventional devices," IEEE Int. Conf. on Rob. and Auto., Florida, IEEE Computer Society Press, Los Alamitos, 3844–3849 (2006)

[10] DiMaio, S., Samset, E., Fischer, G. S., Iordachita, I., Fichtinger, G., Jolesz, F. and Tempany, C., "Dynamic MRI Scan Plane Control for Passive Tracking of Instruments and Devices" MICCAI 2007, LNCS, vol. 4792, 50–58, Springer, Heidelberg (2007)

[11] Lee, S., Fichtinger, G. and Chirikjian, G.S., "Numerical algorithms for spatial registration of line fiducials from cross-sectional images," Med. Phys., vol. 29, 1881–1891 (2002)

[12] Susil, R. C., Anderson, J. H. and Taylor, R. H., "A Single Image Registration Method for CT Guided Interventions," MICCAI 1999, Cambridge, England, LNCS 1679, 798-808 (1999)

[13] Tokuda, J., Fischer, G. S., Csoma, C., DiMaio, S. P., Gobbi, D. G., Fichtinger, G., Tempany, C. M. and Hata, N., "Software strategy for robotic transperineal prostate therapy in closed-bore MRI," Med Image Comput Comput Assist Interv Int Conf Med Image Comput Comput Assist Interv 11(Pt 2), 701–709 (2008)