Robert Odenbach*, Parisa Parsanejad and Michael Friebe

Automated alignment detection of an additively manufactured Z-frame marker to process instrument targeting signals in interventional MRI

Abstract: MRI-guided interventions (iMRI, e.g. prostate biopsy) are usually performed under a free-hand instrument targeting approach to guide and feed the instrument (e.g. biopsy needle) along the desired trajectory. However, this technique requires many iterative movements either from the interventionist or of the patient (with the MRI table) in and out of the MRI tunnel, which is cumbersome, time-consuming and expensive. To overcome these downsides, interventional MRI procedures can be facilitated with remotely controllable assistance systems for instrument alignment. Such systems require an accurate registration and tracking of the position and orientation of the instrument. Passive fiducial marker frames (e.g. additively manufactured Z-frame marker) are capable of providing full information about a device's orientation within the image.

In this paper, we present an automated alignment detection algorithm to track a Z-marker from system-independent screen-captured images. We evaluated the precision of the detection algorithm by analysing its computation results from schematic gold standard images in different marker orientations in comparison to MR-images with the same orientations. Our combined setup consists of a precise alignment system, an additively manufactured Z-frame marker and the related detection algorithm. It offers a fast, simple, independent and accurate automated instrument targeting for iMRI. For future work, we plan to conduct phantom targeting tests in combination with robotic alignment systems.

Keywords: Passive Marker, Tracking, Z-frame Marker, Alignment Detection, robotic interventional MRI

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*Corresponding author:

Robert Odenbach*: Department of Medical Engineering, Otto-von-Guericke University, Universitätsplatz 2, Magdeburg, Germany, e-mail: robert.odenbach@ovgu.de

Parisa Parsanejad and Michael Friebe: Department of Medical Engineering, Otto-von-Guericke University, Universitätsplatz 2, Magdeburg, Germany

1 Background

Due to its high soft tissue contrast, magnetic resonance imaging (MRI) is an advantageous imaging modality for guiding minimally invasive interventions. In general, MRI-guided interventions (iMRI) are performed by a freehand approach to guide and feed the instrument along a desired trajectory. This method requires a lot of experience from the clinician and is very cumbersome with regard to the narrow MRI tunnel of commonly used closed bore systems [1, 2].

An MRI compatible and remotely controllable mechanical, semi-robotic or robotic device can be employed in the MRI tunnel to increase the accuracy and to reduce the period of interventional MRI procedures [3–5]. To obtain high accuracy for the instrument alignment, the device and instrument must be tracked precisely. Brown-Roberts-Wells frame (Z-frame) is capable of providing a passive marker-based calculation about the orientation of a device. It contains seven fiducial tunnels (four vertical and three diagonal ones) that are visible as seven white spots in a cross section image slice (see Figure 1 right). By calculating the relative positions of these white spots in reference to each other, the spatial orientation of the marker can be determined relatively precisely in all six degrees-of-freedom [6, 7].

The intention of this work was to automatically detect the alignment of an additively manufactured Z-frame marker to enable the computation of instrument targeting signals for potentially remotely controlled mechanical or robotic devices independently from a specific MRI system, see Figure 1 [8, 9].

Figure 1: The additively manufactured Z-marker placed with a biopsy needle in its center and on top of an MRI phantom (left); a 3D overview measurement showing the internal liquid tunnel structures (center), and a 2D image slice with the seven cross sectioned marker spots (P1 – P7; right)

2 Materials and Methods

2.1 Hardware setup

We decided to acquire the image-based fiducial information for the computation of the marker orientation independently from the specific solutions of each MRI-system. For this purpose, we used an approach of grabbing slice image's from the video signal output that usually is connected to the control monitor. This approach of using screen captured images allows a universal application of our setup on every imaging system (MRI, CT, US), see Figure 2.

Figure 2: Complete hardware setup for the system-independent image capturing method: MRI-system computer (1), control monitor (2), video signal splitter (3), video signal format converter (4), video signal capturing device (5) and the independent computer hosting our program for the detection of the marker and the targeting signal computation (6)

2.2 Marker tracking strategy

Our Matlab-based (MathWorks Inc., MA, U.S.A.) detection algorithm computes the required alignment, which is needed for a potentially mechanically or robotically operated assistance system, to reach a predefined instrument trajectory. The desired instrument trajectory is determined by manually aligning two perpendicular imaging planes between the target object (e.g. center of an estimated tumor region) and the instrument's entry point on the surface (e.g. skin entry point for a biopsy needle). The intersection line of these two imaging planes represents the interventional trajectory. After it, a third imaging plane (called: fiducial marker plane), which is aligned perpendicularly to the first and second one, is placed coarsely above the entry point (estimated region of Z-frame marker).

In the result of an initial 2D measurement from the fiducial marker plane, the marker was measured with its fiducial structures in an arbitrary orientation, see Figure 1 right.

The key strategy for the instrument alignment along the desired interventional trajectory is first to align the Z-marker in a parallel orientation to the fiducial marker plane. This can be achieved simply by rotating the marker setup around two perpendicular axes. In a second step, the center of the marker, which is representing the instrument's position inside the marker (see Figure 1 left), needs to be moved translationally along two perpendicular axes to place it concentrically on the axis of the desired trajectory.

To enable a stageless and precise alignment within these four degrees of freedom (DOF) during the measurements, we placed our marker inside a simple custom made frame, see Figure 3.

Figure 3: The Z-marker placed in our manually operated 4DOF alignment frame. A biopsy needle was placed in the center of the marker to detect potential sources for artifacts.

2.3 Automated detection algorithm

Once a fiducial marker plane of the Z-marker was measured in the MRI-system (Skyra 3T, Siemens Healthineers, Erlangen, Germany), the slice image was captured with the video signal capturing device. After it, the captured image was imported into our program and the marker structures were automatically segmented out of the overall image. Secondly, the image information was enhanced through a sequence of multiple image filtering steps: 2a) "Gaussian filtering" to reduce image noise, 2b) "Contrast enhancement" to sharpen the fiducial edges, 2c) "Binarization" to confine the fiducial structures from the environment, 2d) "Thresholding" to delete minor marker structures and pixel artifacts. In a third step, the center points of the seven fiducial marker spots could be detected and their relative distances were calculated, see Figure 4.

In the fourth step, the orientation of the marker was calculated, see equation (1) and (2). In the result of this calculation, the alignment of the Z-marker with the alignment frame was determined in relation to the fiducial marker plane.

Figure 4: The captured image of the fiducial marker plane (left), the fiducial marker structures after all image enhancement steps (center), and the detected center points of the seven marker spots (right).

$$\begin{bmatrix} p_{2f} & p_{4f} & p_{6f} \end{bmatrix} = \begin{bmatrix} l_x \left\{ -\frac{1}{2} & \frac{1}{2} - f_4 & \frac{1}{2} \right\} \\ l_y \left\{ \frac{1}{2} - f_2 & \frac{1}{2} & -\frac{1}{2} + f_6 \right\} \\ l_z \left\{ -\frac{1}{2} + f_2 & -\frac{1}{2} + f_4 & -\frac{1}{2} + f_6 \right\} \end{bmatrix} \quad (1)$$

$$f_i = \frac{|p_{(i+1)MR} - p_{iMR}|}{|p_{(i+1)MR} - p_{(i-1)MR}|} \quad (2)$$

To evaluate the quality of our detection algorithm against potential sources of systematic errors (e.g. resolution of MRI, resolution of captured image, potential artifacts in printed Z-marker or imprecise manual adjustment of the alignment frame), we compared a set of MR-image-based calculations with a similar set of gold standard images. The gold standard images were taken as cross section images from a digital model (computer aided design model) of the printed marker and oriented precisely in the different alignments that were chosen with the alignment frame.

The test sets for the alignment frame rotation and the gold standard image alignments were chosen around the x- and y-axes of the marker in incremental rotation steps of three degrees within a range of 30° around the neutral or parallel orientation ($x = 0^\circ$ and $y = 0^\circ$).

3 Results

We repeated the alignment calculation tests ten times. Figure 5 shows one exemplary plot of one rotation set. The results show a high goodness of fit with $R^2 > 99,50\%$ indicating little influence of random errors and a high quality of replicability for both the MR image-based and for the gold standard image-based measurements. The average root-mean-square deviation (RMSD) from the regression lines is 0.29° for the gold standard image-based measurements and 0.50° for MR image-based measurements. The average RMSD from the gold standard images is considered as the registration error which emanates from the accuracy of our detection algorithm.

Figure 5: The regression models of the computed rotation around the x-axis (top) and y-axis (bottom). The horizontal axis indicates the nominal or desired rotation while the vertical axis indicates the value computed from the detection algorithm. The gold standard set is highlighted in blue and the MR image-based set is highlighted in red.

It highlights that a deviation of 0.21° is caused from influences next to the detection algorithm.

4 Conclusion

Considering all influences of potential error sources in our captured image-based approach, we rate the quality of our algorithm as high with an average precision of 0.29° . Thereby,

we demonstrated that our transformation algorithm enables a system independent detection of the orientation of an additively manufactured Z-frame marker. After the Z-frame's orientation was determined, a fast automated calculation for the required orientation of a potentially applied mechanical or robotic device could be given. These information can be used to process kinematic relations for a device to reach a desired target pose in iMRI procedures.

Whenever a robot-assisted navigation will be needed, the additively manufactured Z-frame marker and the related detection algorithm provide an automated and remote instrument alignment during simultaneous visualization of both the interventional device and the patient's anatomy. Our solution offers a potentially faster, simpler, cheaper and more accurate targeting of biological regions of interest in iMRI.

In future work, we will perform multiple phantom targeting studies in combination with robotic alignment systems to investigate the precision of instrument placements. Furthermore, structured targeting studies will be made in a clinical environment to prove the applicability of our instrument alignment approach in a clinical routine.

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