3D-printed Z-frame marker for MRI-guided interventions

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1. Problem

The performance of interventional procedures during magnetic resonance imaging (MRI) guidance brings multiple advantages compared to other imaging modalities, such as the elimination of ionizing radiation and high quality soft tissue differentiation. Clinicians prefer to use MR-imaging for certain interventional procedures including MRI-guided biopsies [1] and ablations [2]. Real time MR-imaging provides the visualization of the biopsy needle during its introduction into the target structure. An important challenge in MRI-guided interventions is the registration of MR-images to the instrument or tool holder.

Technical approaches to determine the position and the trajectory of the interventional instrument include optical tracking or the use of MRI-visible markers. In this paper, we propose a new strategy for the creation of a simple, passive and generatively manufactured fiducial marker that is suitable for visible alignment of instruments and tools in different types of MRI-guided interventions.

2. Material und Methods

Brown-Roberts-Wells frame (also called Z-frame) has been widely used in MRI-guided interventions to detect the interventional device's spatial coordinates inside the MRI scanner [1]. Multiple commercially available fiducial marker capsules filled with Gadolinium doped fluid (Gd, MR-SPOT® 121, diameter: 7.5 mm, Beekley Corp.) are placed in a 3D-printed plastic frame. That frame is designed with internal cylindrical tunnels, which are aligned in vertical and 45°-orientation at three sides (= Z-shape). The Gd-capsules are inserted concentrically in these tunnels. The total material costs for that marker design is about 18 € (3,50 € for printed marker frame; 2,05 € per Gd-capsule). Once the Z-marker crosses the MR-image plane the liquid provides an appropriate resonance signal as can be seen in figure 1. The benefit from the Z-shaped marker design is that the full 6-DOF (DOF = degree of freedom) pose of the device can be extracted from the relationship of the dots that show up on the image.

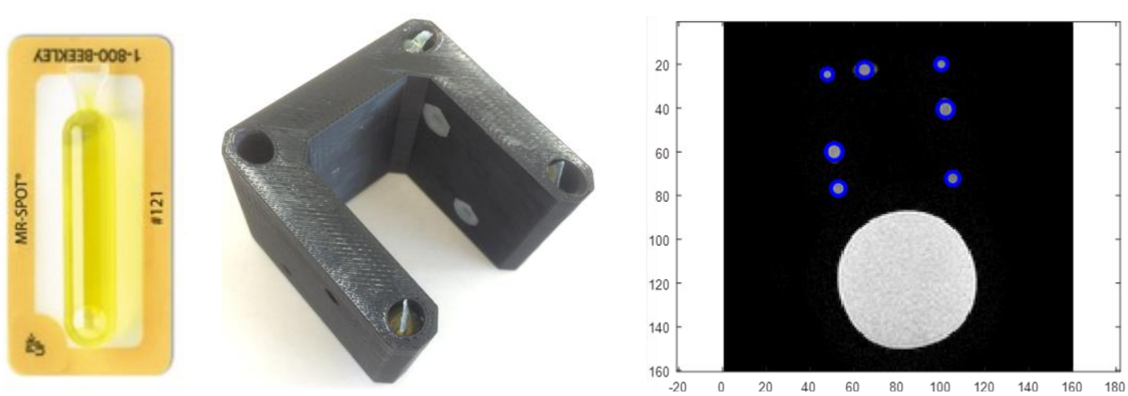

Fig. 1: Previous Z-marker concept of [1] including seven of the Gd-based marker capsules (left) that are inserted into the 3D-printed frame (middle). This marker concept provides a distinct resonance pattern in the MR-image with a fiducial registration error of FRE = 2.10 mm (seven white dots, right)[1].

Our new marker concept uses the same design with the Z-shaped tunnels, but it is fully generatively manufactured (commonly known as rapid-prototyping = RP) with one polymer material only using the method of stereolithography (SLA) technology [3]. The fabrication material for the marker-model is a liquid and photosensitive polymer (VisiJet SL Tough, 3D Systems, Inc.), which is locally hardened by a laser beam. The model is build up layer by layer with the laser hardening the model volume. The principle of the SLA-method allows the enclosure of defined geometrical structures filled with unhardened liquid resin. These structures are created inside the solid model body without any openings to the outside. For this reason, only the structure surrounding the desired marker-geometry is hardened by the laser. The marker-geometry itself remains a liquid. Since it is made entirely from polymeric material, this marker is passive and totally MRI-safe.

A prototype of our Z-RP-MR-marker concept was fabricated with outer dimensions of length × width × height = (48 × 48 × 41) mm³. The internal Z-shaped tunnels were designed with a diameter of 5 mm and a center distance of 40 mm. Multiple holes with a diameter of 1 and 2 mm are included beside the marker-tunnels at defined distances to provide a concentric passage of interventional tools (e.g. needles).

The marker was taken out of the SLA-printer and tested in our 3T MRI-system (Skyra, Siemens, Germany). Several initial scans with different sequences were made in order to determine suitable scan parameters. A body coil was used for signal acquisition. After a comparison of the different imaging qualities, a 3D imaging sequence (matrix = 160×160 pixels, voxel size = 0.5 mm) providing best quality was used. Figure 2 shows the internal Z-shaped structures from the digital model, the actual SLA-printed marker and the 3D-MR-image.

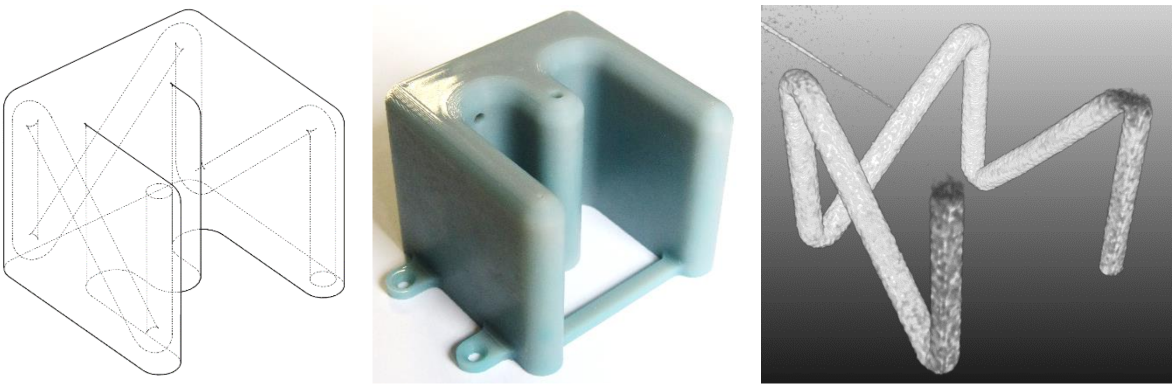

Fig. 2: The Z-RP-MR-marker with the distinct shaped internal tunnels in the CAD-view (left), the printed marker without any openings to the outside (middle), and the measured 3D-MR-image of the Z-shaped tunnels (right, 0.5 mm per voxel).

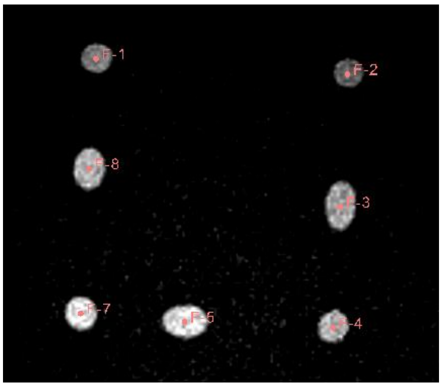

Fig. 3: View of a single MR-image plane (0.5 mm per voxel) showing the seven tunnels in cross section which are used as marker points to determine the instrument alignment.

3. Results

The marker was fabricated with total material costs of less than 10 € and did not cause any visible MR-image artefacts. All Z-shaped tunnels of the marker were fully and clearly measured in the MRI, see figure 3. The internal liquid RP-resin enabled easy positioning of the image plane with a fiducial registration error of FRE = 0.9 mm.

The target registration error (TRE) was calculated by selecting a point of interest at the needle insertion trajectories. We compared our results with the ones from [1] as shown in table 1. In conclusion, the Z-RP-MR-marker achieves better performance in FRE and TRE compared to the Gd-based Z-marker.

Table 1: Comparative study of the Gd-based Z-marker and the Z-RP-MR-marker

	Gd-based Z-marker	Z-RP-MR-marker
FRE	2.1mm	0.9mm
TRE	2.8mm	1.5mm

4. Discussion and Conclusion

In this work we have proven that the RP-fabrication-process allows a faster, cleaner and less expensive marker fabrication compared to the conventional Gd-capsule-based Z-marker. As the marker material completely consists of a hydrocarbon compound it does not produce any type of susceptibility artefact in a MRI-system. The RP-resin and the Z-shaped tunnel design provide sufficient imaging contrast and more precise marker qualities for MRI-guided interventional procedures. In medical application the clinician can benefit from the facilitated availability of the printed marker and the more precise alignment of the instruments, e.g. of needles in biopsy procedures.

In future work, the internal geometric structures of the marker will be improved to minimize the dimensions and to improve the precision. Furthermore the influences by using different resin materials with different colors will be investigated to evaluate the protection qualities for the internal liquid structures against any negative influence by light from outside. Finally, a detailed analysis on the optimal scanning parameters and a comparative study will be made to enable the application for real time MR-instrument-guidance of instruments and mechanical assistance systems inside the MRI-tunnel.

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