Real-Time Navigation of an Untethered Ferromagnetic Device using an MRI system in a Human Carotid Phantom based on Pre-Acquired Waypoints

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Introduction

A comprehensive navigation platform for an untethered device in a MR compatible carotid phantom using a real-time MRI system with no hardware modification is described. The device, composed of ferromagnetic material, is propelled using the magnetic gradient coils already present on every MRI systems for imaging purposes [1]. Relying on the same system for the propulsion, tracking and control of the device makes such innovative tool an interesting potential medical instrument available to most real-time clinical MRI systems. The device herein considered is a 1.5 mm diameter chrome steal bead with a measured magnetization of 1.35×10^6 A/m. Using a specially developed software architecture coupled with a dedicated controller and an off resonance tracking method adapted for ferromagnetic devices [2], the real-time navigation of the device along a predetermined set of waypoints in a water filled MR phantom has been successfully achieved on a Siemens Avanto 1.5 T with an operational frequency of 33 Hz.

Method

The device real-time navigation relies on a specially developed software architecture that lies in the Siemens software environment. The “Integrated Development Environment for Applications” (IDEA) module is responsible for the design and execution of the pulse sequences running on the scanner. The “Image Calculation Environment” (ICE) on the other hand, is responsible for the image reconstruction following the data acquisition in the pulse sequence. In the developed pulse sequence, the propulsion gradients and the tracking sequence are successively executed. The amplitude and orientation of the magnetic gradients are changed in real-time at each acquisition via the feedback loop between the ICE program and the pulse sequence. The data acquired relative to the device’s position from the tracking sequence is sent to the ICE program for position analysis. Command calculation for the upcoming acquisition is based on the computed positions and is triggered by a special synchronisation event noted ADC on Fig. 1. Three main modules are responsible for the position calculation, command generation and path navigation. These implemented modules are controlled and managed via a main agent, also in charge for the real-time communication between the ICE program and the running pulse sequence. Following a displacement of the device, a set of 3D waypoints positions are matched with the moving bead. A proximity sphere with a user defined radius ρ is centered at the waypoint’s location. If the device’s position is contained within the proximity sphere, target waypoint is considered reached and the next waypoint is loaded in the controller’s next set point. The controller used is as simple 2D Proportional, Integral, Derivative (PID) algorithm [3]. An overview of the running events and communications between the pulse sequence and the ICE program is shown on Fig.1. A minimum real-time feedback delay must be allowed for the ICE controller routine to finish before the next acquisition starts. As shown on Fig.1, the real-time feedback delay is defined as :

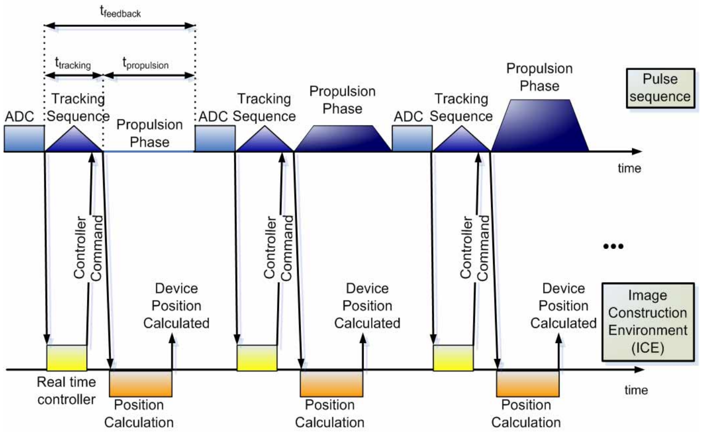

Fig 1 : Overview of the real-time sequence and running processes for the navigation of the ferromagnetic device.

$$t_{feedback} = t_{propulsion} + t_{tracking} \qquad (1)$$

The tracking phase duration for the x, y and z axis is constant and is executed in 15 ms. Thus, the propulsion phase duration depends on the real-time feedback delay chosen by the user at the beginning of the procedure and the system limitations in terms of magnetic gradient coils heating performance and a allowed duty cycle.

Results and discussion

The navigation of the device was tested in a carotid MR phantom filled with water. The system is connected to a mechanical pump providing a user controlled valve for quiescent flow adjustments. Before the bead is injected, an angiogram of the phantom is acquired for path planning. Waypoints are placed using an external visualization software before being exported in a file prior to navigation. The MR phantom along with the chosen waypoints are shown on Fig. 2. The bead is then inserted in the phantom and placed at the starting waypoint via a catheter system. Using a proximity sphere radius of ρ=10 mm, a real-time feedback delay of 30 ms and 2000 acquisitions, 2D closed loop control of the bead along the chosen path in the xz plane has been achieved. Device position against time is illustrated in Fig. 3. Experimental navigation results superposed on the chosen waypoints are presented on Fig. 2 The maximum gradient amplitude allowed by the MRI system and used for the navigation is 40 mT/m in x, y and z direction according to the standard MRI orientation scheme. Such limitation in magnetic gradient amplitude prevents the bead to levitate against its own weigh and justifies why only 2D navigation has been considered.

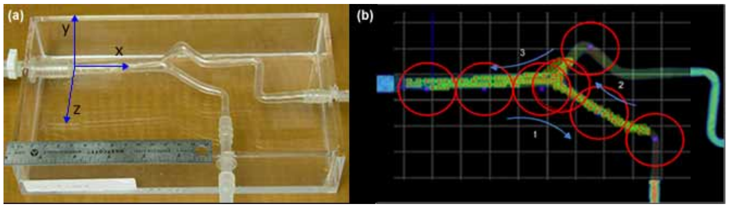

Fig 2 : Illustration of the MR carotid phantom (a) and overview of the waypoints set for the chosen navigation (circles) with ρ=10 mm along with the experimental navigation results (b)

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References

[1] Mathieu, J.-B., Beaudoin, G., and Martel, S., IEEE Transactions on Biomedical Engineering, 2006
[2] Chanu, A., Aboussouan E., Tamaz S., and Martel S., Proceedings of the 28th IEEE-EMBS, 2006.
[3] Tamaz, S. and Martel S., Proceedings of the 28th IEEE-EMBS, 2006.

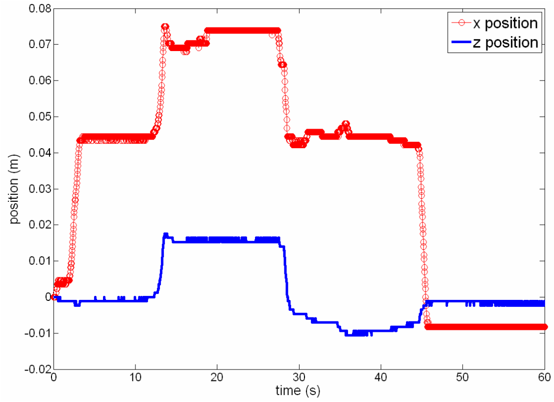

Fig 3 : Device’s displacement along time on the x and z axis