

# Real-time Magnetic Resonance Gradient-based Propulsion of a Wireless Microdevice Using Pre-Acquired Roadmap and Dedicated Software Architecture

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**Abstract**—A new method for the propulsion of a spherical ferromagnetic device along a given path in a water filled phantom with no human interaction is presented using an 1.5 T Magnetic Resonance Imaging (MRI) clinical system. A special real time loop is implemented and presented that feeds the scanner with the appropriate gradients amplitudes and directions based on a pre determined path. This paper studies the necessary propulsion conditions and limitations such as device dimensions and necessary gradient amplitude as well as overall latency problems such as communication delays and computation delays needed to achieve precise propulsion. It also presents a dedicated software environment for path control and validation, propulsion and tracking of such device.

**Keywords**—Real-time, microdevice, magnetic resonance, magnetic gradient, dedicated software environment

## I. INTRODUCTION

Although Magnetic resonance Imaging (MRI) systems are commonly used for image acquisition purposes, many new approaches involve using it for advanced tool manipulation during interventional MRI procedures. Most of these new methods that deal with real-time feedback techniques mainly involve catheter tracking using either active [1], semi-active [2] or passive techniques [3]. Such devices are usually manually controlled by a physician during surgical treatments and are limited to relatively accessible intravascular locations mainly due to size restrictions. Access to these limited remote locations could lead to new medical treatments such as highly localized drug delivery or thermal treatment of precise cells. Interventional MRI (IMRI) allows specialists to use the powerful imaging capabilities of magnetic resonance imaging to constantly monitor specific locations of the human body tissues and organs while attempting surgeries treatments. For such benefits and commodities, IMRI is becoming the future of advanced medical treatment supporting either minimally invasive or open procedures. This paper describes the use of a new magnetic propulsion method technique [4,5,6] combined with a special real-time communication loop in order to have a wireless device to follow a pre-planned route within space and time constraints of the applications. It is estimated that a

ferromagnetic core could be controlled and propelled in any directions with various velocities if sufficient gradient amplitudes combined with adequate real-time control loops, a dedicated software environment for path guidance and a position control can be successfully implemented. Real-time clinical MRI systems could benefit from this new navigation technique without the need for additional hardware or hardware modifications to current clinical MRI systems.

## II. METHODOLOGY

### A. Experimental setup

A ferromagnetic sphere made of 1010/1020 carbon steel with a diameter of 3.14 mm and a saturation magnetization of  $1.376 \times 10^6$  A/m is first placed in a custom made MRI phantom. As shown on Fig. 1, the phantom consists of a straight 118 mm long PMMA tube placed in a rectangular reservoir also made of PMMA and held in place through the two opposite walls of the reservoir. The sphere, later referred to as the device, is placed in the tube before the phantom is filled with water. The tube and the device are then submerged in water. The whole setup is placed horizontally in the MRI bore. To maintain the initial experiments simple, no flow has been considered in the present study.

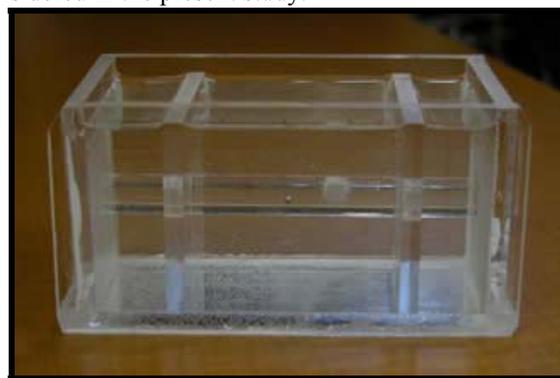


Fig. 1 View of a custom propulsion environment phantom

## B. Propulsion

The magnetic force  $\vec{F}_{magnetic}$  (N) acting on a ferromagnetic core in an MRI bore can be calculated from [4]

$$\vec{F}_{magnetic} = \vec{M} * V_{ferro} \cdot \nabla \vec{B} \quad (1)$$

In Eq.1,  $\vec{M}$  is the magnetization of the material (A/m),  $V_{ferro}$  is the volume of the ferromagnetic body (m<sup>3</sup>) and  $\nabla \vec{B}$  is the spatial field variation (mT/m). Using a 1.5 T Siemens Avanto with a maximum gradient amplitude of 40 mT/m in the X and Y directions and 45 mT/m in Z direction, the maximum force that can be applied on the device is  $F=5.018*10^{(-4)}$  N considering a propulsion in the Z direction. These values prove to be insufficient for vertical displacement with the given ferromagnetic sphere [4]. In this paper, the device's navigation is considered in a single axe (here being horizontal). The necessary mechanical force to propel and navigate the device through the phantom is obtained from the same magnetic gradients used for imaging on the MRI.

Some limitations remain due mainly to the limited gradients amplitude available. With the given set of coils, there is not sufficient gradient amplitude to propel the core against its own weight and against gravity in a vertical phantom. Nevertheless, much more powerful gradient peak amplitude can be achieved with alternate coils as seen in previous achievements [7]. With such custom made or optional coils, more force demanding applications could be considered involving horizontal and vertical reciprocal flow propulsion and navigation.

The navigation of the device relies mainly on three aspects: the propulsion gradient amplitude and direction as well as the time period of the application. Gradients amplitude and maximum time of application are mainly limited by the scanner's specifications. Modifying the resultant gradient amplitude affects the force applied on the device according to Eq.1 and changing the resultant gradient direction will affect the orientation of the device during the motion. In order to change the direction of the propulsion gradient, the rotation matrix that translates the logical coordinates into the physical coordinates is modified. Indeed, the three orthogonal gradients in the logical system (phase, readout and slice selection) are respectively converted into the physical system X, Y and Z through the rotation matrix R as follow:

$$\begin{bmatrix} G_x \\ G_y \\ G_z \end{bmatrix} = R \cdot \begin{bmatrix} G_{phase} \\ G_{ReadOut} \\ G_{slice} \end{bmatrix} \quad (2)$$

In Eq.2 and supposing that we are facing the front of the MRI system,  $G_x$  refers to the horizontal axis from left to right,  $G_y$  refers to the vertical axis from bottom to up and  $G_z$  refers to the last axis that is oriented towards us. The time period of the application can vary depending on the desired distance to be traveled. It is also possible to compensate a shorter time of application with higher propulsion gradients amplitude. The desired gradient amplitudes and directions for the device navigation are provided via, IDEA (Integrated Development Environment for Applications), the pulse sequence environment of the Siemens MRI.

## C. Software environment

In order to correctly propel the ferromagnetic core on the pre-planned path, robust software architecture must be present to seamlessly and precisely compute and apply the necessary gradients information through the scanner. The presented architecture lies on two software environments provided with the Siemens MRI. IDEA is the pulse sequence software that generates, at a higher level of abstraction, the necessary physical events for the MRI sequence such as the gradients information, the RF pulse and the ADC parameters. ICE (Image Calculation Environment) is the dedicated image reconstruction environment that receives the raw data from the scanner and computes among other things, the Fourier transform for data visualization.

Sitting on this given architecture is the required real-time feedback loop that allows the system to react on the scanner without having to wait for the end of the sequence. By modifying this optional feedback loop, it is possible to precisely select the correct rotation matrix, propulsion gradient amplitude and time of application in order to orient and propel the device. Fig. 2 shows an overview of the proposed software architecture. The developed software that computes the required gradients information and the future control mechanism is implemented in a ICE routine that is called at each measurement in the sequence execution. The path to follow is represented as an array of varying gradients amplitudes combined with a specific rotation matrix. This array can be thought as a simple roadmap for the device. This roadmap could be further obtained from a precisely reconstructed volume of the target and serve as a detailed set of waypoints in an in-vivo environment. The dedicated routine reads the next gradient amplitude and rotation matrix to be applied at each measurement and encapsulates the information in a data structure. This data structure is passed to the sequence through the real-time feedback loop. Once passed, the data structure is used to modify the current rotation matrix that is responsible for gradient orientation in space and to select the correct gradient amplitude to apply on the scanner.

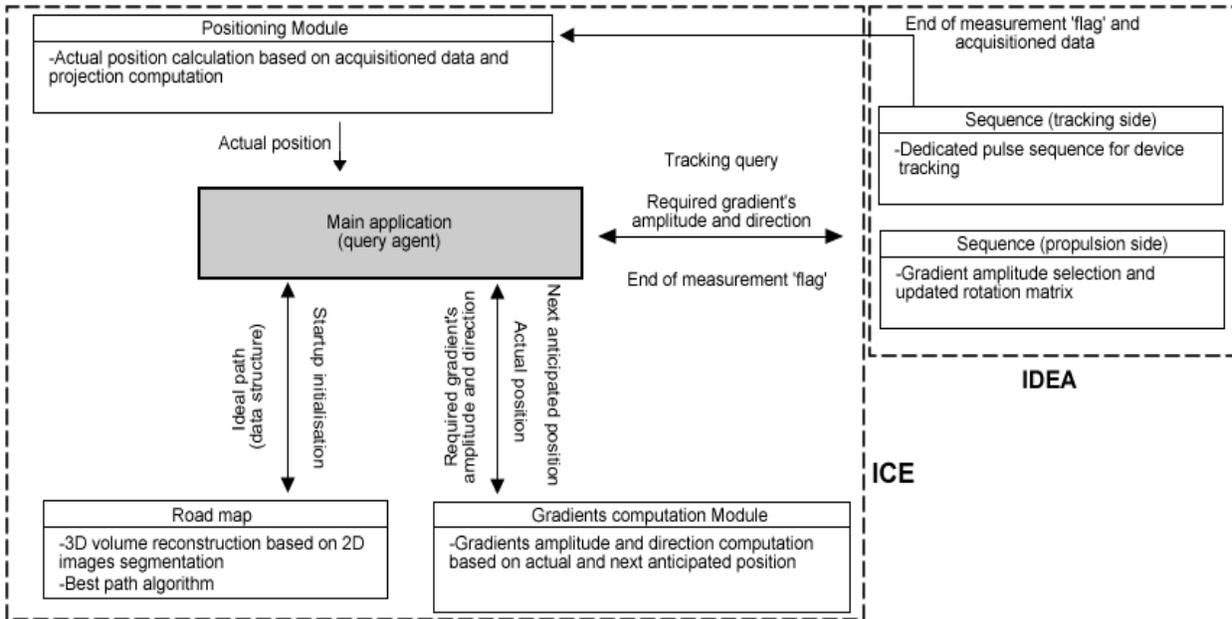


Fig. 2 View of the current system architecture

Once executed, the next position is computed in the ICE routine and sent again to the sequence, until the number of waypoints is achieved. In the current experimentation, no control of the device's position is implemented due to the fact that dynamic tracking is currently under development. Hence, the device's correct displacement has to be assumed.

Since the many environment parameters such as the volume of the device, its shape and the magnetization greatly affect the physics of the propulsion [4], a complete set of C++ classes regrouped in 3 modules and a software agent takes care of the different requirements for the upcoming complete environment. Both, the agent and the 3 modules are built around an ICE program. A complete path modeling and validation module known as the roadmap module as well as a precise propulsion module and positioning module have been developed to take care of all the necessary calculations and decisions during the displacement of the device.

The path modeling module is meant to construct the device's route in its environment (phantom, arteries...) either based on a precise roadmap of the region from a high resolution scan or based on an ASCII file. The route consists of waypoints in space encapsulated in a data structure. The structure is sent to the agent before the beginning of the device's propulsion. The propulsion module analyses the required destination from the path modeling module via the agent and computes the required propulsion gradient amplitude, the time of propulsion as well as the correct direction coordinates for the rotation matrix. A new data structure is then created and sent to the agent. These requirements for the sphere's propulsion are based on the current device's position in the environment and the next

planned position to achieve. The agent sends the required data to the sequence via the real-time feedback loop as soon as it receives the data structure from the propulsion module. A special routine in the sequence analyses the received data and chooses the correct propulsion gradient and propulsion time to be applied. It also fills the rotation matrix accordingly. Once everything is prepared, the computed parameters are fed to the scanner for the propulsion. A positioning module is implemented to periodically gather the actual device's position during the navigation. This module communicates with the agent when the device's actual position is required in order to modify the running sequence for positioning purposes.

#### IV. DISCUSSION

In order for the device to correctly follow a given path, without missing a set of waypoints, minimum feedback delay must be considered. This delay involves the time to send a request for immediate data analysis from the sequence to the ICE module, the time to compute the next waypoint to be achieved and encapsulate it into a data structure, the delay to send back the structure and the time to compute the new rotation matrix and to apply the new propulsion gradient amplitude. This real-time delay (RTD) is determinant in the eventual control of the device and must be minimized at all cost. This RTD is determined empirically and can be part of the sequence protocol. It can be easily found by successively testing the feedback structure until the device starts moving in the phantom. Indeed, if the RTD is too short, the ICE modules and the

agent don't have enough time to compute and send back the required data to the sequence, resulting in an unclosed feedback loop and device's stagnation. If such a loop is not ended correctly, the sequence can't apply the necessary propulsion gradients. Depending on the location where the feedback loop is broken, a wrong estimated device position can happen if the propulsion module has already computed the next waypoint and the necessary propulsion gradient is not applied. Since no error control is considered in this method, it could be difficult to compensate for any such broken loop.

## V. CONCLUSION

The presented method suggests using an MRI environment to propel a ferromagnetic core inside a water filled phantom by exploiting the real-time features of most clinical MRI systems. The propulsion of such microdevice in any direction relies on three basic concepts which are the maximum gradients amplitude available, the maximum time of application for a given gradient amplitude (duty cycle) and the rotation matrix. The main constraints for the propulsion of such device considering a no flow environment are only limited to the scanner's specifications such as the maximum gradients amplitude and duty cycle. Custom gradient coils [7] with higher maximum amplitude could help reaching a stronger force to be applied on the device. Heating problems emerging from such coils could be eliminated by using additional multilayer propulsion gradient coils.

In order to correctly follow a given path and being able to react against eventual propulsion errors, one must consider using a control and tracking method to evaluate such error. A tracking method is being developed and will allow the correct positioning of the microdevice in the image despite the strong artifacts caused by the altered magnetic field near the device. Besides, a control environment is also being developed for precise position error corrections. Such an environment would consist of a PID controller being included in an ICE module and merged to the present propulsion architecture.

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