35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Magnetic Resonance Tracking of Catheters and Mechatronic Devices Operating in the Vascular Network with an Embedded Photovoltaic-based Microelectronic Circuit

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Abstract— **Tracking of a catheter through the arterial system is critical in several medical interventions. To avoid excessive dose of x-ray irradiation, Magnetic Resonance Imaging (MRI) has been proposed. In such a case, a simple ferromagnetic sphere placed at the tip of the catheter could be used. However, due to the artifact created by the ferromagnetic core, it becomes impossible to gather an image of the tissues surrounding such a marker. Hence, in this paper we propose replacing the ferromagnetic marker with a microchip containing a coil and a photovoltaic cell. By radiating light to the photovoltaic cell, the coil generates a magnetic field which is detected as an artifact in MR images. By turning off the light, the effect of the coil is eliminated allowing images of tissues next to the marker to be taken. In this paper, simulated results based on experimental data from the preliminary designs suggest that this approach could be viable not only for catheters but also, it could potentially be used in various tools as well as mechatronic devices being moved inside the body.**

I. Introduction

Catheter steering through the arterial system is a major issue in several medical applications. A surgeon with a high level of endovascular skills needs to manipulate a catheter manually through a complex blood vessel network. Catheters must be placed and steered carefully to avoid major injuries such as the perforation of an artery. Traditionally, several shapeable guide wires and catheters can slide inside each another to perform catheter steering. A physician can use a linear back and forth movement as well as rotating the catheter around its axis in order to steer it. This method of actuation might cause many complications such as exposing the patient to more radiation, longer procedure time, hematoma, and the puncture of vessels [1]. Some methods use x-ray fluoroscopy to guide the catheter through the arterial system. Fluoroscopy uses ionizing radiations that lead to radiation exposure to the patient and the medical specialist. This phenomenon may lead to serious health effects on each person who attends the procedure in case of overexposure [2].

* This work was supported in part by the Research Chair of École Polytechnique in Nanorobotics and a Discovery Grant from the National Research Council of Canada (NSERC). The equipment used in this study was acquired with a grant from the Canada Foundation for Innovation (CFI).

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The idea of using an upgraded Magnetic Resonance Imaging (MRI) system to facilitate the steering of a catheter has been proposed and investigated in many studies [2-5]. Using an MRI system not only excludes the ionizing radiation exposure but also enhances the soft tissue contrast in the images [3]. Moreover, fluoroscopy can only describe the lumen of the vessels while MRI can visualize the morphology of the soft tissue surrounding the blood vessels [1, 4]

Different researches propose the idea of placing wound coils at the distal end of a catheter to MR-guide the catheter during intravascular procedures. A catheter with three orthogonal coils on its tip is proposed in [2]. The artifact of the current induced magnetic field of the coils and can be detected in MR images. However, the radio frequencies used for imaging and the intermittent current passing through the coils induce ohmic heating of the catheter wiring which can burn the surrounding tissues. To solve this problem, the use of ferromagnetic spheres instead of the coils has been proposed [5]. In this case, one or two optimally distanced ferromagnetic spheres are attached at the distal tip of the catheter. However, due to the generated artifact, it is impossible to visualize the tissues within a few centimeters of the catheter tip in MR images .

In this paper, we propose replacing the ferromagnetic spheres with a microchip containing a coil and a photovoltaic cell as a power supply. By radiating light to the photovoltaic cell the coil will generate magnetic field which is detectable as an inhomogeneity artifact in MR images. By turning off the light, the effect of the coil as an artifact in the images is eliminated allowing the surrounding tissue to be visualized.

The remainder of this paper is organized as follows: Section II describes the theory behind the MRI and the photovoltaic cell. In Section III, we present our simple microchip and the simulation framework. Finally, the results are represented in Section IV followed by conclusion in Section V.

II. Theory

A. Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) is a non-invasive modality that provides high contrast images containing the anatomical information. In theory, MRI imaging works on the assumption of a perfectly homogeneous magnetic field B_0. Ferromagnetic materials cause high inhomogeneity in the local magnetic field of the MRI. Inhomogeneity appears in MR images in the form of a signal loss.

In addition, any field variation other than the applied linear gradient during MR images acquisitions causes spins to be spatially encoded at the wrong position in MR images.

There are different types of magnetic field inhomogeneities. Macroscopic field generates non-exponential signal decay [6]. There are modeled by linear gradients and causes image distortion and echo shifting artifacts. Microscopic field inhomogeneities are magnetic field inhomogeneities over distances with orders of magnitude smaller than the voxel size. These kinds of inhomogeneities cause an irreversible signal decay ($R_2=1/T_2$).

Assuming a constant proton density across the voxel, signal decay in a voxel of volume V is expressed as

$$S(t)_{voxel} = \rho / V . e^{-\frac{t}{T_2}} .\text{sinc}\,(\gamma g_x l_x / 2).\text{sinc}\,(\gamma g_y l_y / 2)\ .\text{sinc}\,(\gamma g_z l_z / 2) \qquad (1)$$

where ρ is the proton density, l_x, l_y, l_z are the voxel dimensions, and field inhomogeneities along one direction i are expressed with a linear gradient ($\Delta B_i = g_i . i$) [7]

B. Photovoltaic Cell

When it comes to providing power to a microchip for an in-vivo application, wireless power transmission methods are generally employed. In this area, inductive coupling is a very popular method. In this approach, the secondary coil which is used to receive power, should be implemented to the microchip. However, the size of the secondary coil limits the achievable level of miniaturization. Moreover, the power transmission efficiency is very dependent on the distance between the two coils. Other methods such as radio and microwave-based power transmissions have the same drawbacks. Photovoltaic cells are one of the most well-known techniques for scavenging energy in both large and small scale applications. The photovoltaic effect generates voltage by radiating light which causes the transfer of electrons between different energy bands of the semiconductor and as a result generate electric field. The light direction should be straight and perpendicular to the cell surface to gain the maximum efficiency. For medical applications, a new structure of a photovoltaic cell has been proposed in [8]. The experimental results applying four cascaded cells of an area of 200 μm × 200 μm show a short circuit of 70 μA and an open voltage of 0.48 V [8] .We consider using this structure as a power supply of the proposed microchip.

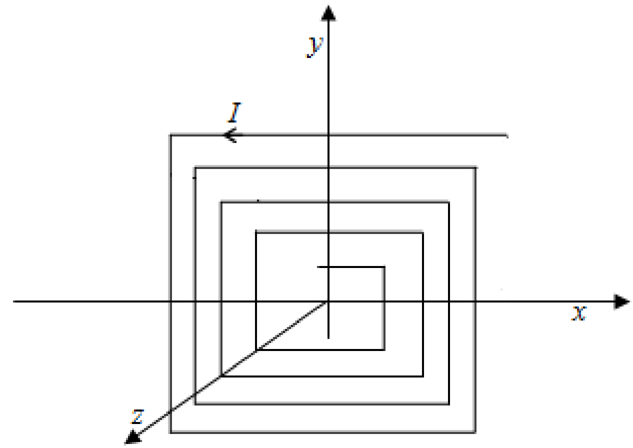
III. MATERIALS AND METHOD

The proposed microchip contains a photovoltaic cell with an architecture described in [9] and a micro-coil.

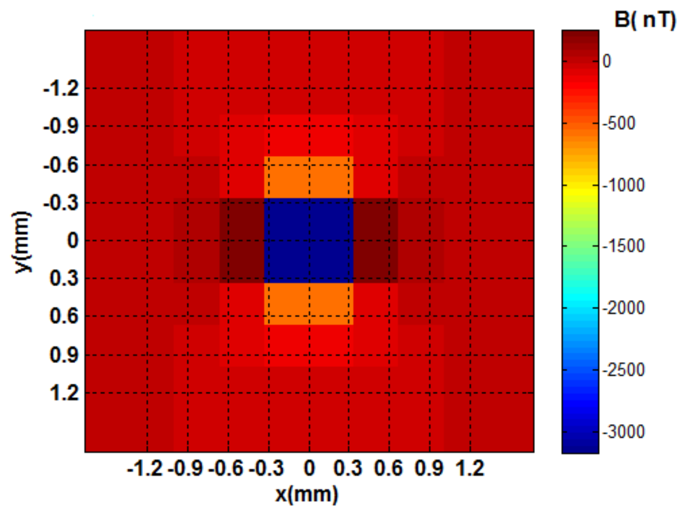
We use the following methodology to simulate the effect of a current induced magnetic field in an MR image:

A. Generating the field map inhomogeneity

A current of 70 μA was applied to a double layer coil with total size of 200 μm × 200 μm and the amount of magnetic field was simulated using MATLAB. It was assumed that the coil is in the x-y plane and it is surrounded by water. Fig. 1 shows the magnetic field of the coil in x-y plane. It was assumed that each square is equal to one pixel of the simulated MR image (0.3 mm) which is described in next section. As mentioned in [9], the magnetic field in the order of 100 nT is visible in MR image. As shown in Fig. 1 the magnetic field generated by the coil is higher than 100 nT and hence the coil is visible in the MR image. The result of this step which is current induced magnetic field was imported to the MRI simulator as a field map inhomogeneity.



(a)



(b)

Figure 1. (a) The schematic of the coil (b) Current induced magnetic field of a double layer coil on x-y plane. Coil specifications: Inner diameter = 140 μm, Gap size = 5 μm, Track width = 5 μm. Number of turns = 6 in each layer. I = 70 μA

B. MRI simulation

We used the SIMRI simulator as explained in [10] to simulate the MRI images. SIMRI is an interactive 3D MRI

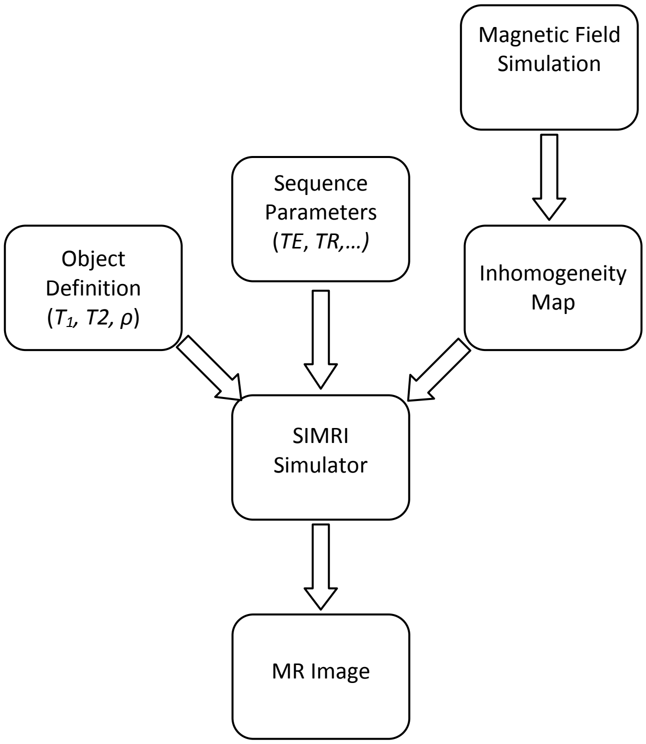


Figure 2. Simulation framework

simulator, implemented in C language to simulate images affected by different types of artifacts, including the inhomogeneities produced due to the static fields. As illustrated in Fig. 2 the simulation process contained object definition, computation of its corresponding magnetic field inhomogeneities and simulation of the MRI test. The object was placed in an external static field and was excited by applying an RF pulse with the frequency equal to the spins precession frequency. Spatial encoding was done by applying three magnetic field gradients in three directions. Following the excitation, the signal is recorded in complex form in k-space. The final image was acquired by applying the Fourier transformation of the k-space data. SIMRI can create the susceptibility effects, i.e. signal loss,

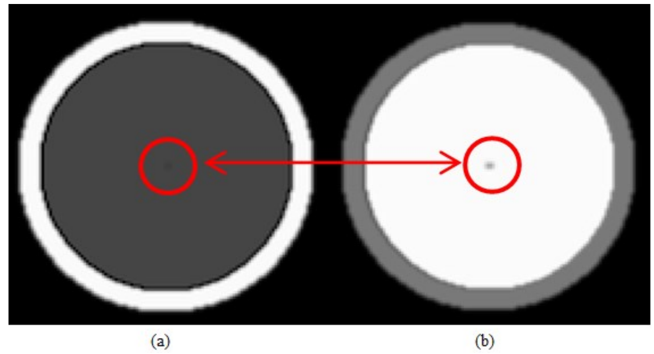


Figure 4. Signal weighting. (a) T1-weighted TR=140 ms, TE=20 ms (b) T2-weighted TR=2500 ms, TE=90 ms. T2-weighted image has better contrast.

geometrical and intensity distortions along the direction of the readout gradient by integrating the field inhomogeneities [7, 10]

The resolution of the image was 256×256 with a pixel size of 300 μm in both directions.

Since the inhomogeneity artifact is more pronounced in the gradient echo (GE) sequence rather than in the spin echo (SE) sequence, a GE sequence was used for the MR imaging.

IV. Results

Fig. 3 compares the MR image of a ferromagnetic sphere with the diameter of 800 μm with our proposed microchip with the total size of 400 μm × 600 μm. Our proposed method generates fewer artifacts in MR images. Therefore it is possible to visualize the surrounding tissues while the catheter is inside the blood vessels.

The result of imaging parameters on the visibility of the microchip in MR images was described in following section.

A. Effects of imaging parameters

Imaging parameters including the repetition time (TR), the echo time (TR), pixel spacing and field of view affect the contrast and the generated artifact by the current induced magnetic field of the microchip in MR images

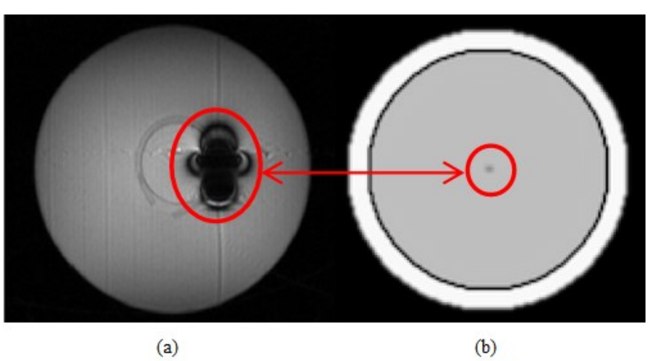


Figure 3. A Comparison between (a) the ferromagnetic sphere(Diameter=0.8 mm) and (b) our proposed microchip in MR images.

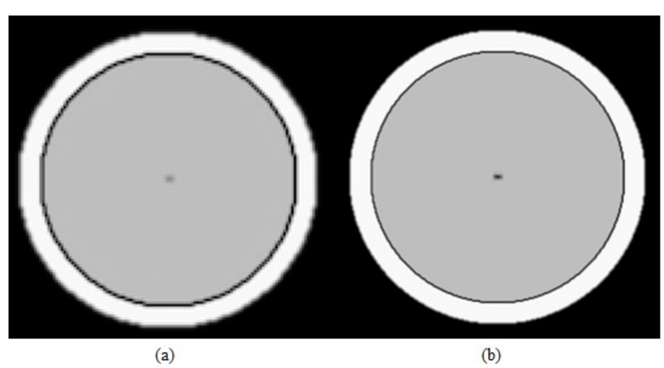


Figure 5. Effect of pixel size. TR=300 ms, TE=60 ms. (a) Pixel size is 300 μm × 300 μm (b) The pixel size is decreased to 200 μm × 200 μm

- **Effect of the repetition and echo time**

As mentioned in Section II, the magnetic field of the coil appears in MR images in the form of a signal loss (dark area). To improve the image contrast, the imaging parameters should be chosen so that the media around the coil appears bright. Water was considered as the surrounding media of the coil. Long echo times (TE) and long repetition times (TR) (TR=2500 ms, TE=90 ms in our simulation) lead to T_2-weighted images in which tissues with long T_2 relaxation time such as water appear bright (Fig. 4).

- **Effect of the Pixel size**

Decreasing the pixel size will enhance the image resolution at the cost of increasing the acquisitions time (Fig. 5). Depending on the amount of the magnetic field generated by the coil, the resolution should be selected so that the magnetic field generated by the coil affects at least 3 MR image pixels. This is necessary to distinguish the magnetic field-based artifact from the other sources of negative contrasts in the human body.

V. CONCLUSION

In this paper, we proposed the idea of replacing the attached ferromagnetic spheres at the distal tip of the catheter by a photovoltaic based microchip. By radiating the light, photovoltaic cell delivers current to the micro-coil. The current induced magnetic field can be detected in MR images. This approach reduces the artifact to an acceptable size for imaging purposes. Moreover, it is possible to completely eliminate this artifact in imaging state, by turning off the light.

Four cascaded photovoltaic cell with the total area of 400 μm × 400 μm deliver 70 μA current to the micro-coil with the total area of 200 μm × 200 μm. Simulated results show that the consequent magnetic field is large enough to become visible in MR images.

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