Augmented Reality System for Freehand Guide of Magnetic Endovascular Devices

S. Parrini, F. Cutolo, C. Freschi, M. Ferrari, and V. Ferrari

Abstract— **Magnetic guide of endovascular devices or magnetized therapeutic microparticles to the specific target in the arterial tree is increasingly studied, since it could improve treatment efficacy and reduce side effects. Most proposed systems use external permanent magnets attached to robotic manipulators or magnetic resonance imaging (MRI) systems to guide internal carriers to the region of treatment. We aim to simplify this type of procedures, avoiding or reducing the need of robotic arms and MRI systems in the surgical scenario. On account of this we investigated the use of a wearable stereoscopic video see-through augmented reality system to show the hidden vessel to the surgeon; in this way, the surgeon is able to freely move the external magnet, following the showed path, to lead the endovascular magnetic device towards the desired position.**

In this preliminary study, we investigated the feasibility of such an approach trying to guide a magnetic capsule inside a vascular mannequin. The high rate of success and the positive evaluation provided by the operators represent a good starting point for further developments of the system.

I. Introduction

Guiding magnetically responsive endovascular devices or magnetically labeled cells [1, 2] towards specific targets through blood by externally applied magnetic fields is an increasingly promising area of research. Magnetic carriers can be microrobots (e.g. endovascular capsules) releasing the active principle once they reach the point of treatment; in other approaches, a suspension of functionalized particles of active principle can be injected and magnetically targeted to the site of interest. This type of treatment could be very relevant in maximizing cure efficacy, localizing the therapy only to the site of the disease, and in minimizing side effects thus reducing the systemic concentration at the same time [3]. Targeted therapies could be problematic indeed: local infusion and direct injection can be applied only for sites that are reachable from the body surface or via a catheter in the blood stream; systemic injection suffers otherwise from low targeting efficiencies because the lungs and the spleen extract a high amount of administered therapeutic agents from the blood stream. Moreover, in many cases compensation via an increase in the quantity of administered cells or medicals may not be practically feasible [1].

The feasibility of such strategies has been investigated in several papers. Most methods proposed in the literature [2, 4-6] rely on the use of an external permanent magnet placed in close proximity to the target site: exploiting the blood stream, magnetic tagged cells or drugs are attracted by the external magnetic field and they concentrate in the specified site. However, just due to the dragging force of the blood stream, a great amount of magnetic carriers can slip away from the magnet; moreover, in many cases the magnetic carriers have to be driven for long distances from the entry site to the target lesion, thus many of them can be lost along the path due to lack of specific homing [2]. In both cases the efficacy of the therapy is reduced. Therefore, a direct dragging of magnetically labeled cells or therapeutic agents to the site of treatment results preferable. Moreover, when using an endovascular microcapsule to deliver medicals, such magnetic homing is not practically feasible. In [1] cells labeled with iron oxide particles are guided within a vascular phantom using the magnetic field gradients of an MRI scanner. Also in [7] a model for the magnetic steering of a microrobot in blood vessels controlled under MRI is presented. Various other approaches have been proposed for the magnetic steering and control of microrobot for biomedical purposes [8, 9]. In [10, 11] a 2D actuation system composed of two pairs of Helmholtz and Maxwell coils is proposed to steer a small cylindrical magnet used as microrobot. In systems based on the use of MRI, the tracking of the endovascular device can be achieved directly thanks to MRI itself [7]; in MRI-free approaches the tracking can be obtained instead by means of an ultrasound (US) system, as proposed in [12].

In this innovative and preliminary study, we aim to demonstrate the feasibility of an alternative, simple and smart approach for the external guidance of magnetic carriers. Our approach is based on the use of augmented reality (AR), that in medicine actualizes the enrichment of the surgeon's view with synthetic information (mainly 3D models of hidden or unexposed anatomical structures) extracted by medical datasets. In our case the user put on a wearable stereoscopic video see-through AR system, which allows him/her to see where the vessel is and, therefore, the path that the endovascular device has to follow. Moving a small permanent magnet over the patient's skin the surgeon can guide the magnetic carrier towards a target site following the trajectory showed by the stereoscopic visualization device.

This work has been partially supported by Fondazione Cassa di Risparmio di Pisa within the Scientific Project "Micro-VAST".

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978-1-4244-7929-0/14/$26.00 ©2014 IEEE

II. MATERIALS AND METHODS

We addressed several issues in the realization of the experimental setup. First of all the construction of the *in-vitro* phantom (section II A), then the creation of the 3D virtual model (section II B) and finally the adjustment of the AR vision system (section II C) to our specific application. Afterwards, we performed some trials to evaluate system efficacy (section II D). The following paragraphs explain each of these topics in more details.

A. Construction of the in-vitro phantom

A Poly(methyl methacrylate) (PMMA) container was built with some drilled holes serving as housings for the vascular model connections. The model consists of a 10 mm inner diameter PVC tube assembled to create a typical "Y-shape" vascular model (Fig.1a). This model can be mounted in many ways, taking advantage of the several connectors, thus to create different vascular configurations.

B. Creation of the 3D virtual model

To obtain the 3D virtual representation of the entire vascular model we implemented a panoramic reconstruction algorithm that permits to obtain a 3D US extended volume by merging several single volumes. A common 3D US probe acquires single volumes of the anatomical portion under examination. Nevertheless, the major limitation of this type of probe is that it is possible to acquire only small volumes at a time. To overcome this drawback, thus to acquire a volume covering all the area of interest, we attached an optical position sensor to the probe (Fig. 1b). The optical sensor permits to know the position and the orientation of the probe with respect to a fixed reference system (the optical localizer reference frame); knowing the calibration transformation between the probe and the US volume reference systems, we can infer the position and the orientation of every US volume in space. An algorithm was implemented to coherently combine the partial volumes in a single global volume, containing the entire vascular model. Once the volume was reconstructed, the vascular structure was segmented to obtain its 3D mesh (Fig. 1c). In our experiments we used a 3D US transducer (VL13-5) and a Philips iU22 ultrasonic system (Philips Medical Systems, N.A.; Bothell, WA); the optical localizer employed was the Optotrak Certus (Northern Digital Inc., Waterloo, Ontario, Canada). The reconstruction algorithm was implemented in C++. Regarding the segmentation part we used a software application implemented in the open source platform ITK-SNAP [13].

C. AR vision system

As stated before, AR in medicine enhances real views of the patient with virtual information consisting in patient specific 3D models of anatomies extracted from medical datasets. Since AR paradigm aspires to provide physicians with the ability to virtually see through the patient's skin and examine covered anatomical structures before exposing them, it can potentially bring several benefits in medicine, especially in surgery [14].

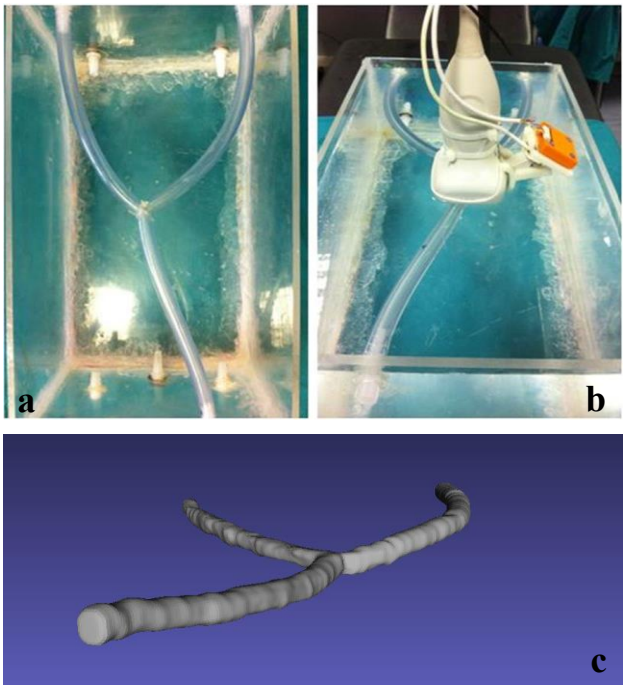

Figure 1. a) PVC vascular phantom. b) US probe with an optical sensor on it, scanning the entire vascular phantom to create the 3D virtual model. c) 3D virtual model of the vascular phantom after reconstruction and segmentation.

Depending on the type of surgery, the AR scene can be offered in different ways. In our case head-mounted stereoscopic devices are the preferable solution, since they allow the surgeon to better evaluate object depth dislocation, like in a natural binocular view [15]. Using head-mounted display the surgeon can see in real time the virtual scene from his actual point of view.

In this work we used a simple, light, and cheap 3D head-mounted stereoscopic video see-trough system (Fig. 2a) derived from a previous work [15]. The augmented view is achieved by combining virtual anatomical models, obtained by processing volumetric radiological images (CT, MRI or 3D US), and real patient live images, acquired by means of cameras [16]. The real-time alignment between real and virtual scene does not require the use of an external localizer for tracking head movements: real-time geometric data to coherently register the virtual scene and real one (rotation and translation components) are obtained tracking the position of a set of colored markers relative to the cameras and knowing their position in relation to the volumetric reconstruction of the vascular phantom.

Some preliminary tests of the AR guide were performed in order to find the most useful and ergonomic display modality for the magnetic targeting application. We eventually concluded that the most ergonomic solution for our application is to provide the operator with an augmented view of vessel centerline projection over the operating plane on which the magnet had to be slid, more than the actual 3D model of the phantom itself (Fig. 2b).

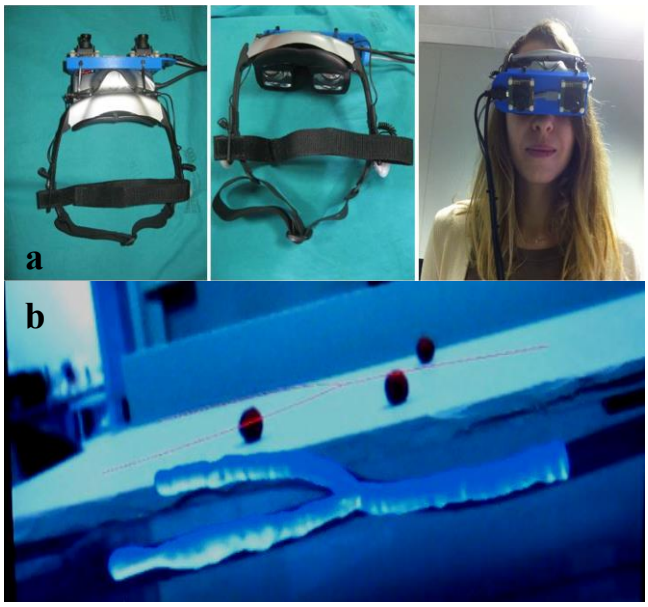

Figure 2. a) The 3D head-mounted stereoscopic video see-trough system. b) Example of visualization provided by the system: it is possible to see the 3D virtual model of the vessel (sky blue) overlapping the real vascular phantom and, in a more ergonomic way, the centerline projection on the plane where the magnet has to be moved (red line). The three red circles are the fiducial markers for the registration between virtual model and real vessel.

D. Experimental trials

We tested the proposed system with a set of trials. The vascular phantom was covered with an ad-hoc lid to be hidden from surgeon's view. Moreover we selected three points over the lid where to place the fiducial markers necessary for the registration between virtual model and real vessel.

Ten operators were recruited for the test session. Every operator was asked to move the external magnet, following the trajectory showed by the visor along three different paths (Fig. 3a). The operators had to move the capsule from point A to point B (first path), then from point B to point C (second path) and finally from point C to point A (third path) (Fig. 3b). The number of successes (i. e. the capsule inside the vessel followed the movement of the external magnet towards the desired final point) was recorded for every operators.

The capsule was a N45 Neodymium cylindrical magnet (length: 10 mm; diameter: 4 mm), with diametric magnetization. The external permanent magnet was a N42 disc-shaped magnet (height: 15 mm; diameter: 30 mm), with axial magnetization. The vascular phantom was mounted to have a maximum distance between the external magnet and the endovascular capsule of 50 mm.

III. RESULTS

The mean rate of success (rs) among all operators and all paths was 90%. The greatest number of failures (i. e. when the capsule did not follow the movement of the external magnet) was registered in the first path, likely due to an internal imperfection of the vascular phantom that partially

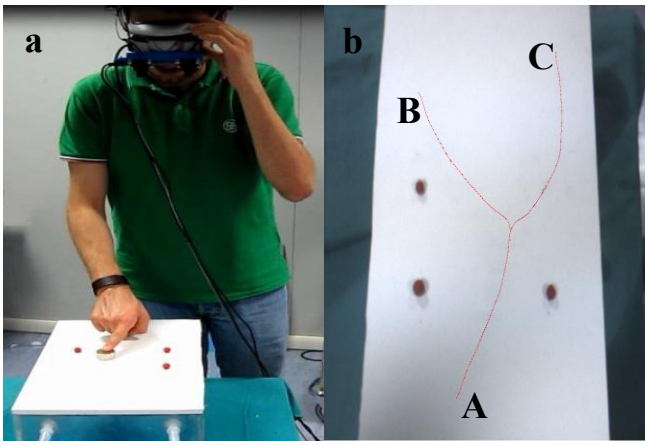

Figure 3. a) An operator moves the external magnet following the path showed by the 3D stereoscopic visualization device. b) The projection of the vessel centerline on the lid surface shown during the trials; the points A, B and C define the three paths that the capsule has to go through.

obstructed the lumen in that branch; eight out of ten operators succeeded in this path (rs: 80%). All ten operators succeeded in the second path (rs: 100%), while nine out of ten operators succeeded in the third path (rs: 90%). Table I summarizes the rs for the three paths. The mean times needed to move the capsule along the three paths were respectively 11.8 ± 2.5 s, 8.7 ± 1.4 s and 11.3 ± 1.1 s (in cases of success).

IV. DISCUSSION

In this preliminary study we present a simple and smart method for the external guidance of magnetic carriers based on the use of AR. Our method belongs to the group of approaches that directly guide magnetic carriers to the site of treatment, hence aimed at reducing side effects for the patient while maximizing the therapy efficacy. It employs a wearable stereoscopic AR video see-through system showing the surgeon the path that the endovascular device has to follow. The surgeon can carry the magnetic capsule towards the desired location by using a small permanent magnet. Our method was designed to simplify the current state-of-art systems which generally require robotic arms or MRI scanners for guiding the magnetic capsule in the desired way, thus reducing the overall amount of space needed and costs. The system was tested by ten operators, who had to guide a cylindrical capsule inside a vascular phantom with an external permanent magnet, according to the path shown by the 3D visor. The mean rs among all operators and all paths was 90%. In the remaining 10% of cases, magnet was not correctly moved causing the magnetic link between external magnet and the capsule to be lost. Most failures were registered in the first of the three chosen paths: this was partially due to an internal defect of the vascular phantom that obstructed the lumen in the bifurcation. All the operators were however enthusiastic about the system and positively evaluated the proposed approach.

This paper mainly intends to demonstrate the feasibility of using AR paradigm for freehand magnetic advancing of endovascular devices. To date our approach still lacks of a

TABLE I. RATES OF SUCCESS

	Rate of success (%)
First path	80
Second path	100
Third path	90

well-structured validation study: it has to be considered as a proof-of-concept study. Our method also lacks of a real-time tracking of the endovascular device. A visual feedback to know in real time the position of the device could allow the trajectory of the external magnet to be readjusted if the magnetic link between external magnet and internal capsule gets lost. In [12] a tracking system based on the use of US is proposed as it has adequate resolution, high speed and elevate frame rates; moreover, US does not suffer from safety problems related to the use of fluoroscopy on the one hand, and from equipment complexity and encumbrance difficulties related to the use of MRI on the other hand. However, the lack of a visual feedback of the endovascular device position may be not excessively limiting employing soft tethered capsules: the presence of a cable makes the endovascular advancing safer, allowing both the continuous control of the capsule and the possibility of blocking it if the magnetic link gets lost.

The clinical translation of this technology requires some conditions to be met. Firstly, as all the other systems based on the magnetic guide of endovascular devices, a not large distance between internal and external magnets has to be maintained. For this reason, these systems could be used only to carry endovascular devices from the entry point to the desired site along paths that are near the patient skin. Another issue concerns the creation of the vessels 3D model and its registration with the real patient. US could be not always applicable to extract the model (sometimes the presence of bones or air would prevent the use of US); however, the 3D model can be obtained from other preoperative or intraoperative available imaging (CT, MRI, 3DRA). The use of an intraoperative imaging source, allowing the reconstruction of the vessels 3D model just before the intervention, assures a precise correspondence between the volumetric images and the anatomy. It is then necessary that the interested anatomical part remains static during the procedure for a precise and correct alignment of the model with the real vessel.

The elevate scores achieved during the trials and the extremely positive feedbacks provided by the operators suggest us that the proposed approach could be interesting for the magnetic guidance of endovascular capsules. More exhaustive studies are however necessary to better validate the system and to solve the open problems. As an instance, in order to overcome the simplicity of the used PVC phantom, we have realized a silicone-made, patient-specific phantom, reproducing a tract of abdominal aorta, with renal arteries and iliac arteries. This will allow us to test our system in guiding endovascular devices in more realistic vascular structures.

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