MYOKINETIC PROSTHESIS CONTROL ORIENTED ENVIRONMENTAL MAGNETIC DISTURB ANALYSIS

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ABSTRACT

Several medical applications involve the use of remote magnet tracking for retrieving the position of tools instrumented with one or more magnets, when a free line-of-sight between the magnets and the tracker is not available. Our group recently proposed to implant passive magnetic markers (i.e. permanent magnets) in the forearm muscles of an amputee in order to track the displacements of those muscles during contraction. The idea is to use the retrieved information to control a hand prosthesis. We called this the *myokinetic control interface*. However, besides the system feasibility, how much its accuracy and precision are affected by external noise sources has not been quantified yet.

Here, through an experimental setup, we investigated the influence of different magnetic/electromagnetic interferences on the localization accuracy of three permanent magnets. The magnetic field generated by the magnets was collected both in interference-free conditions and in presence of disturbances. Localization errors achieved under different conditions, and for both raw and low-pass filtered signals, were derived. Results showed that the steel bar caused the maximum average localization error, equal to 9.8 mm and 74° in terms of position and orientation, respectively. The microwave oven caused instead the maximum localization variability, with a standard deviation of 0.21 mm and 2.2°. The low-pass filtering operation (5 Hz cut-off frequency) did not lead to significant improvement in the accuracy, resulting in an error decrease always below 7% compared to the unfiltered signals.

This work is important because it gives a quantitative measure of the disturbances encountered in everyday life which could cause the failure of those systems exploiting remote tracking.

INTRODUCTION

The deprivation of a hand is an event that significantly affects a person's ability in performing working and daily living activities (AdL), thus having a strong impact on his/her social life. In order to restore the lost motor functions in individuals with a hand amputation, two important factors are needed: first, the development of a dexterous prosthesis; secondly, the development of an intuitive Human-Machine Interface (HMI). Despite the recent research efforts to find a solution to these problems, both are still far from being solved. Indeed, on one hand a prosthesis able to replicate the dexterity of the natural limb has not been realized yet; on the other, commercially available prostheses often have more Degrees of Freedom (DoFs) than those controllable with current control strategies. In this regard, commercial hand prostheses are currently driven through HMIs which exploit the so-called direct control [1]. The latter consists in mapping the EMG signal recorded from agonist/antagonist muscle pairs using surface electrodes to a unique function in the prosthesis. Despite being intuitive and robust [2], this approach is hardly applicable to the control of multiple functions/DoFs, due to the lack of accessible independent control sources [3].

In order to overcome this limit and enhance the number of naturally controllable DoFs, our group recently introduced an alternative solution, dubbed the *myokinetic control interface* [4]. The idea is to implant permanent magnets into the residual forearm muscles, track their displacement using external magnetic sensors, and use this information as control input for the prosthesis. This approach would allow to physiologically (i.e. simultaneously and proportionally) control multiple, independent DoFs of the prosthesis by exploiting simple, passive implants.

In our previous work [5], we presented an embedded system which proved able to accurately localize in real-time up to five magnets. Such a system could potentially be used to control a robotic hand/arm. In order for this technology to be used in real-world scenarios, we need to make it robust against an environment which is largely corrupted with noise. Indeed, the presence of ferromagnetic elements and electromagnetic noise can potentially compromise the accuracy of the magnet tracking system. This problem has been poorly studied, since most of magnet tracking applications found in the literature are carried out in dedicated environments (e.g. an operating room), where the different noise sources can be avoided or modelled [6].

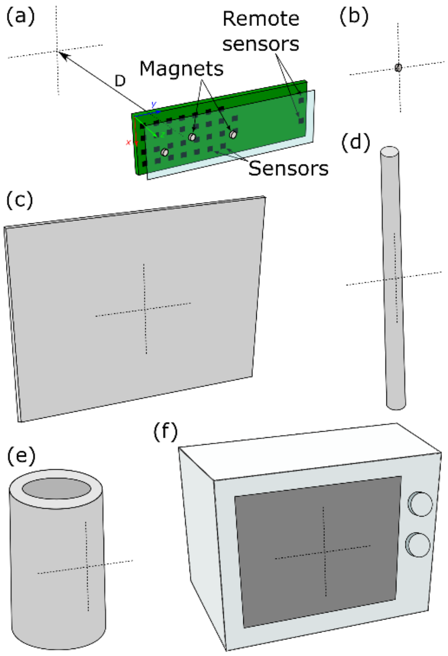

Figure 1: Experimental setup. The acquisition board and the three magnets to be localized are shown w.r.t. the disturbing object position (a). Those objects are: the magnet (b), the steel sheet (c), the steel bar (d), the hollow steel cylinder (e) and the microwave oven (f).

Preliminary results on the efficacy of a shielding strategy were presented in our previous study [4]. However, a deeper understanding of the problem in a real-world scenario remains to be tested. For this reason, it is of pivotal importance to investigate the effects of different interferences in a real experimental setup, in order to quantify the entity of the disturbances and find solutions to ultimately reject them.

MATERIALS AND METHODS

System Architecture

A *myokinetic control interface* is composed by two elements, namely the implanted magnets and a localizer embedded into the prosthetic socket which is responsible for continuously retrieving their poses (localization process). The latter is achieved by solving the so-called inverse problem of magnetostatics which, akin to previous works [4][5][7], was done by exploiting the well-known Levenberg–Marquardt optimization algorithm [8]. The acquisition unit already introduced in our previous work [5] was used to collect the magnetic field generated by the magnets. It consists of a custom board that collects signals from 32 three-axis magnetic field sensors (MAG3110, NXP Semiconductors NV, Eindhoven, Netherlands; full-scale output of ±10 G and sensitivity of 1 mG), arranged in a 4 × 8 matrix, except for two sensors that are placed remotely to compensate for the geomagnetic field. The sensors are connected to a 16-bit architecture microcontroller (dsPIC33EP512MU810-I/PT, Microchip Technology Inc., Chandler, AZ, USA) which samples their readings and transmits them to the actual localizer.

In our previous work [5] we proved the equivalence in terms of localization precision and accuracy between the embedded localizer implemented in C (running on a MIMXRT1050–EVKB, NXP Semiconductors, Eindhoven, NL) and the PC implementation of the same algorithm in Matlab (MathWorks, Natick, MA, USA). In this work, the latter was used in order to simplify the data analysis phase.

Experimental Setup

There exist different error sources which can affect the magnets pose estimation. Those due to model approximations, cross-talk effect between magnets, as well as sensor fluctuations have been extensively studied in our previous works [4][5][7]. Here, we addressed localization inaccuracies caused by environmental factors through a dedicated experimental setup (Figure 1).

Specifically, three axially magnetized neodymium cylindrical magnets (d = 4 mm; h = 2 mm; M = 0.0254 A·m^2 and B_r = 1.27 T) were fixed in anatomically relevant positions w.r.t the acquisition unit, using a rigid frame. Their magnetic field in presence of different noise sources (Table 1) was acquired and stored for offline analysis. Such interferences included the presence of close magnetic/ferromagnetic objects, as well as active electromagnetic noise sources (e.g. microwave oven, moving elevator).

Table 1: Settings details

	Disturbance	**Distance (D)**	**Notes**
Representative elements	Magnet	5 cm; 15 cm; 25 cm.	Same type of magnet as those used for the localization process.
	Steel bar		C40 steel. D = 2.5 cm, h = 80 cm
	Hollow steel cylinder		C40 steel. D_{ext} = 1.3 cm, d_{int} = 67 cm, h = 24 cm
	Steel sheet		0.5 mm thick stainless steel. l_1 = 32 cm, l_2 = 27 cm
AdL elements	Microwave oven		Samsung, model GW712K. Acquired with power set to 750 W.
	Electrical substation	40 cm	Distance is from the substation door.
	Elevator	70 cm	Distance is from the floor. Produced by BAMA srl. Acquired both while elevator is still and moving.
Ref.	Disturbance-free	-	Acquisition unit held still with no disturbance. Used as reference.

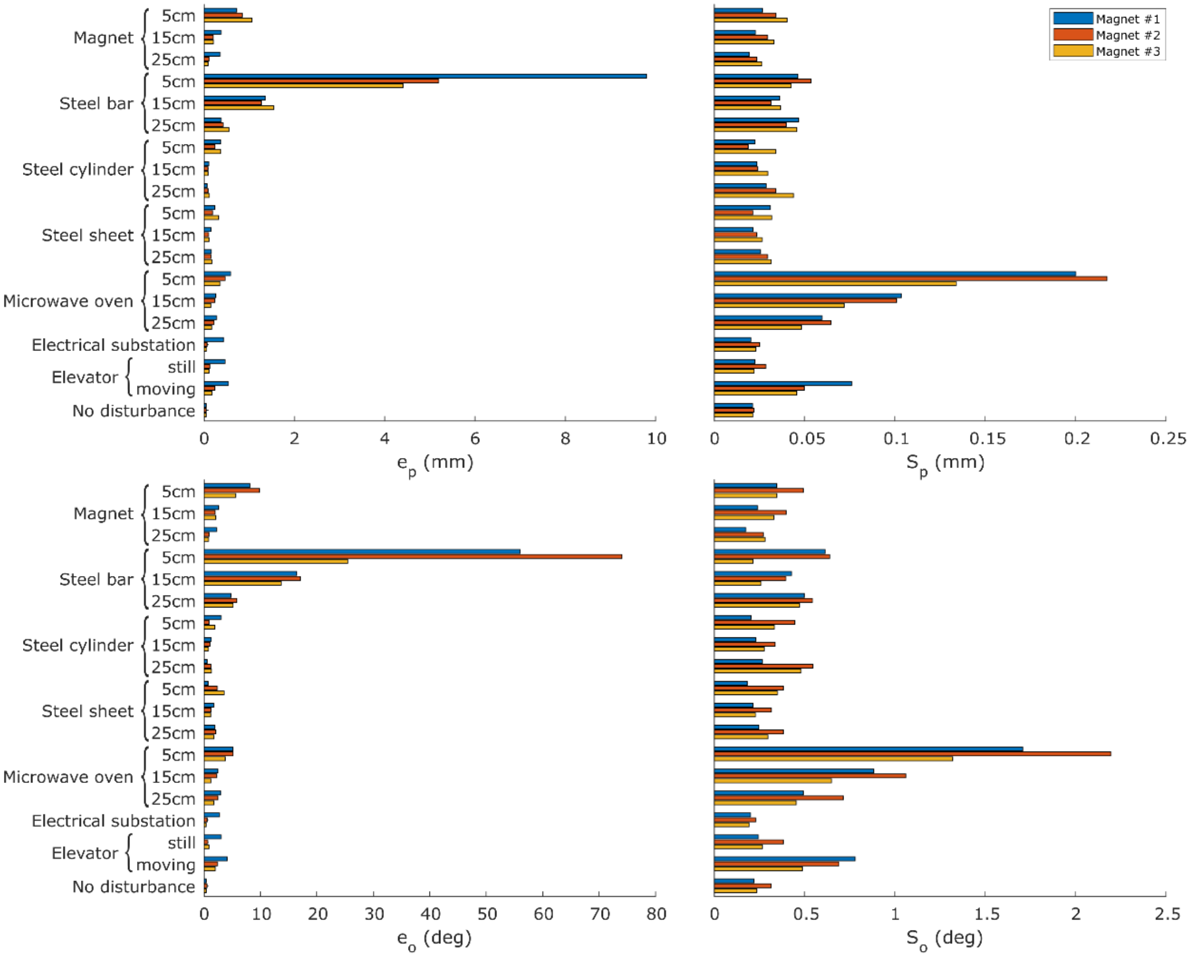

Figure 2: Results. Average position and orientation errors (e_p, e_o) and relative standard deviations (S_p, S_o) for the three magnets in all the experimented settings.

The tested noise sources were selected as representative of objects that can be encountered in AdL. For instance, a locker gives an interference comparable to that of a metal sheet, while a mobile phone originates a disturbance due to the two magnets present in its speakers. Some noise signals were acquired by considering different board - noise source distances (namely, 5 cm, 15 cm and 25 cm), because it was interesting to see how they affected the localization process for different interference intensity. Others, instead, were only measured at a single distance (Table 1). 2000 samples per configuration were acquired with a sampling frequency of 13 Hz, resulting in ~150 seconds per recording session. A pre-processing step was implemented by subtracting the field measured by the remote sensors and subsequently applying a low pass filter with a 5 Hz cut-off frequency, which we considered a reasonable bandwidth for human movements. Both the raw and the low-pass filtered acquisitions were used for estimating the pose (i.e. position and orientation) of the three magnets, in order to compare the results.

For assessing the entity of the disturbance, the average position and orientation errors (e_p, e_o) and their relative standard deviations (S_p, S_o) were derived. In order to isolate the noise contribution from the model and the cross-talk error, the mean value of the magnets poses derived using the interference-free signals were considered as a ground-truth reference.

RESULTS

The average localization error in terms of both position and orientation proved generally higher in presence of the interference cause by the steel bar (Figure 2). In particular, a maximum e_p of 9.8 mm was shown by magnet #1 when the steel bar was put at the minimum tested distance (i.e., 5 cm). Such error was comparable to the expected range of motion of the implanted magnets inside the muscle, which is ~10 mm [9]. In the same configuration, magnet #2 showed the maximum e_o across all configurations, equal to 74°. All other noise sources generally led to a lower accuracy deterioration, resulting in a maximum e_p (e_o) value of 1.1 mm (9.8°) in presence of the magnet at 5 cm.

The variabilities S_p and S_o acquired in presence of active noise sources proved significantly higher than those derived from the disturbance-free acquisitions (Figure 2). In particular, the maximum variability was always caused by the presence of the microwave, for which a maximum S_p and S_o value of 0.21 mm and 2.2° were derived, respectively. Ferromagnetic noise sources showed instead a smaller variability.

The 5 Hz low-pass filtering operation generally led to a small error reduction when compared to the error obtained using the raw signals (<7% reduction). Indeed, a median relative error reduction of less than 1% for both e_p and e_o, and between 5% and 7% for S_p was derived (Figure 3).

DISCUSSION

In this work, we evaluated the effect of different noise sources that can be encountered in everyday life and can affect the tracking performance of a *myokinetic control interface*. Everyday objects and dedicated tools that mimic their characteristics were studied to assess this effect. Our results showed that, while it is possible to retrieve the poses of the three magnets under different noisy conditions, some settings led to a significant deterioration of the localization accuracy.

Indeed, we found that specific ferromagnetic materials caused a considerable shift in the pose estimation, comparable to what is expected to be the range of motion of the magnets inside the muscles. Furthermore, some active noise sources (e.g. the microwave oven) induced high frequency oscillations in the estimated poses. The latter could be removed by applying a proper filtering approach. The cut-off frequency used in this work (5 Hz) led to modest improvements in the localization results, and we hypothesize this to be due to aliasing effects. Indeed, since the acquisition unit worked at 13 Hz, while the active noise sources may present higher frequencies, we were not able to entirely remove the interferences. However, by setting a higher frequency for the sensors acquisition, we can expect the noise contribution to be better discriminated and filtered. This remains to be tested in future works. Nevertheless, in most cases, the entity of the localization variability (S_p and S_o) was not relevant compared to the expected magnets range of motion (Figure 2).

The outcomes of this work demonstrate the importance of developing a magnetic shielding system able to make the *myokinetic control interface* robust and reliable in a real-world scenario. They are important because they provide a quantitative measure of the disturbances that could cause the failure of remote tracking applications.

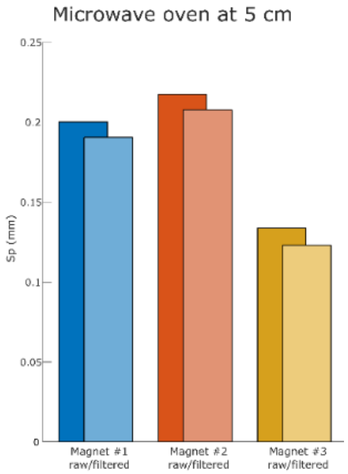

Figure 3: Comparison between the position error standard deviation (S_p) in localizations from raw and filtered data in the microwave oven at 5 cm.

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