Real-time pose detection for magnetic-assisted medical applications by means of a hybrid deterministic/stochastic optimization method

M. Alb[1,3], P. Alotto[1], M. Guarnieri[1], C. Magele[2], W. Renhart[2]
[1]Dipartimento di Ingegneria Industriale, Università di Padova, Padova, Italy
[2]Institut für Grundlagen und Theorie der Elektrotechnik, TU Graz, Graz, Austria
[3]The Virtual Vehicle Competence Center, Graz, Austria

Some classes of bone fractures are routinely stabilized and aligned by the use of intra-medullary nails. The identification of the pose, i.e. the position and orientation of the drill holes hidden by bone and tissue is currently obtained by X-Ray with all the well known disadvantages of this technology. The idea of substituting this methodology with an eddy-current based one has been explored in previous work but, in spite of interesting features, the developed technique suffered from some shortcomings. In this paper we propose a novel technique which is so computationally efficient that it provides real-time identification performance.

***Index Terms*—Inverse problem, pose detection, magnetic-assisted medical applications, stochastic optimization**

I. Introduction

The basic identification problem addressed in this work is schematically shown in Fig. 1. A conductive implant of known shape, called *nail* and usually manufactured with titanium alloys, is to be inserted inside a bone and the pose, i.e. the position (x, y and z) and orientation (angles ϑ and φ), of one (or more) drill hole has to be determined. In previous work [1] a saddle-coil arrangement was used to induce eddy currents in a copper ring attached to the nail and the reaction field was measured by Giant Magneto Resistance (GMR) sensors. Such technique showed some significant shortcomings since the field produced by the eddy currents was iso-frequential and small compared to the one produced by the main coil. Furthermore, the whole arrangement required rather expensive power amplifiers to drive the saddle-coil and lock-in amplifiers to pick up and discriminate the small signal produced by the eddy-currents. In the new arrangement proposed here, the saddle-coil and copper ring are substituted by a strong cylindrical permanent magnet, embedded in one of the drill holes, which produces a much larger field which, furthermore, is not superimposed onto another one thus avoiding the need for filtering. It can be assumed that the area surrounding the permanent magnet, at least in reasonable vicinity, does not contain ferromagnetic bodies and thus the field produced by the permanent magnet can be considered unperturbed. In the new system, the configuration for measuring the magnetic field produced by the permanent magnet consists of an array of two semi-circular sensors layers positioned along the y-axis, each consisting of 11 GMR sensors positioned on a circuit board. The distance between the permanent magnet and the sensors is in the order of 3-5 cm. A further advantage of the new system design is that the field, which was before computed with computationally expensive finite element procedures, can now be evaluated analytically [3] thus providing real-time identification, which is of high practical interest if the procedure is to become a routine surgical procedure. Techniques of this kind are receiving increasing attention in several areas of medicine [2] although their application is still largely limited to research applications.

II. Inverse Problem Solution

The inverse problem associated with the medical application at hand consists in finding five degrees of freedom, collected in the array $\mathbf{p}$, i.e. the previously mentioned pose parameters of the object, by measuring the magnetic flux densities at the field points given by the GMR sensors, collected in the array $\mathbf{B}$. Thus, the problem consists in minimizing the difference between the noisy measurement data vector $\mathbf{B}^\delta$ and the forward problem solution vector $\mathbf{B}(\mathbf{p})$ for a certain parameter configuration $\mathbf{p}$. In principle, the problem can be approached by deterministic as well as stochastic methods: while the former methods are generally faster but perform local searches, the latter techniques operate globally and tend to be more reliable, especially for noisy objective functions. Since a fast, accurate and robust algorithm is required for the specific application, the advantages of both methods can be combined or the disadvantages eliminated, respectively, by

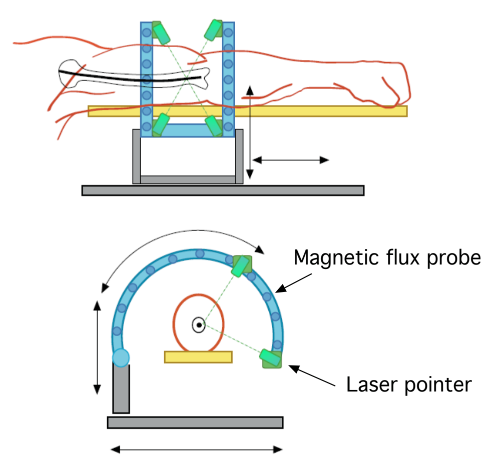

Fig. 1. Schematic representation of the a possible problem configuration.

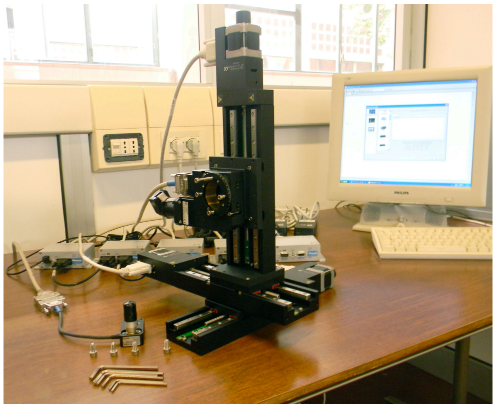

Fig. 2. Automated test rig

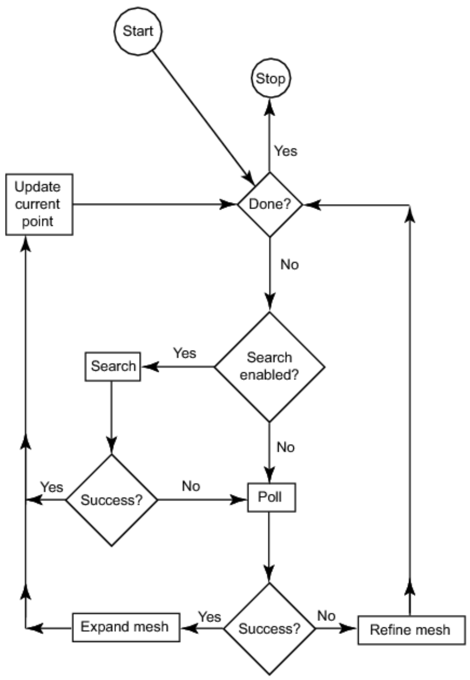

Fig. 3. Flowchart of PS-DE

applying a hybrid optimization method. The hybrid deterministic/stochastic optimizer, PS-DE, used in this paper [4] and schematically shown in Fig. 3, based on an extension of the well-known Pattern Search method [5], due to its deterministic nature, enjoys provable convergence properties. Indeed, 100% of all tested samples (different parameter configurations) were identified successfully by PS-DE. The robustness with respect to actual operational noise levels and tolerances is currently under investigation by means of the automated test rig, featuring micrometrical accuracy, shown in Fig.2.

III. Numerical Results

Since the static magnetic field of the permanent magnet is measured directly, the signal as well as the sensitivity can be increased significantly compared to the eddy current measurement method applied in [1]. Table I shows the minimum and average parameter sensitivities for 10 representative poses. It can be observed that all sensitivities are approximately 4-5

Table I
Sensitivities of the eddy current model (Old) and the permanent magnet model (New) evaluated for 10 representative configurations.

	Min. sensitivity				
	x $[T/m]$	y $[T/m]$	z $[T/m]$	ϑ $[T/deg]$	φ $[T/deg]$
Old	3.9E-11	1.1E-09	5.2E-10	1.5E-15	2.5E-14
New	2.4E-6	2.2E-5	3.6E-5	4.1E-10	2.1E-10
	Mean sensitivity				
	x $[T/m]$	y $[T/m]$	z $[T/m]$	ϑ $[T/deg]$	φ $[T/deg]$
Old	2.8E-6	2.6E-6	2.9E-6	1.0E-9	8.6E-10
New	6.8E-2	9.3E-2	1.2E-1	3.7E-5	2.2E-5

orders of magnitude higher using the enhanced method, while the orientation parameter sensitivities remain clearly worse compared to the positioning sensitivities. Preliminary results show that the object to GMR distance can be increased up to 10 cm while maintaining the desired accuracy and reliability, and this can be of high practical interest for real applications in the surgical environment. The computation time is in the order of 30 seconds on standard hardware with unoptimized Matlab code.

IV. Conclusions

This paper addresses the problem of identifying the pose, i.e. the position and orientation, of hidden intra-medullary nails, a promising magnetic-assisted medical procedure. The work aims at improving previous work which highlighted some critical issues in the application of optimization techniques to this class of problems. The proposed approach, which employs a particular optimization algorithm, simplifies and extends the practical implementation of the system, significantly improves the computational performance and allows a very satisfactory robustness of the procedure. The extended paper will include a detailed explanation of the optimization procedure, comparisons with other optimization strategies as well as further results including different sensor arrangements, and experimental validation based on an automated test rig.

V. Acknowledgement

This work was supported by the University of Padova PRAT2011 grant CPDA115285.

References

[1] A. Reinbacher-Köstinger, C. Magele, W. Renhart, “Fast, accurate and reliable identification of hidden conductive objects with deterministic and stochastic methods,” *International Journal of Applied Electromagnetics and Mechanics*, Vol. 39, No. 1, pp. 157-166, 2012.
[2] C. Di Natali, M. Beccani, P. Valdastri, “Real-Time Pose Detection for Magnetic Medical Devices,” *IEEE Transactions on Magnetics*, Vol. 49, No. 7, pp. 3524-3527, 2013.
[3] Vitezslav Pankrac and Jan Kracek, “Simple Algorithms for the Calculation of the Intensity of the Magnetic Field of Current Loops and Thin-Wall Air Coils of a General Shape Using Magnetic Dipoles,” *IEEE Transactions on Magnetics*, Vol. 48, No. 12, pp.4767-4778, 2012.
[4] P. Alotto and G. Capasso, “A Deterministic Multiobjective Optimizer,” Proc. of 16th IGTE Symposium, Sept. 14-17, Graz, Austria, 2014.
[5] A.L. Custdio, J.F.A. Madeira, A.I.F. Vaz and L.N. Vicente, “Direct multisearch for multiobjective optimization”, *SIAM Journal on Optimization*, Vol. 21, No. 3, pp. 1109-1140, 2011.