Enhanced Identification of Hidden Conductive Objects with Deterministic and Stochastic Methods

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Abstract—**The identification of conductive objects of known shape embedded in low- or non-conductive regions is a special application of non-destructive testing, with possible important applications in some surgical procedures. In particular, some classes of fractures are routinely stabilized and aligned by the use of intra-medullary nails. Identifying the position and the orientation of the drill holes hidden by bone and tissue is currently done 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 hard to address shortcomings. In this paper we propose a new technique which is computationally efficient and inexpensive to implement.**

Index Terms—**Inverse problem, non-destructive testing, stochastic optimization**

I. Introduction

The basic identification problem addressed in this work is shown in Fig. 1. A conductive implant of known shape, called *nail* and usually made by titanium alloys, is to be inserted inside a bone (not shown) and its position (x, y and z) and orientation (angles ϑ and φ) 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, [2], [3]. Such technique showed some non-negligible shortcoming 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 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.

In the new system, the configuration for measuring the magnetic field produced by the permanent magnet consists of an array of three circular sensors layers positioned along the y-axis, each consisting of 8 GMR sensors positioned on a circuit board. The distance between the permanent magnet and the sensors is in the order of 3 cm. A further advantage of the new system design is that the field, which so far was computed with computationally expensive finite element procedures, can now be evaluated analytically [4].

This is of high practical interest if the procedure has to be implemented in hardware for real-time surgical procedures.

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 position and angle parameters of the object, by measuring the magnetic flux densities in 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 applying a hybrid optimization method.

A suitable deterministic method to solve general non-linear, ill-posed inverse problems is the well-known Iteratively Regularized Gauss-Newton (IRGN) algorithm [5]. The IRGN method was already applied to the previous version of the

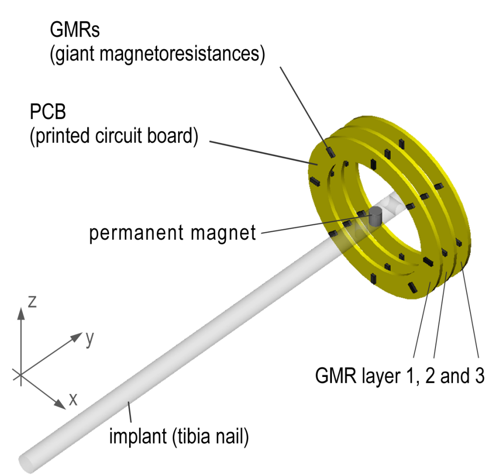

Figure 1: Basic problem configuration.

problem, i.e. the one in which the reaction field was produced by the eddy currents flowing in the copper ring, and it was found out that the technique is fast and accurate but not reliable enough (10-20% of the runs fail to converge to the correct solution of the problem).

A further possibility to solve the inverse problem is to apply a stochastic method, e.g. a $(\mu/\rho, \lambda)$ Evolution Strategy (ES) [6]. With this method a reliable and accurate solution is reachable but the convergence speed is very low. This was a severe limitation in the original system which required the solution of the forward problem by means of finite element simulations, whereas in the current system fields can be computed analytically thus the relatively low speed of convergence is no longer a very critical issue. However, especially in the view of a real-time implementation of the system, overall speed still remains one of the main goals.

In order to minimize the drawbacks of each method a combined stochastic-deterministic approach is used. Since starting values which are far away from the true values are the main reason for the failure of IRGN, a pre-Evolution Strategy (pre-ES) is initially performed to provide a good starting point for the very fast and accurate IRGN.

In very few cases the angle parameters are not well identified within the IRGN sequence (the angle sensitivities are much smaller), thus, a post-ES is started to improve these results. 100% of all tested samples (different parameter configurations to be identified) were identified with this hybrid method. In [1] the characteristic parameter behaviour of the hybrid identification method as well as identification results can be found.

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 parameter sensitivities for one single object position and orientation. It can be observed that the sensitivities are approximately 4-5 decades 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.

In the eddy current model the forward problem was solved by finite element method (FEM). To reduce the computation time of the identification process itself to a reasonable dimension, FEM simulations were pre-computed for an appropriate number of sampling points in the parameter space first. Using this dataset the forward problem for an arbitrary parameter set was approximated by using cubic interpolation between the sampling points. To hold the desired approximation accuracy, 18 225 samples have been pre-computed in approximately 4 months. Solving the forward problem analytically using the proposed, enhanced method, only takes a few milliseconds with no loss of accuracy.

Table I: Parameter sensitivities of the eddy current model (Model 1) and the permanent magnet model (Model 2) evaluated for a set of 10 parameter configurations.

	Min. sensitivity				
	x in T/m	y in T/m	z in T/m	ϑ in T/deg	φ in T/deg
Model 1	3.9E-11	1.1E-09	5.2E-10	1.5E-15	2.5E-14
Model 2	2.4E-6	2.2E-5	3.6E-5	4.1E-10	2.1E-10
	Max. sensitivity				
	x in T/m	y in T/m	z in T/m	ϑ in T/deg	φ in T/deg
Model 1	3.9E-4	1.8E-4	2.2E-4	1.4E-7	9.4E-8
Model 2	10.0	26.5	33.5	7.2E-3	7.8E-3
	Mean sensitivity				
	x in T/m	y in T/m	z in T/m	ϑ in T/deg	φ in T/deg
Model 1	2.8E-6	2.6E-6	2.9E-6	1.0E-9	8.6E-10
Model 2	6.8E-2	9.3E-2	1.2E-1	3.7E-5	2.2E-5

IV. Conclusion

This paper addresses the problem of identifying the position and orientation of hidden conductive 3D objects, which finds important applications in some surgical procedures. 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, combining stochastic and deterministic optimization algorithms, 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.

V. Acknowledgement

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