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Research Article

Design of Meander-Line Antennas for Radio Frequency Identification Based on Multiobjective Optimization

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This paper presents optimization problem formulations to design meander-line antennas for passive UHF radio frequency identification tags based on given specifications of input impedance, frequency range, and geometric constraints. In this application, there is a need for directive transponders to select properly the target tag, which in turn must be ideally isotropic. The design of an effective meander-line antenna for RFID purposes requires balancing geometrical characteristics with the microchip impedance. Therefore, there is an issue of optimization in determining the antenna parameters for best performance. The antenna is analyzed by a method of moments. Some results using a deterministic optimization algorithm are shown.

1. Introduction

The low cost of electronic microcircuits and their low power consumption have turned practicable the development of identification systems through radio frequency, especially from the 1990s. Radio frequency identification (RFID) allows not only storing a relatively large amount of information, but also changing and processing information.

Radio frequency identification is a growing and promising technology that has been used in a variety of applications. It has been applied for tracking of products, luggage, books, and animals, where the tags can be attached to the objects, injected under the skin, or mounted in holes made in parts of the itens [1]. Antitheft systems, asset management, anesthetic dosages, car manufacturing, and many other identification applications, such as passports and restricted area access, are examples of how the RFID technology is flexible and dynamic.

RFID total market value in 2009 grew to $5.56 billion, of which $2.18 billion was spent only on passive tags [2]. Therefore, optimizing radio frequency identification systems has become crucial in improving the productivity and lowering costs in industry and supply chains.

A RFID system consists basically of a receiver (tag), an emitter (reader), and a computational system (direct link). The tags have two main structures: the microchip, which provides the necessary power to transmit and receive information, and the antenna. The tags can be active, passive or semiactive, depending on the mechanism of powering the microchip and transmitting information. Active tags have a local power source and electronics for performing specialized tasks [3]. This local power source, which is usually a battery, provides energy for the operation of the microchip and transmission of information. The semiactive tags also have a battery, but they use the power received from the reader to send the message back. Finally, passive tags do not have any power source and need to rectify the energy received from the reader to generate enough voltage for the microchip operation. The type of the RFID tags is chosen based on a specific application. For low-cost tags and relatively short read ranges (around 3 m [4]), the passive tags are the most appropriate ones.

The entire RFID system depends on the performance of the tag, which relies on its elements. In the direct link, the reader sends modulated RF power that reaches the tag; this power is captured by the tag antenna and is transmitted to the microchip. In order to ensure a great power transmission coefficient and decrease the losses, the tag antenna impedance must match the complex input impedance of the tag microchip, which is commonly capacitive. Usually, the antenna is the element to be matched to a specific chip available in the market.

Due to the diversity of materials and packages that need to be identified, tag antennas development for passive UHF RFID systems has become challenging. The performance of the tag antennas is very dependent on the properties of the objects which the tags are attached to. The material of the objects can influence the capacitive characteristics of the tag antenna, as well as modify its radiation pattern. Many studies have been carried out in order to investigate these effects on tags attached to metallic surfaces and water [5, 6] and to dielectrics [7, 8]. Efforts to find the most optimized tag antenna for a given application improve the performance of the entire RFID system because it can increase the power transmission coefficient and the read range.

The design in this paper was motivated by application in coffee business. In this business, the product is stored in sacks in the producers' farms and needs to be transported to the local cooperatives. Each cooperative receives coffee sacks from different producers, normally using treadmills, and the receiving process demands time and labor force and is usually inefficient. Besides, the origin of the coffee must be traced until it reaches the final consumer and the material flow must be controlled in real time. In this context, RFID systems can be used to improve the productivity and competitiveness and reduce costs.

Tracking coffee containers in real time using RFID technology, from the shipment to the moment the container arrives in the USA, is already being used by a coffee importer named Sara Lee, in Santos harbour (São Paulo, Brazil). Moreover, the ST Café, a Brazilian company, is using RFID tags to identify the coffee sacks individually in rural properties.

Meander-line antennas are one of the most commonly used in UHF RFID tags, mainly because of their tunability and size. Several papers have been published on RFID meander-line antenna design. Some articles have sought achieving improved antenna gains and small size by using different configurations of meander-line antennas for passive RFID, which were explored applying genetic algorithm (GA) optimization and the method of moments (MoM) [9, 10]. The moment method (MoM) with Rao-Wilton-Glisson (RWG) basis functions [11] is used to calculate the electromagnetic characteristics of the antenna. In [8], a loaded meander-line tag antenna was designed focusing on a specific application: box tracking in warehouses; the box content and the sensitivity to fabrication process were also considered. Some methods have been used to characterize impedances and design meander-line antennas [12], and GA has been shown to be an efficient optimization tool for selecting globally optimal parameters of the antenna [13]. This paper introduces design techniques using optimization in order to cope with operation inside a frequency range, where the main innovation lies in the formulation of single and multiobjective optimization problems and the suitability of state-of-the-art optimization algorithms to solve them.

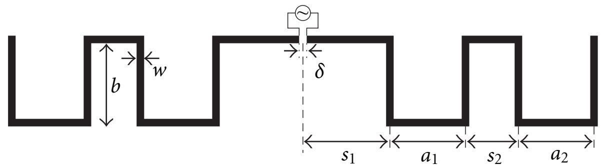

Figure 1: Geometry of the meander-line antenna for $c = 2$.

2. Antenna Design

One of the most convenient forms of RFID tags is a labellike, so that they can be stuck on objects. This work analyzes a meander-line antenna that is very suitable for this application.

3. Model and Parameterization

The application of coffee business required the use of a passive UHF RFID tag antenna (902-928 MHz). In order to perform the simulations, some design specifications were established. The microchip, which has been used as a reference in this work, is ALIEN Higgs TM-3, EPC Class 1 Gen 2, whose equivalent input impedance is (27.41-200.90j) at 915 MHz. The meander-line antenna geometry (see Figure 1) is parameterized by the number of meanders c in each side, feed gap δ, trace width w, height b, meander step length a_i, and spacement between meanders s_i, $i = 1, \dots, c$.

The antenna is discretized into regular quasiregular triangles and analyzed using a method of moments with a voltage gap feed which considers $\delta = 0$. The implementation was validated with classical antenna simulation software.

The parameters other than δ compose the design variables

$$x = \begin{bmatrix} w \\ b \\ a_1 \\ \vdots \\ a_c \\ s_1 \\ \vdots \\ s_c \end{bmatrix} \quad (1)$$

and can be used to optimize the antenna to desired profiles.

4. Optimization Problem

A meander-line antenna cannot provide high directivity. This is a desired behavior considering that isotropic radiation

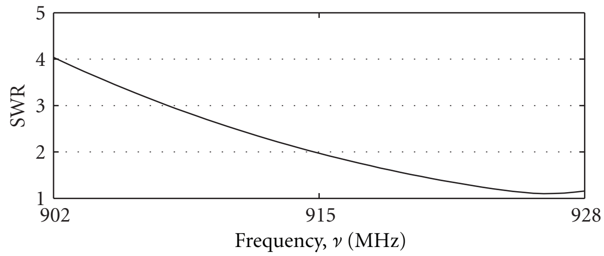

Figure 2: Optimal standing wave ratio behavior inside frequency range for multiobjective formulation.

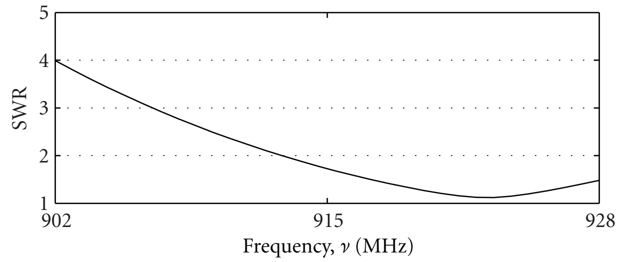

Figure 3: Optimal standing wave ratio behavior inside frequency range for worst case formulation.

would not be ideal for the application. The remaining features of interest are input impedance and size, which are used in the multiobjective optimization problem formulation

$$\begin{aligned} &\text{minimize } f(x) = \text{SWR}(x, \nu) \\ &\text{subject to } g(x) = \begin{bmatrix} L_{\min} - L(x) \\ L(x) - L_{\max} \end{bmatrix} \leq 0, \\ &x_{\min} \leq x \leq x_{\max}, \end{aligned} \tag{2}$$

where $x \in \Re^n n$ is the vector of design variables (1), $n = 2+2c$, SWR is the standing wave ratio, L is the antenna length, and $\nu \in \Re^o$ is the vector of sample frequencies. There is one-objective function for each sample frequency, hence, o-objective functions.

The optimization problem (2) queries for antennas with minimum SWR in each sample frequency whose overall length and design variables lie inside an interval.

To optimize the worst case SWR inside the frequency range, the monoobjective optimization problem formulation

$$\begin{aligned} &\text{minimize } f(x, t) = t \\ &\text{subject to } g(x, t) = \begin{bmatrix} \text{SWR}(x, \nu) - t \\ L_{\min} - L(x) \\ L(x) - L_{\max} \end{bmatrix} \leq 0, \\ &x_{\min} \leq x \leq x_{\max}, \end{aligned} \tag{3}$$

can be derived, where t is the worst case SWR.

5. Optimization Results

The optimal variables results of (2) for $c = 4$ and $o = 5$ sample frequencies inside the frequency range are shown in Table 1. The target impedance, frequency range and length constraints are given in Table 2. The length was 71.51 mm and the worst case standing wave ratio (SWR) was 4.04 for the optimal antenna. SWR behavior inside the frequency range is shown in Figure 2. The result took 395 problem oracle queries within 9 iterations of the multiobjective deterministic algorithm with monotonic convergence [14, 15].

In order to compare the two formulations (multiobjective and worst case), the CEDA algorithm was limited to 395 oracle queries to optimize problem (3) for $c = 4$, $o = 5$ and settings in Table 2, whose optimal results are shown in Table 3. The length was 62.67 mm and the worst case standing wave ratio (SWR) was 3.99 for the optimal antenna. SWR behavior inside the frequency range is shown in Figure 3.

6. Overview of the Optimization Algorithm

As mentioned before, the optimization algorithm used in the meander-line antenna design, named henceforth the cone of efficient directions algorithm (CEDA) [14], is supported by guarantees on monotonic convergence. Its fundamental idea comes from the cone of efficient directions, that is, the set of directions where there exists at least one infinitesimal step that decreases all objective functions at the same time. When the oracle query point is infeasible, the constraints are treated as objectives. Given an efficient direction, a line search algorithm with guarantees on feasibility preserving and strict improvement of starting point takes place. A brief overview is shown next. For further details, please refer to the original paper [14].

6.1. Search Direction. If a point is not a local optimum, then there must be a better feasible neighbor point, by definition. If a function $f : \Re^n \mapsto \Re$ is differentiable, then its local behavior is mainly linear by Taylor series, that is,

$$f(x) \approx \tilde{f}(x) = f(x_k) + \nabla^T f(x_k)(x - x_k), \tag{4}$$

here x_k is the oracle query point at iteration k and $\nabla f : \Re^n \mapsto \Re^n$ denotes the gradient of f. Hence, $f(x) < f(x_k)$ whenever $\nabla^T f(x_k)(x - x_k) < 0$ within some neighborhood of x_k. Considering a nonnull step $\alpha > 0$ from x_k towards a direction d_k, that is,

$$x_{k+1} = x_k + \alpha d_k, \tag{5}$$

leads to $\nabla^T f(x_k) d_k < 0$.

Consider a differentiable multiobjective optimization problem in the form

$$\begin{aligned} &\text{minimize } f(x) \\ &\text{subject to } g(x) < 0, \\ &x_{\min} \leq x \leq x_{\max}. \end{aligned} \tag{6}$$

When the oracle query point x_k is feasible (i.e., $g(x_k) \leq 0$), it is desirable to minimize the objective functions in order to get better feasible points. Otherwise, it is desirable

Table 1: Optimization problem variables for multiobjective formulation.

	Parameter (mm)									
	w	b	a_1	a_2	a_3	A_4	s_1	s_2	s_3	s_4
Max	0.50	12.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Min	0.80	21.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
Opt	0.78	15.11	4.70	3.98	6.42	5.66	3.80	1.42	6.00	3.77

Table 2: Specifications and optimal antenna profile.

Parameter	Value
L_{min} (mm)	10
L_{max} (mm)	100
V_{min} (MHz)	902
V_{max} (MHz)	928
Zs (Ω)	27.4–200.9i

to minimize the violated constraint functions (without violating new ones) in order to find a feasible point. Hence, the cone of efficient directions for constrained multiobjective problems in the form (6) can be defined as

$$d_k : M_k^T d_k > 0, \tag{7}$$

where

$$M_k = \begin{cases} -\left[\nabla f(x_k) \nabla g_{I_k}(x_k)\right], & g(x_k) \leq 0, \\ -\left[\nabla g_{J_k}(x_k) \nabla g_{I_k}(x_k)\right], & \text{otherwise,} \end{cases} \tag{8}$$

where the gradient of a vector function $\nabla f : \Re^n \mapsto \Re^m$ is $\nabla f = [\nabla f_1 \cdots \nabla f_m]$. The set of active I_k and violated J_k constraint functions are given by

$$\begin{aligned} I_k &= \{i \perp g_i(x_k) = 0\}, \\ J_k &= \left\{j \perp g_j(x_k) > 0\right\}. \end{aligned} \tag{9}$$

Considering unit efficient directions, the one opposite to the gradient would be the best choice for the linear approximation of a single-objective function since it provides the greatest decrease per step length. Thus, the intersection between the cone of efficient directions (7) and its dual cone

$$d_k = M_k \lambda, \quad \lambda \geq 0,\ \lambda \neq 0, \tag{10}$$

contains good efficient directions. One of these good efficient directions can be found by the linear problem

$$\begin{aligned} &\text{minimize} - 1^T \lambda \\ &\text{subject to} - M_k^T M_k \lambda \leq o, \\ &0 \leq \lambda \leq 1, \end{aligned} \tag{11}$$

which queries for the search direction $d_k = M_k \lambda^*$ of maximum relative weight λ^* sum. This problem is infeasible or $\lambda = 0$ only when the cone of efficient directions is empty since the intersection between a cone and its dual is empty only when the cone itself is empty.

6.2. Multiobjective Line Search. The multiobjective line search algorithm solves the problem

$$\begin{aligned} &\text{minimize } f(x_k + \alpha d_k) \\ &\text{subject to } g(x_k + \alpha d_k) \leq 0, \\ &0 \leq \alpha \leq \alpha_{\text{max}}, \end{aligned} \tag{12}$$

when $g(x_k) \leq 0$, and

$$\begin{aligned} &\text{minimize } g_{J_k}(x_k + \alpha d_k) \\ &\text{subject to } g_{\bar{J}_k}(x_k + \alpha d_k) \leq 0, \\ &0 \leq \alpha \leq \alpha_{\text{max}}, \end{aligned} \tag{13}$$

otherwise, where $\bar{J}_k$ denotes the set of nonviolated constraints (i.e., complement of J_k).

The maximum step length is given by

$$\alpha_{\text{max}} = \max \alpha : x_{\text{min}} \leq x_k + \alpha d_k \leq x_{\text{max}}, \quad \alpha > 0, \tag{14}$$

which can be easily solved analytically (point where the ray $x_k + \alpha d_k$, $\alpha > 0$ intersects the box $[x_{\text{min}}, x_{\text{max}}]$). If $\alpha^* = \alpha_{\text{max}}$, then the respective activated constraint (design variables bound) is added to the set of active constraints used in the definition of M_{k+1}.

6.3. Stop Criteria. The natural stop criteria for the multiobjective optimization algorithm are when any column of M_k is null, problem (11) is infeasible, $d_k = 0$, or $\alpha^* = 0$.

6.4. Theoretical Guarantees. When $g(x_k) \leq 0$ and no stop criteria are met, it is easy to verify that the conditions

$$\begin{aligned} f(x_k + \alpha^* d_k) &< f(x_k), \\ g(x_k + \alpha^* d_k) &\leq 0 \end{aligned} \tag{15}$$

hold true, which are the respective monotonic convergence and feasibility preserving guarantees.

7. Optimization Algorithm Suitability

The first notable features of CEDA are its monotonic convergence and feasibility preserving theoretical guarantees. They are also very desired in practice, considering that they lead to robustness against bad-behavior functions and provide better intermediate results during the optimization process.

Another notable feature of CEDA is that the stop criteria are met earlier when the number of objective functions increases. This can be observed in the optimization of the

Table 3: Optimization problem variables for formulation worst case.

	Parameter (mm)									
	w	b	a_1	a_2	a_3	a_4	s_1	s_2	s_3	s_4
Max	0.50	12.60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Min	0.80	21.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
Opt	0.60	15.81	5.95	2.26	3.82	1.94	4.39	3.13	4.25	6.09

meander-line antenna, where minimizing SWR at sample frequencies is faster than minimizing its worst case. This occurs because CEDA treats multiobjective problems as so and the dimension of the Pareto optimal set of a problem is, in nondegenerate cases, the number of objective function minus one. CEDA can be considered an extension of the classical gradient algorithm to multiobjective problems. Indeed, it also presents a slow convergence rate when the functions Hessian matrices are ill conditioned. Second-order directions (e.g., Newton directions) solve this problem for monoobjective and also multiobjective problems [16]. Nevertheless, the CEDA performance in this work was satisfactory. More examples of multiobjective antenna optimization can be found in [17] where satellite antennas and bow tie antennas for ground penetrating radar are studied.

8. Conclusion

The best SWR of about 1 was verified inside a frequency range of ±1.4% around 915 MHz for optimal 4-meander antennas, even though with a worst case SWR of about 4. More degrees of freedom could be considered in order to improve worst cases (e.g., increasing the number of meanders or parameterizing each meander height individually). Nevertheless, the main purpose of this paper was achieved: optimal meander-line antennas for a real-life demand using different formulations.

The multiobjective formulation is faster to converge than the single-objective one. Furthermore, the theoretical guarantee of always improving all objective functions after each iteration may be very suitable in real-world applications. However, considering that SWRs of 1 and 40 at sample frequencies could be considered Pareto optimal for the former formulation, the solution of the worst case formulation may be regarded more meaningful, that is, a good decision rule, even though it is either dominated or included in the optimal Pareto set.

Acknowledgments

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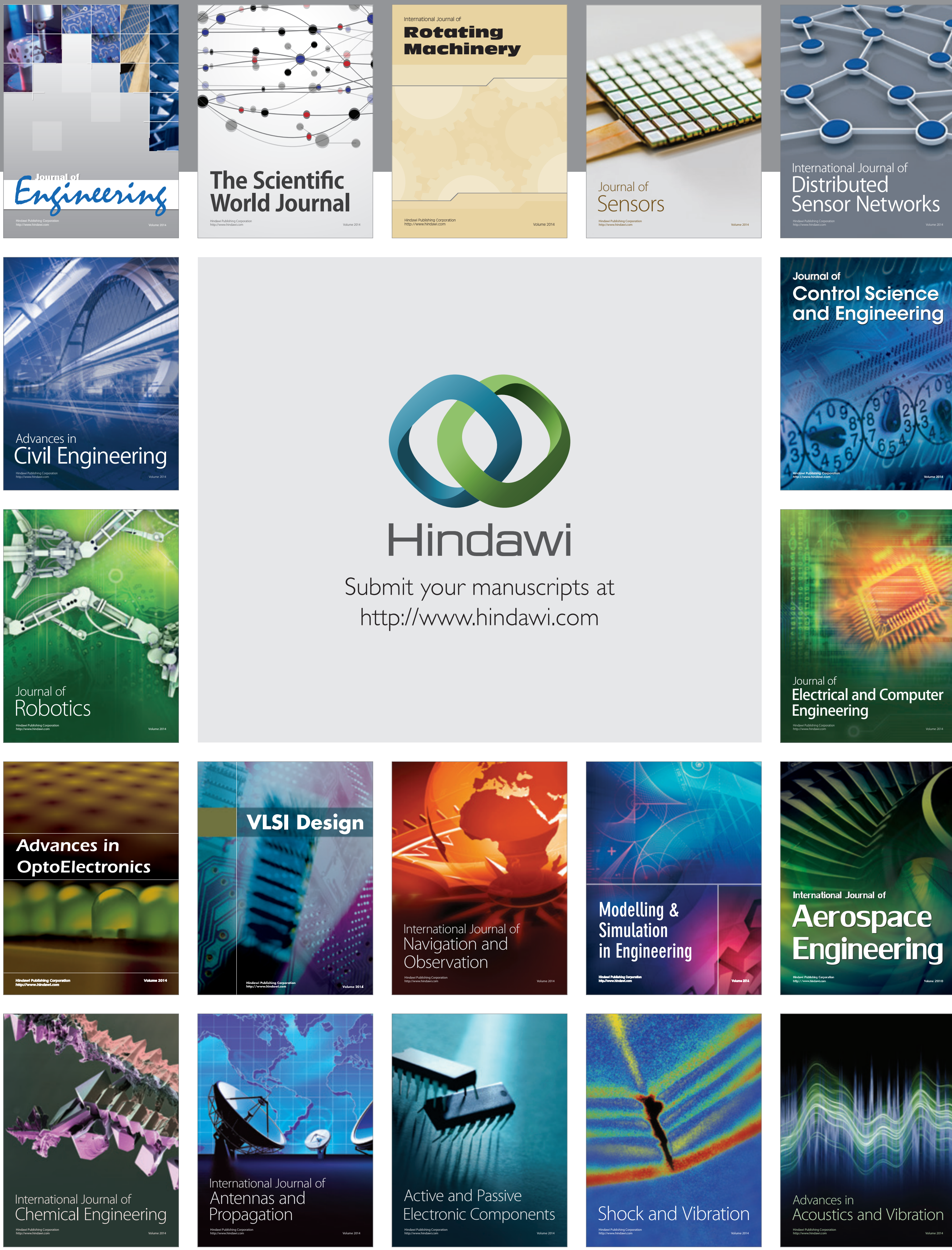
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