Patch Antenna Design with Improved Sequential Quadratic Programming for Automotive Applications

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***Abstract*—This paper proposes a novel methodology to automate the design process of patch antennas using Improved Sequential Quadratic Programming (ISQP). Patch antennas are widely used in the automotive domain and are a key enabler of car-to-car and car-to-infrastructure communication. Although simulation tools have been improved in term of accuracy, a manual design process still takes a lot of time as well as computational efforts and relies to a large extent on human experience. In this paper, a fully automatic approach is presented and two major challenges are solved inherently. First, the conversion of a multi-objective problem into a single-objective problem is performed appropriately such that can be handled by classic Sequential Quadratic Programming (SQP). Second, the problem of being trapped in local optima is solved by a sophisticated exploration of the search space. Compared to other automation methods, our proposed methodology is fast, produces excellent results, needs limited computational efforts, no longer requires relevant domain knowledge, and is applicable to other types of antenna design. Experimental results of a truncated patch antenna with circular polarization are presented, achieving a good design point within 1470 seconds.**

***Index Terms*—Sequential Quadratic Programming, design automation, multi-objective, patch antenna.**

I. Introduction

The past decade has seen a drastic development of wireless communication. As a result, many antennas with outstanding characteristics have been proposed. Some examples are presented in [1], [2], and [3]. Automotive radar applications with patch antennas are reported by [4]. The work in [5] presents the dedicated short range communication of vehicles with patch antennas at low frequency. Among all types of antennas, patch antennas have received special attention in automotive industry for car-to-car and car-to-infrastructure communication because of their natural advantages of low profile, low cost and ease of integration and fabrication. This novel form of communication between cars and the infrastructure will allow a more sophisticated route planning and transportation. However, together with excellence in performance and its applications come huge design efforts. Although there has been large improvements using simulation tools, the design automation of patch antennas has not been addressed effectively.

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Automation and optimization are applied in almost every field of science and engineering, see [6]. So even small methodology improvements might lead to large achievements in practice. Design automation of antenna design is difficult in term of complexity.

Contributions of the paper: This paper presents a novel method for the design automation of patch antennas using Sequential Quadratic Programming (SQP). SQP is a method for solving complex optimization problems with significant non-linearity. However, there are two challenges when applying SQP in antenna design. First, SQP is only able to handle single-objective problems but in antenna design there are inherently multiple conflicting objectives such as return loss, gain, and axial ratio. Thus, it is necessary to propose a sophisticated approach to convert the multi-objective problem into the single-objective problem. Second, SQP does not guarantee globally optimal solutions. Thus, it becomes necessary to avoid local optima that do not satisfy the optimization goal. Our proposed methodology based on SQP addresses these two challenges by providing appropriate solutions. The design process is automated thoroughly, requiring significantly less time and computational efforts, little or even no background and experience, and produces excellent results compared to other existing approaches such as [7] and [8]. Moreover, it is also applicable to other types of antenna design. Experimental results of a sample truncated patch antenna with circular polarization are presented. Within a runtime of 1470 seconds a good design point is obtained. This proves the efficacy and efficiency of our proposed method that is especially helpful for the design of complex antennas.

Organization of the paper: The remainder of the paper is organized as follows. Section II describes the proposed methodology and SQP with the proposed improvements. Section III formulates the example problem of a truncated patch antenna with circular polarization. Experimental results are presented in Section IV before the paper is concluded in Section V.

II. Improved Sequential Quadratic Programming

SQP is an iterative method to solve non-linear optimization problems where a global perspective on the objective function f is not available. Often the determination of f at a point

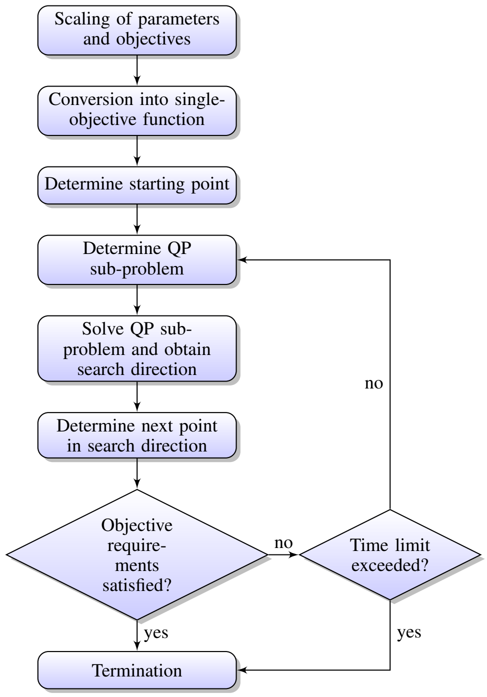

Fig. 1. Illustration of the SQP optimization flow.

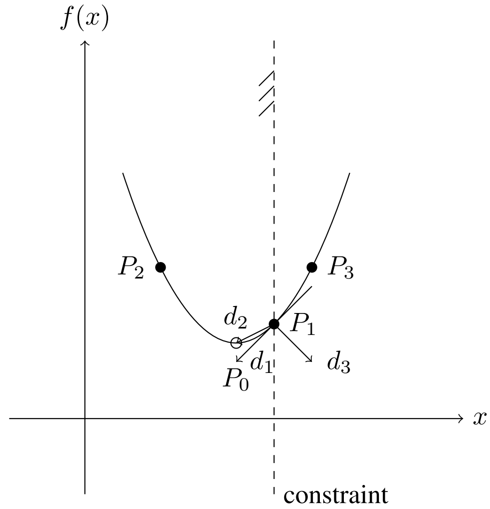

Fig. 2. Illustration of the determination of the search direction.

x is expensive such that algorithms that do not require a high number of objective function evaluations are usually preferred, see [9]. This exactly applies for antenna design because the accurate relationship between design parameters and performances is unknown and simulations are indeed expensive.

SQP is illustrated in Figure 1. Initially, the parameters and objectives are scaled appropriately and converted to a single-objective function. A starting point within the constraints is determined. From this point, a quadratic model and Quadratic Programming (QP) sub-problem are determined to obtain a search direction. With the search direction, a new point is determined. If the objective requirements are satisfied or the time limit is exceeded, the optimization is aborted. Otherwise, the optimization is continued with the new point.

Scaling of parameters and objectives: The first step of the whole process is to scale all the parameters and the objectives. If an objective in the range of 0 to 100 is put together with another objective ranging from 0 to 10000, the first objective will almost be ignored. This is not correct because significance should be given to those objectives which are more important in the context of the design rather than those which can reach a larger value. So all the parameters and objectives need to be scaled appropriately to the same level.

Conversion into single-objective function: Since SQP only solves single-objective problems, we need to convert the multiple objectives of the antenna design into one single objective. Here, the method of weighted sum with dynamic weighting factors is applied. In general, the weighting factors are static, which means that once they are chosen, they never change. Different performances are assigned with different factors and then summed up. However, when it comes to the situation that the importance of each performance varies with the optimization process, dynamic factors reflecting real-time status give us much better results. When a performance becomes more important, it is assigned with a larger factor, otherwise a smaller factor. For example, return loss is usually required to be lower than -10 dB. So it has a larger factor when higher than -10 dB and a smaller factor when lower than -10 dB, which means that if the current value has satisfied the requirement, it becomes less important. More details are given in Section III.

Determine starting point: Following the scaling and conversion, a starting point is randomly chosen within the boundary of constraints. This can be either done manually with domain knowledge or by solving the constraints of the problem.

Determine QP sub-problem:

SQP is an iterative process, which searches for appropriate design points until a suitable one is found. The determination of the search direction for the next point is illustrated in Figure 2 that shows a simplified one-dimensional optimization problem. In this case, x is the only parameter and $f(x)$ is the only objective to be minimized. The entire function which is the relationship between x and $f(x)$ is unknown.

Imagine that the current point is P_1, then the goal is to find the next point that had better be closer to the optimum. First of all, we need the information of the other two points of P_2 and P_3 around P_1, then we have a quadratic model that can be used to approximate the real function. The quadratic model is defined as follows:

$$\min_{\mathbf{x}} q(\mathbf{x}) = \frac{1}{2}\mathbf{x}^T\mathbf{H}\mathbf{x} + \mathbf{x}^T\mathbf{d} \tag{1}$$

subject to

$$\mathbf{a}_i^T\mathbf{x} = b_i, \quad i \in \mathcal{E}, \tag{2}$$

$$\mathbf{a}_i^T\mathbf{x} \geq b_i, \quad i \in \mathcal{I}, \tag{3}$$

where $\mathbf{H}$ is the symmetric $n \times n$ Hessian matrix at a specific point, $\mathcal{E}$ and $\mathcal{I}$ are finite sets of constraints, and $\mathbf{d}$, $\mathbf{x}$, and $\{a_i\}$, $i \in \mathcal{E} \bigcup \mathcal{I}$, are vectors with n elements, representing the gradient, the search direction, and constraints, respectively.

Solve QP sub-problem and obtain search direction: Solving the QP determines the search direction. There are several ways to decide the search direction as illustrated in Figure 2. One choice is d_1 that is the steepest descent at P_1 opposite to the gradient. Another choice is d_2 which points to the minimum point of this quadratic model, but not necessarily that of the real function. Both of these methods have no consideration of the constraints. If there is a constraint as shown in Figure 2, both d_1 and d_2 are inappropriate decisions, pointing to the space violating constraints. In our case, we solve the QP problem to get the direction d_3 which points to the direction of descend and avoids violating constraints at the same time.

Determine next point in search direction:

After we have the search direction, the next thing to decide is the step length. A simple way is to set the step length to be 1. Then we evaluate the next point in the design space. If the function value is better than the requirement, then the algorithm terminates, otherwise it keeps searching for the next point until the time limit is reached, see Figure 1.

One major pitfall of SQP is that it might easily get into local optima. To overcome this drawback, we change the process of choosing the step length in order to enable the methodology to avoid locally optimal points. This is done by choosing different step length as proposed in Algorithm 1. f_c represents the expected value of the objective and T is a set to store all tested step length. Whenever we have a new value of x, all the choices of step length with different values of y are tested and compared. The best one is picked up. If it is better than the requirement, the algorithm terminates and the corresponding step length is chosen, otherwise we increase the value of x. In this paper, we set $n = 3$, which means that if no value is better than f_c after all the cases have been tested up to $x = 3$, the algorithm terminates and the best step length that was found within the search process will be chosen.

Input: f_c $f_{best} = \infty$ $T = \{\}$
Output: α

for $x \in \{0, 1, ..., n\}$ **do**
  for $y \in \{1, 2, ..., 2^x\}$ **do**
    if $\frac{y}{2^x} \notin T \wedge f(\alpha = \frac{y}{2^x}) < f_{best}$ **then**
      $f_{best} = f(\alpha = \frac{y}{2^x})$
      $\alpha_{best} = \frac{y}{2^x}$
    end
    $T = T \cup \{\frac{y}{2^x}\}$
  end
  if $f_{best} < f_c$ **then**
    $\alpha = \alpha_{best}$
    break
  end
end
Return $\alpha = \alpha_{best}$

Algorithm 1: Algorithm to determine the step length.

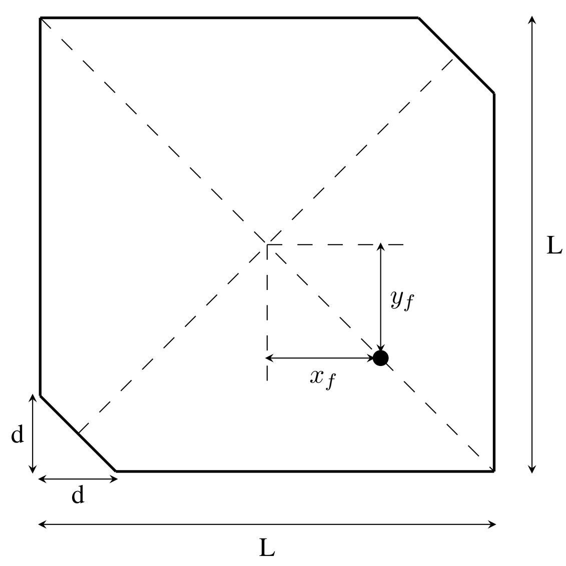

Fig. 3. Illustration of the dimensions and parameters of the patch antenna.

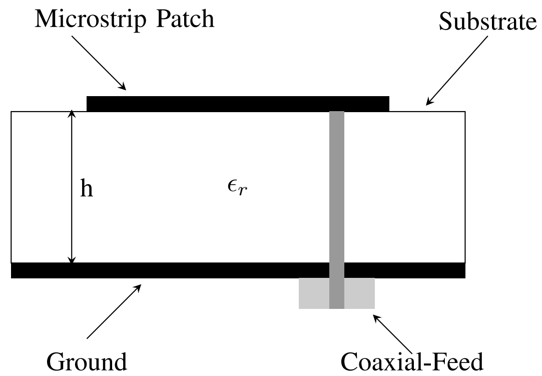

Fig. 4. Illustration of the patch structure.

III. Problem Formulation

The example investigated in this paper is a truncated patch antenna with circular polarization for car-to-car and car-to-infrastructure applications. The dimensions and structure of the patch antenna are illustrated in Figure 3 and Figure 4.

As illustrated in Figure 3, three parameters are defined to be x_f and y_f for the coordinates of the feeding point and d for the side length of the truncated isosceles triangle. Three performance objectives are identified to be f_0, f_1, and f_2 for return loss, axial ratio and gain, respectively. These objectives are all obtained from simulation using HFSS [10], a simulation tool for 3D full-wave electromagnetic field simulation. The side length of the square patch is fixed to be 31.6 mm.

TABLE I
EXPERIMENTAL RESULTS

Iteration	x_f	y_f	d	f_0	f_1	f_2	f	c0	c1	c2	c3	c4	c5	Direction	Step
1	1	5	5	-5.81	7.89	4.74	9.665	16.8	14.8	20.8	10.8	5	26.6	(-1,-1,-3)	1
2	0.7	4.7	4.1	-6.49	6.31	4.78	6.68	16.5	15.1	20.5	11.1	4.1	27.5	(-1.5,1,-3.5)	1
3	0.32	4.95	3.21	-9.09	5.31	4.75	3.72	16.12	15.48	20.75	10.85	3.21	28.39	(-1,1.4,-2.8)	0.5
4	0.1	5.25	2.61	-11.04	5.73	4.79	3.7453	15.9	15.7	21.05	10.55	2.61	28.99	(-1,-2.5,1.9)	0.125
5	-0.01	4.98	2.81	-10.63	1.89	4.77	-1.456	15.79	15.81	20.78	10.82	2.81	28.79	N.A.	N.A.

Thresholds of return loss, axial ratio, and gain are set to -10 dB, 3 dB and 3 dB as usually demanded. The weighting factors for return loss and axial ratio are 2 and 5, when the requirement is met or not respectively and the weighting factor of gain is 1. This results in the actual objective f_{0s}, f_{1s}, and f_{2s}. A sample algorithm for scaling and weighting of return loss is shown in Algorithm 2:

Input: f_0
Output: f_{0s}

if $f_0 > -10$ **then**
  $f_{0s} = \frac{(f_0-(-10))}{10} \times 5$
else
  $f_{0s} = \frac{(f_0-(-10))}{10} \times 2$
end

Algorithm 2: Sample algorithm of scaling and weighting of return loss.

The resulting single objective f is defined as follows:

$$f = f_{0s} + f_{1s} + f_{2s}. \tag{4}$$

The optimization problem is formulated as follows:

$$\min_{x_f,y_f,d} f, \tag{5}$$

subject to

$$c1 = x_f + 15.8 \geq 0, \tag{6}$$

$$c2 = -x_f + 15.8 \geq 0, \tag{7}$$

$$c3 = y_f + 15.8 \geq 0, \tag{8}$$

$$c4 = -y_f + 15.8 \geq 0, \tag{9}$$

$$c5 = d \geq 0, \tag{10}$$

$$c6 = -d + 31.6 \geq 0. \tag{11}$$

IV. EXPERIMENTAL RESULTS

The algorithm is implemented in MATLAB using HFSS 13 [10] for the simulation. For the presented case study, the runtime was 1470 seconds. Almost all the time consumption results from simulation in HFSS. In the case with three parameters, information of 10 points is needed to build up the complete quadratic model for approximation. Four models have been built up to Iteration 5, which require 40 rounds of simulation. Five rounds of simulation are run due to the process of choosing step length and one last round of simulation achieves the final design point. Experimental results are shown in Table 1. It can be seen that the constraints are respected and that the trend of the function value f is improving. Slight deterioration of the funciton value from iteration 3 to iteration 4 can be seen, corresponding to our relaxation concept to avoid locally optimal points. After five iterations and 46 rounds of simulation, the antenna with the return loss of -10.63 dB, the axial ratio of 1.89 dB, and the gain of 4.77 dB at 2.48 GHz is obtained.

V. CONCLUSION

This paper proposes a novel methodology to automate patch antenna design. The method is based on ISQP and addresses two challenges of conversion from a multi-objective problem into a single-objective problem and avoidance of being trapped in locally optimal points. Experimental results of a sample truncated patch antenna with circular polarization prove that the proposed methodology works effectively and efficiently.

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