Design of a Crooked-Wire Antenna by Differential Evolution and 3D Printing

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ABSTRACT

Antenna design often requires dealing with multiple constraints in the requirements, and the designs can be modeled as constrained optimization problems (COPs). However, the constraints are usually very strange, and then the feasible solutions are hard to find. At the same time, the robustness for antenna design is an important consideration as well. To solve the above issues, the combination of differential evolution algorithm (DE) and 3D-printing technique is presented to design a new crooked-wire antenna. In the design process, DE is adopted to handle the constraints since DE is simple and efficient in finding feasible solutions. The objective of the modeled COP, which is the sum of variance of the gain, axial ratio, and VSWR over the frequency band, is used to enhance the robustness of the antenna and widen the frequency band without additional computational cost. The precision of fabricating the antenna is ensured by using 3D-printing. The design of the NASA LADEE satellite antenna is chosen as an example to verify the method of this paper. Experimental results show that the performance of the evolved antenna meets the design requirements.

KEYWORDS

Constrained Optimization Problem, Differential Evolution Algorithm, Small Satellite Antenna

INTRODUCTION

A great increase of computational resources to deal with science and engineering problems has happened in the last thirty years. The progress has led to the rapidly development of many advanced numerical algorithms (Arianos et al., 2012). As a kind of the global optimization search method, evolutionary computation methods have been widely applied in the variety of fields, such as Artificial Intelligence (Wang, 2015; Thabit, 2019), engineering (Bilbao, 2015; Yu, 2019), bioinformatics (Pei, Zhou, Chen, Liu, &Wang, 2015), economics (Kim, 2015; Miralles-Pechuán, 2018), and so on. In addition, the further improvement in computational power for the future will strengthen the role of efficient numerical methods for handing complex problems, especially the nonlinear optimization problem.

Since the early 1990s, evolutionary optimization methods had been widely applied to electromagnetics (Weile & Michielssen, 1997). With the development of artificial intelligence for

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decades, evolutionary algorithms (EAs) such as genetic algorithms (GAs) (Altshuler, 1997; Rogers, 2002; Kerkhoff, 2007), differential evolutions (DEs) (Zheng, 2017; Goudos, 2017), particle swarm optimizations (PSOs) (Jarufe, 2018; Wu, 2019), evolution strategies (ESs) (BouDaher & Hoorfar, 2015), and other evolutionary optimization techniques, are widely employed to deal with antenna design problems. Wire antenna designs were optimized by using GAs in papers (Altshuler, 1997; Smith, 2019). A quadrifilar helical antenna was designed in (Lohn, Kraus & Linden, 2002) where a co-evolutionary GA was applied to optimize the gain and size of the quadrifilar helical antenna. The group further designed an X-Band antennas for NASA's Space Technology 5 Mission (Hornby, Lohn & Linden, 2011). In this research, two EAs were used: the first used a vector of real-valued parameters and the second used a tree-structured generative representation for constructing the antenna, and experimental results show that the proposed method is effective. In paper (Yang &Adams, 2016), a systematic method was presented to the shape optimization of compact, single-aperture MIMO antennas based on characteristic modes and GA. A new approach of controlling antenna radiation power pattern were introduced based on both GA and newly technology 3-D printing of special dielectric materials (Wu, Abdelrahman, Liang, Yu, & Xin, 2017). Dynamic and multi-objective techniques are integrated into EAs to deal with antenna array problems with many local optima (Jiao, Zeng, Alkasassbeh, & Li, 2017). The paper (Ma, Yang, Chen, Qu, & Hu, 2019) proposed an effective optimization approach for the pattern synthesis of 4-D irregular arrays based on the maximum-entropy model and DE. The above researches all deal with the two challenges. The feasible solutions of antenna design problem are hard to be found, because the design constraints are very strange. In addition, the precision of fabricating the antenna maybe can not guarantee. However, the outcomes were very satisfactorily.

To overcome the difficulties of multiple design constraints and the precision of fabricating for the antenna design, the combination of DE and 3D printing would be used to obtained the antenna which meets the needs of design requirements. Based on our previous work (Ye et al., 2017), a crooked wire antenna is designed in this paper. The wire antenna design is modeled as a COP. The geometric structure of the antenna is mainly composed of a crooked wire for radiation, a coaxial feed line and a metal cup for reflection. The constraints are handled by using DE (Storn & Price, 1997). The fitness of the antenna during the design process is simulated and evaluated with Ansoft HFSS. The robustness of the antenna is enhanced by constructing the objective as the sum of variance of the gain, axial ratio, and VSWR over the frequency band (Hu et al., 2019). The precision of fabricating the antenna is increased by using 3D-printing. The NASA LADEE antenna (Lohn, Linden, Blevins, Greenling, &Allard, 2015) is chosen as an example to verify the method of this paper. The performance parameter of the fabricated antenna such as antenna gain is measurand and compared with the results of the simulated antenna by Ansoft HFSS. The experiment results show that the optimal crooked wire antenna by the proposed method in this work satisfies the needs of design requirements.

After Section 1, the remaining of this paper is organized as follows: The related work about the way to the model of the COP for the antenna design and the DE algorithm is formulated in Section 2. The detail of the modeled COP for the wire antenna design is presented in Section 3, which includes antenna design requirements, antenna structure, objective function, and constrained function. Then, the COP for the wire antenna design is deal with by the proposed DE, and the optimal wire antenna is fabricated by using 3D-printing next. Simulated results are compared with the referred literature, and the differences between them are analyzed and discussed in Section 4. Finally, the summaries of this paper are drawn in Section 5.

RELATED WORK

Antenna design often needs to meet multiple constraints from design requirements. Therefore, antenna design problems are usually modeled as COPs, and then DEs are used to find the global optimal solution. In this section, a formulation of the COP and a DE for antenna design will be introduced.

Constrained Optimization Problem (COP)

Without loss of generality, the COP usually has an objective function, some constraints, and a suitable search space. The COP can be written as in Equation (1).

$$\begin{aligned} &\min \ \ y = f\left(\vec{x}\right) \\ &st \ \vec{g}\left(\vec{x}\right) = \left(g_1\left(\vec{x}\right), g_2\left(\vec{x}\right), \ldots, g_m\left(\vec{x}\right)\right) \leq \vec{0} \\ &where \ \vec{x} = \left(x_1, x_2, \ldots, x_n\right) \in X \\ &\qquad X = \left\{\vec{x} \middle| \vec{l} \leq \vec{x} \leq \vec{u}\right\} \\ &\qquad \vec{l} = \left(l_1, l_2, \ldots, l_n\right), \vec{u} = \left(u_1, u_2, \ldots, u_n\right) \end{aligned} \tag{1}$$

where $f\left(\vec{x}\right)$ is the objective function, $\vec{g}\left(\vec{x}\right)$ are the vector of the constraints, $\vec{x}$ is antenna design variables, X is the solution space, $\vec{l}$ and $\vec{u}$ are the lower and upper boundary of the solution space, *n* is the number of antenna design variables, m is the number of the constraints.

For the optimizers convenient to tailor the COP formulation, we normalize the solution space, that is, $X = \left[\vec{0}, \vec{1}\right]$. And $X = \left[\vec{l}, \vec{u}\right]$ is normalized by using transformation in Equation (2).

$$\vec{x} = \frac{\vec{x} - \vec{l}_l}{\vec{u}_l - \vec{l}_l} \tag{2}$$

If there are equality constraints $h\left(\vec{x}\right) = 0$ in the COP, the equality constraints will be converted in the inequality constraints, that is, $\left|h\left(\vec{x}\right)\right| - \varepsilon \leq 0$, ε is very small positive number, such as 0.0001.

If a solution $\vec{x} = \left(x_1, x_2, \ldots, x_n\right) \in X$ satisfies $\vec{x} = \left(x_1, x_2, \ldots, x_n\right) \in X\vec{g}\left(\vec{x}\right) \leq \vec{0}$, it is said to be feasible; otherwise $\vec{x}$ is said to be infeasible. The feasible set S_F consists of all feasible solutions of the COP, as shown in Equation (3).

$$S_F = \left\{\vec{x} : \vec{x} \in X, \vec{g}\left(\vec{x}\right) \leq \vec{0}\right\} \tag{3}$$

The constraint violation value of a constraint $g_i\left(\vec{x}\right)$ is evaluated as in Equation (4).

$$G_i\left(\vec{x}\right) = \max\{g_i\left(\vec{x}\right), 0\}, i = 1, 2, 3, \ldots, m \tag{4}$$

The constraint violation value of a solution $\vec{x}$ for all the constraints is written as in Equation (5).

$$\psi\left(\vec{x}\right) = \frac{1}{m}\sum_{i=1}^{m} \frac{G_i\left(\vec{x}\right)}{\max\limits_{\vec{x}_0 \in P(0)}\left\{G_i\left(\vec{x}_0\right)\right\}} \tag{5}$$

Where $P(0)$ is the initial population in the EA. If there is $\max\{G_i(\vec{x})\} \leq 1, i = 1,2,3,\ldots,m$, defining $\max\{G_i(\vec{x})\} = 1$. Note the constraint violation value defined in Equation (5) is actually a normalized one.

Differential Evolution (DE)

In this paper, the DE algorithm (Storn & Price, 1997) would be applied to deal with the above COP. In paper (Price et al., 2005), many different schemes were provided for DE, in this work, the DE strategy (DE/rand/1/bin) is employed which is presented as follow in *Algorithm1*.

By comparing the objective value and constraint value of one solution, a better solution is obtained. For $\forall \vec{a}, \vec{b} \in X$:

(1) If two solutions are both of feasible, the one which has smaller objective is better;
(2) If one solution is feasible, another is infeasible. Then the feasible solution is better than the infeasible one;
(3) If two solutions are both of infeasible, the one which has smaller constraint violation value is better.

Algorithm 1. differential evolution algorithm

```
Algorithm 1. DE/rand/1/bin
1. Generate the initial population P = {x_1, x_2, ..., x_NP}, NP is the
population size;
2. Evaluate the objective value and constraint values of each
individual in P;
3. while the halting criterion is not satisfied do:
for i=1 to NP do
Select rndomly a ≠ b ≠ c ≠ i
   j_rand = randint(1, n)
for j=1 to n do
  if rndrealj(0,1) < CR or j_rand == j then
     u_ij = x_ai + F*(x_bj − x_cj)
  else
     u_ij = x_ij
  end if
  end for j
  end for i
  for  i=1 to NP do
    Evaluate the offspring u_i
if u_i is better than x_i then x_i is replaced by u_i
  end if
  end for
  end while
4. Output population P = {x_1, x_2, ..., x_NP}.
```

FORMULATING ANTENNA DESIGN AS COP

In the stage of modeling the antenna design problem as a COP, there are three steps, namely the determination of the solution space, the construction of the objective function, and the establishment of constraint functions.

Antenna Requirements

The LADEE antenna (Lohn, Linden, Blevins, Greenling, & Allard, 2015) is used, and the design requirements are shown in Table 1.

Table 1. Antenna requirements.

Parameter	Requirement(s)
Frequency	2200MHz - 2290MHz
Polarization mode	Right-Handed Circular polarization (RHCP)
Input impedance	50 Ohm
VSWR	$\leq$ 2
Gain pattern range	$\geq$ 9 dB, $0^0 \leq \varphi \leq 360^0$, $-20^0 \leq \theta \leq 20^0$
Size	Diameter $\leq$ 229mm, height $\leq$ 127mm

According to the experience of antenna design, each section of wire is neither too short (provisions not smaller than 1/10 of the wavelength) or too long (no longer than half a wavelength), the angle of two adjacent wires cannot be too narrow, otherwise it maybe lead to instability in electromagnetic computing software (angle of not less than 20 degrees), combined with the requirements, evolutionary design requirements to consider the constraints as follows in Table 2.

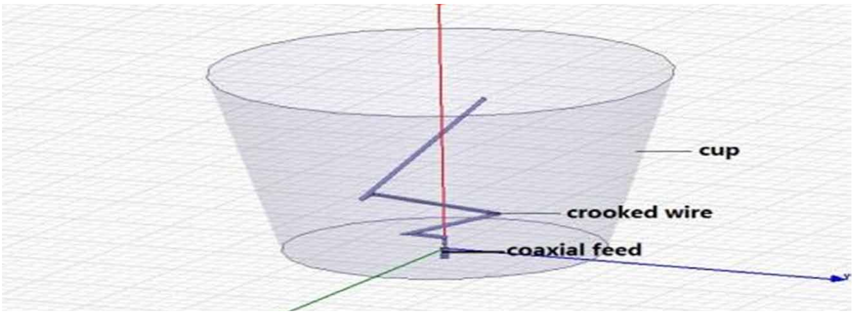
Table 2. Evolutionary Design Requirements to Consider the Constraints

Gain	$\geq$ **9 dB,** $0^0 \leq \varphi \leq 360^0$, $-20^0 \leq \theta \leq 20^0$
Length of each piece of wire (L)	$\lambda / 10 \leq L \leq \lambda / 2$
Adjacent angles	$\alpha \geq 20^0$

Representation of the Antenna Structure

The overall structure of the selected LADEE wire antenna is shown in Figure 1.

Figure 1. LADEE wire antenna optimization model



The LADEE wire antenna is mainly composed of seven crooked wire antenna, coaxial feed, and a metal cup for reflection.

The structure of wire: the crooked-wire consists of seven segments which stays in a cubic with size of 14.0cm * 14.0cm *10.0cm.

To sum up, the solution space of the LADEE wire antenna structure variables is shown in Table 3.

As can be seen from Table 3, the 19 variables determine the geometric structure model of LADEE wire antenna. The solution(x) is shown in Equation (6).

$$\vec{x} = \left(z_0, x_1, y_1, z_1, x_2, y_2, z_2, x_3, y_3, z_3, x_4, y_4, z_4, x_5, y_5, z_5, x_6, y_6, z_6\right) \quad (6)$$

The solution space (X) for the LADEE wire antenna is Equation (7) and Table 3.

$$\begin{aligned} X &= \left\{ \vec{x} \middle| \vec{l} \le \vec{x} \le \vec{u} \right\} \\ \vec{x} &= \left(z_0, x_1, y_1, z_1, x_2, y_2, z_2, x_3, y_3, z_3, x_4, y_4, z_4, x_5, y_5, z_5, x_6, y_6, z_6\right) \\ \vec{l} &= \left(3, -70, -70, 0 - 70, 70, 0, -70, -70, 0, -70, -70, 0, -70, -70, 0, -70, -70, 0\right) \\ \vec{u} &= \left(12, 70, 70, 100, 70, 70, 100, 70, 70, 100, 70, 70, 100, 70, 70, 100, 70, 70, 100\right) \end{aligned} \quad (7)$$

Table 3. the Solution Space of LADEE Wire Antenna Structure Variables.

Parameters	range (mm)
z_0	[3, 12]
x_1	[-70, 70]
y_1	[-70, 70]
z_1	[0, 100]
x_2	[-70, 70]
y_2	[-70, 70]
z_2	[0, 100]

Table 3 continued on next page

Table 3 continued

Parameters	range (mm)
x_3	[-70, 70]
y_3	[-70, 70]
z_3	[0, 100]
x_4	[-70, 70]
y_4	[-70, 70]
z_4	[0, 100]
x_5	[-70, 70]
y_5	[-70, 70]
z_5	[0, 100]
x_6	[-70, 70]
y_6	[-70, 70]
z_6	[0, 100]

OBJECTIVE FUNCTION

According to literature (Hu et al., 2019), the objective function of the modeled COP in this paper is the sum of the variance of the antenna gain, axis ratio, and VSWR over the frequency band, which can increase the robustness of the antenna design. The robustness of the antenna can be enhanced according to the performance characteristics of the antenna optimization design without additional computational cost. The objective function is in Equation (8).

$$f\left(\vec{x}\right) = \sum_{\varphi}\sum_{\theta}\left(GVariance_{\left(\varphi,\theta\right)} + ARVariance_{\left(\varphi,\theta\right)} + VSWRVariance\right) \tag{8}$$

where $\left(\varphi,\theta\right)$ is the location in the space spherical coordinate system, φ and θ are the azimuth and the elevation angles of the space spherical coordinate system, respectively $\varphi\theta\theta$. Over the frequency band, $GVariance_{\left(\varphi,\theta\right)}$ is the gain performance variance of the antenna at $\left(\varphi,\theta\right)$, $ARVariance_{\left(\varphi,\theta\right)}$ is the axial ratio performance variance $\left(\varphi,\theta\right)$, and $VSWRVariance$ is the *VSWR* performance variance.

In this work, the specific variances of gain, axis ratio, and VSWR over the frequency band for antenna performances are calculated as in Equation (9), Equation (10) and Equation (11).

$$\begin{gathered} GVariance_{\left(\varphi,\theta\right)} = \sum_{freq}\left(Gain_{\left(\varphi,\theta,freq\right)} - MeanG_{\left(\varphi,\theta\right)}\right)^2 \\ MeanG_{\left(\varphi,\theta\right)} = \sum_{freq}\frac{Gain_{\left(\varphi,\theta,freq\right)}}{len\left(freq\right)} \end{gathered} \tag{9}$$

$$ARVariance_{(\varphi,\theta)} = \sum_{freq}\left(Axial_{(\varphi,\theta,freq)} - MeanAR_{(\varphi,\theta)}\right)^2$$
$$MeanAR_{(\varphi,\theta)} = \sum_{freq}\frac{Axial_{(\varphi,\theta,freq)}}{len\left(freq\right)} \quad (10)$$

$$VSWRVariance = \sum_{freq}\left(VSWR_{freq} - MeanVSWR\right)^2$$
$$MeanVSWR = \sum_{freq}\frac{VSWR_{freq}}{len\left(freq\right)} \quad (11)$$

where $Gain_{(\varphi,\theta,freq)}$ is antenna gain with a frequency of *freq* at $\left(\varphi,\theta\right)$, $Axial_{(\varphi,\theta,freq)}$ is the axial ratio of the antenna with a frequency of *freq* at $\left(\varphi,\theta\right)$, $VSWR_{freq}$ is the *VSWR* of the antenna with a frequency of *freq* at $\left(\varphi,\theta\right)$. Over the frequency band for the LADEE wire antenna, Len_{freq} is the total number of frequency points, and *freq* is a frequency point.

Constraint Functions

Antenna optimization design usually has multiple constraint requirements. In this paper, the constraints of the LADEE wire antenna design include the antenna gain constraints, the axis ratio constraints, the VSWR constraints, and the geometric size constraints. Combining the Table 1 and Table 2, the details of the constraint functions are established in the following.

The gain constraint functions are in Equation (12).

$$gGain_{(\varphi,\theta,freq)}\left(\vec{x}\right) = 9 - RHCPGain\left(\varphi,\theta,freq\right) \leq 0$$
$$0^o \leq \varphi \leq 360^o, -20^o \leq \theta \leq 20^o, 2200MHz \leq freq \leq 2290MHz \quad (12)$$

The axis ratio constraint functions are in Equation (13).

$$gAxial_{(\varphi,\theta,freq)}\left(\vec{x}\right) = 6 - Axial_{(\varphi,\theta,freq)} \leq 0$$
$$0^o \leq \varphi \leq 360^o, -20^o \leq \theta \leq 20^o, 2200MHz \leq freq \leq 2290MHz \quad (13)$$

The VSWR constraint functions are in Equation (14).
(14)

Before constructing the geometric size constraint functions, we firstly denote the ends of the seven segments of the crooked-wire as O (0, 0, 0), $A_0\left(0,0,z_0\right)$, $A_1\left(x_1,y_1,z_1\right)$, $A_2\left(x_2,y_2,z_2\right)$, $A_3\left(x_3,y_3,z_3\right)$, $A_4\left(x_4,y_4,z_4\right)$, $A_5\left(x_5,y_5,z_5\right)$, $A_6\left(x_6,y_6,z_6\right)$ respectively. Next we construct the geometric size constraint functions as in Equation (15).

$$
\begin{aligned}
gGeoUpper_{i}\left(\vec{x}\right) &= \left|A_{i-1}A_{i}\right| - \frac{\lambda}{2} \leq 0 \qquad 1 \leq i \leq 6 \\
gGeoLower_{i}\left(\vec{x}\right) &= \frac{\lambda}{10} - \left|A_{i-1}A_{i}\right| \leq 0 \qquad 1 \leq i \leq 6 \\
gGeoAngle_{i}\left(\vec{x}\right) &= 20^{o} - \angle A_{i-1}A_{i}A_{i+1} \leq 0 \quad 1 \leq i \leq 5
\end{aligned}
\tag{15}
$$

Constrained Optimization Problem

Then a COP is formulated for the LADEE wire antenna design as in Equation (16).

$$
\begin{aligned}
&\min f\left(\vec{x}\right) = \sum_{\varphi=0^{\circ}}^{360^{\circ}} \sum_{\varphi=-20^{\circ}}^{20^{\circ}} \left(GVariance_{\left(\varphi,\theta\right)} + ARVariance_{\left(\varphi,\theta\right)}\right) + VSWRVariance \\
&st. \\
&\qquad gGain_{\left(\varphi,\theta,freq\right)}\left(\overrightarrow{x}\right) = 9 - RHCPGain\left(\varphi,\theta,freq\right) \leq 0 \\
&0^{\circ} \leq \varphi \leq 360^{\circ}, -20^{\circ} \leq \theta \leq 20^{\circ}, 2200MHz \leq freq \leq 2290MHz \\
&\qquad gAxial_{\left(\varphi,\theta,freq\right)}\left(\overrightarrow{x}\right) = 6 - Axial\left(\varphi,\theta,freq\right) \leq 0 \\
&0^{\circ} \leq \varphi \leq 360^{\circ}, -20^{\circ} \leq \theta \leq 20^{\circ}, 2200MHz \leq freq \leq 2290MHz \\
&gVSWR_{freq}\left(\overrightarrow{x}\right) = VSWR_{freq} - 2 \leq 0 \\
&2200MHz \leq freq \leq 2290MHz \\
&gGeoUpper_{i}\left(\overrightarrow{x}\right) = \left|A_{i} -_{1} A_{i}\right| - \frac{\lambda}{2} \leq 0 \qquad 1 \leq i \leq 6 \\
&gGeoLower_{i}\left(\overrightarrow{x}\right) = \frac{\lambda}{10} - \left|A_{i} -_{1} A_{i}\right| \leq 0 \qquad 1 \leq i \leq 6 \\
&gGeoAngle_{i}\left(\overrightarrow{x}\right) = 20^{\circ} - \angle A_{i} -_{1} A_{i}A_{i} + 1 \qquad 1 \leq i \leq 5
\end{aligned}
\tag{16}
$$

In next section, the DE is applied to deal with the modeled COP for the design of the LADEE wire antenna, and the corresponding results would be shown.

SOLVING ANTENNA DESIGN BY DE

Setting DE Parameters

Using DE to deal with the LADEE wire antenna, the parameters are set in the following

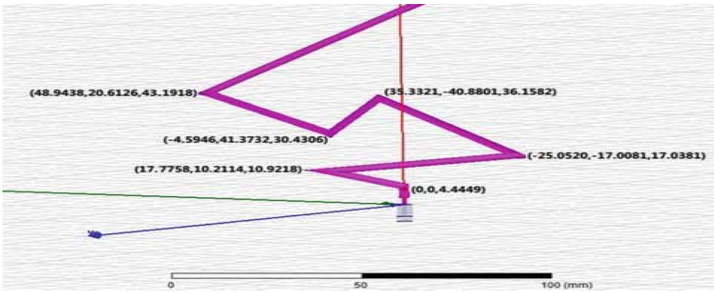
(1) Generations: T = 1000;
(2) Population size: NP = 50;
(3) Scale factor: F= 0.5;
(4) Crossover rate: CR = 0.9.

Results and Discussion

The optimal solution of antenna structure variables $\vec{x}_{opt}$ obtained by the DE algorithm is in the following

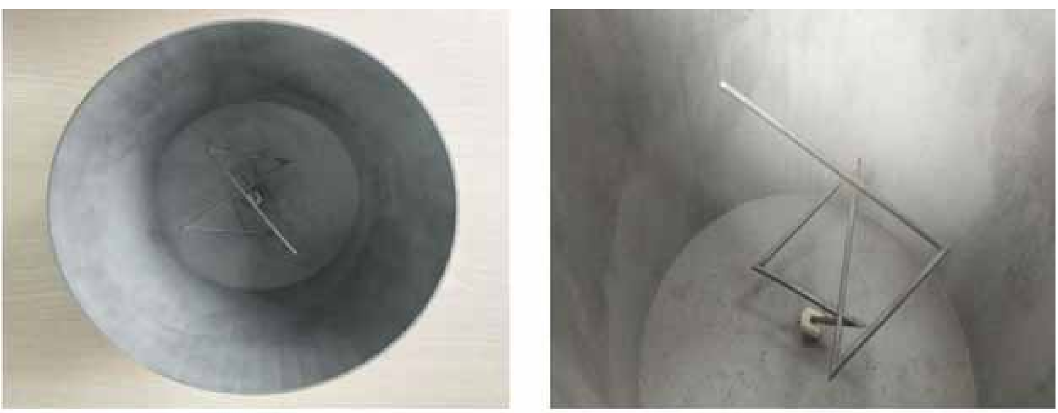
The simulated wire-structure is shown in Figure 2. The optimal solution $\vec{x}_{opt}$ satisfies all the constraints in Equation (16).

Figure 2. Prototype of the evolved antenna



As shown in Figure 2, the antenna structure is strange and very hard to fabricate by hand. To handle the fabrication difficulty, we fabricated the wire antenna by using 3D-printing technique since the 3D-printing nowadays is cheap enough to fabricate the strange antenna. The 3D-printed antenna is shown in Figure 3. The result have little different about axial ratio and gain at all angles of φ , so we choose the case of $\varphi = 0^0$ to show the results.

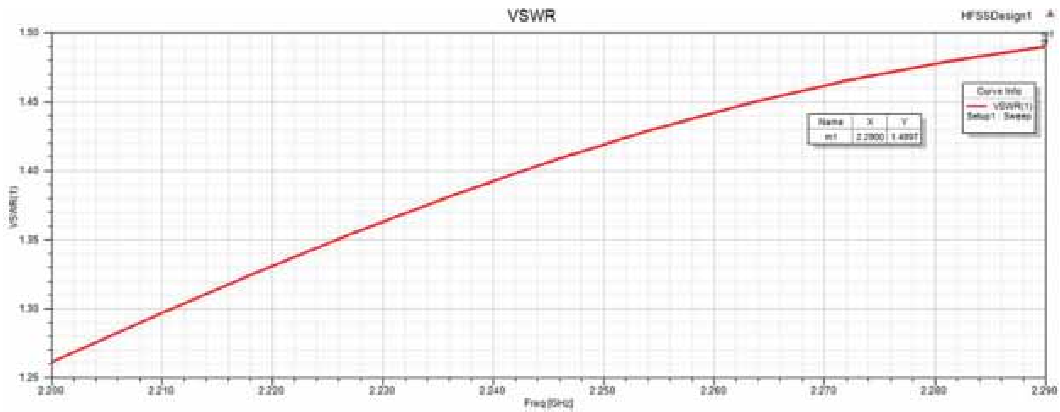
Figure 3. 3D-printed prototype of the evolved antenna



(a) (b)

Figure 4 shows the VSWR of the obtained wire antenna in the frequency range. As can be seen from the Figure 4, the maximum of VSWR is 1.48 in the range of 2200MHz-2290MHz, much smaller than 2.0, which satisfies the needs of the design requirements for the wire antenna.

Figure 4. The VSWR of the obtained antenna ranges of 2200MHz-2290 MHz



The simulated axial ratio of all angles (φ) is shown in Figure 5. The result of measurements and simulations at $\varphi = 0^0$ can be seen in Figure 6, which show that the axial ratio of antenna prototype also matched with simulation. And the measurements are also basically the same as 6.6dB presented in the references (Lohn et al., 2015). Some of the data are about 10dB near $\theta = -20^0$ or 20^0 .

Figure 5. The axial ratio of evolved antenna at the frequency point of 2245 MHz

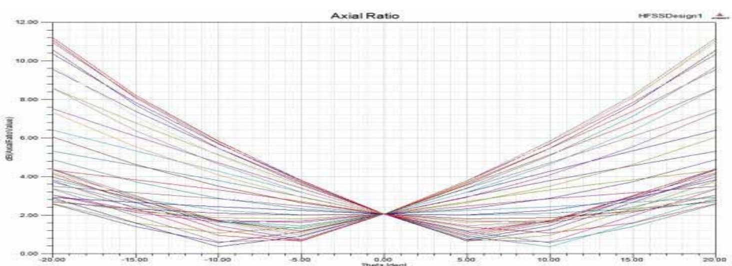
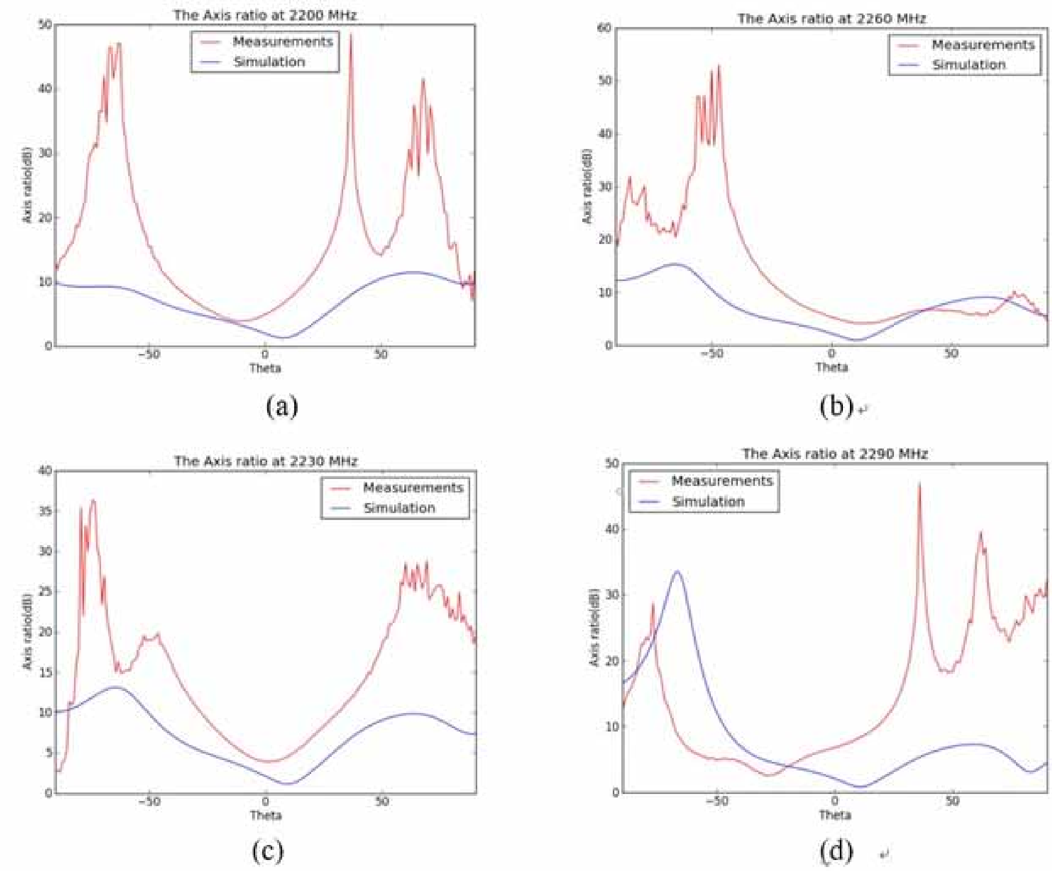


Figure 6. The axial ratio of the evolved antenna for $\varphi = 0^0$



The simulated RHCP gain for the evolved wire antenna at the central frequency point of the 2245 MHz is illustrated in Figure 7. In the antenna radiation range $-20^0 \leq \theta \leq 20^0$, $0^0 \leq \varphi \leq 360^0$, wire antenna gain is more than 9.0 dB, and maximum achieves to 12.4 dB, which satisfies the desired antenna performance requirements. In addition, the 3-D polar plot of the RHCP gain of the obtained wire antenna is shown in Figure 8.

Figure 7. The RHCP gain results of LADEE evolved antennas at 2245MHz

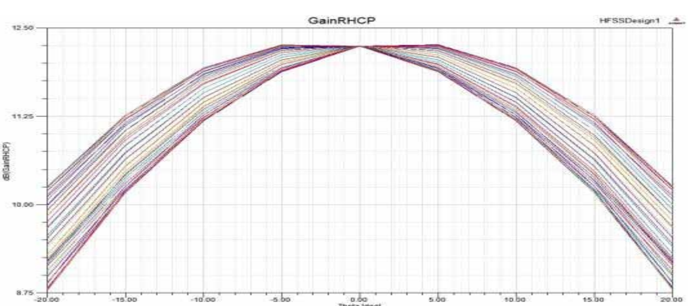
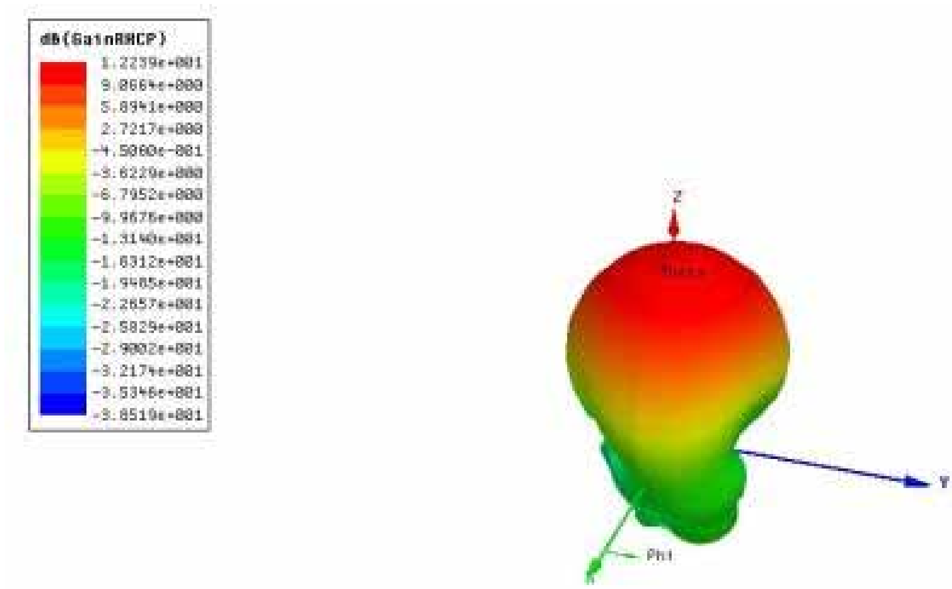
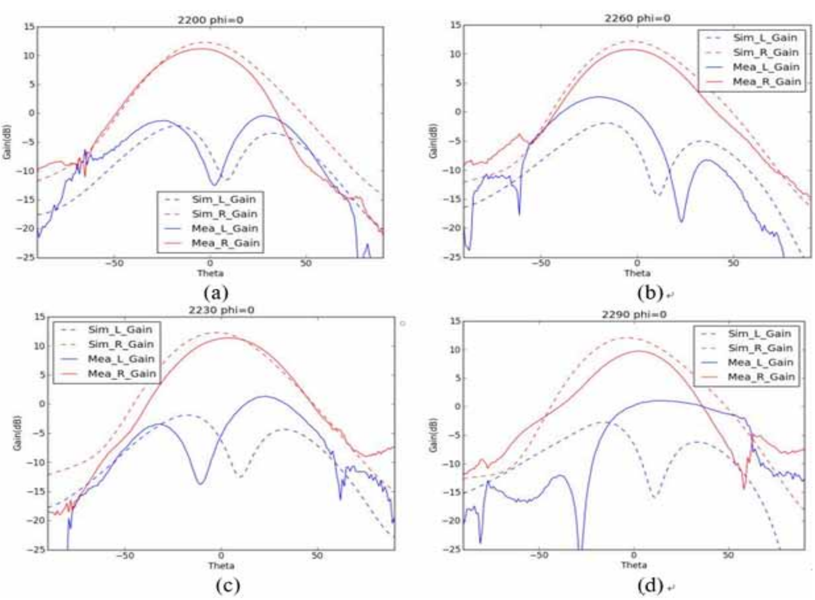


Figure 8. The 3-D polar plot of the RHCP gain at 2245MHz



Simulated and measured elevation cuts at $\varphi = 0^0$ for the antenna are shown in Figure 9, which match well and meet the performance requirements. While there are some differences between simulation result and measurement result at 2290MHz, which may be caused by the material of 3D printing of the Antenna prototype or problems in the process of measurements. So that needs further confirmation and research.

Figure 9. Elevation plots for $\varphi = 0^0$ for the evolved antenna



From the above, the obtained wire antenna by DE and 3D-printing meets the needs of the designed requirements, i.e., antenna geometric size, antenna gain, axis ratio, and VSWR over the frequency band.

CONCLUSION

This paper designs a new crooked-wire antenna by using DE algorithm and 3D-printing technique. The wire antenna design is modeled as a COP, in which the objective is the variance of antenna gain, axis ratio, and VSWR over the frequency band, and the constraints are the antenna geometric size, gain, axis ratio, and VSWR. Next, the DE algorithm is used to find the global optimal solution for the design. The main difference between the antenna design in this work and traditional evolutionary antenna design is that the construction of the objective function and the 3D-printing the antenna. The minimization of the objective can potentially enhance the robustness of the antenna and widen the frequency band without additional computational cost, and the precision of fabricating the antenna is ensured by using 3D-printing. The NASA LADEE satellite antenna design as an example is chosen to verify the effectiveness of the proposed method in this paper. The frequency of the LADEE obtained antenna is between 2200MHz and 2290MHz. The evolved antenna by the proposed method in this work is good to meet the design requirements, i.e., antenna geometric size, antenna gain, axis ratio, and VSWR over the frequency band. The measurements results of antenna prototype matched with simulations. This may provide a new design method for antennas.

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