Evolutionary Algorithm Designed Broadband Plate Antenna for F-5 Vertical Stabilizer

Abstract

Designing successful broadband antennas is a labor intensive and difficult task. This paper explores an alternate method for creating high performance antennas over a wide frequency range using an evolutionary algorithm which performs evaluation, selection and variation. Using this method, novel and unusual designs can be created and optimized to work within strict constraints. In this paper an evolutionary algorithm is used to design an antenna for military voice communication applications. Successful results demonstrate its efficacy when compared to traditional design techniques.

Background

In antennas, Voltage Standing Wave Ratio (VSWR or SWR) is a measure of how efficiently it radiates power. More broadly, VSWR measures the impedance matching in a circuit. It is expressed as a ratio that measures the peak amplitude of the standing waves in comparison to the ideal amplitude. It can be written as a ratio such as 2:1 but is often abbreviated as the first number in that ratio (VSWR of 2 → 2:1). The ideal VSWR of a circuit is 1, where none of the power is reflected and the source and load impedance are perfectly matched. An antenna that radiates 100% of the power at a certain frequency has a VSWR of 1 at that frequency. While a perfect VSWR of 1 is possible at a specific frequency with, for example, a tuned dipole, obtaining a perfect VSWR for a range of frequencies is extremely challenging. Therefore, antenna systems are designed to work with the more achievable goal of low but not perfect VSWRs where half or a third of power is radiated (VSWR of 2 and 3 respectively).

For this application there are some VSWR and spatial constraints. The VSWR must be less than or equal to 2.5 for the frequencies of 108MHz to 162MHz and 225MHz to 400MHz. For this implementation this was approximated to include the whole range from 108 to 400MHz. This covers both aeronautical and maritime bands allowing for communication with distressed vessels [1]. The antenna is structurally integrated into the top of the vertical stabilizer, and its dimensions are constrained by the size and shape of the vertical stabilizer cap. The antenna is embedded within the part and is therefore strictly limited to maximum dimensions of 25.2 cm tall and 70cm wide. The connection to the 50Ohm coax cable is 18cm from the left and 1 cm down.

For this study, antennas were simulated in the computer to evaluate performance of a specific design. This was done with Numerical Electromagnetics Code (NEC), a wire simulation software written in Fortran and originally used with punched cards. Each card would hold information about a component of the antenna or its environment, and a deck of these cards were used to model the antenna which could then be simulated [2]. Modern NEC implementations now use digital cards to hold information and communicate data about the antenna and its environment. NEC can find the real and imaginary impedance at a range of frequencies [3]. It offers close approximations for simple wire configuration but loses accuracy on more complex wire forms [4]. NECpp is a python library that allows NEC2++ to be used through Python [3]. NEC can only run wire simulations but wire outlines of solid 2D shapes offer a reasonable approximation (especially regarding the shape of the VSWR graph) of solid plate antennas. In practice the VSWR is much lower than the simulation suggests; real world antennas function better than predicted. Another approximation taken in antenna simulation is a consistent small segment count in each wire. By having a low segment count per wire, the simulation can run considerably faster but lower segment counts provide worse approximations and some erroneous errors that can be filtered out.

To optimize an antenna shape, an evolutionary algorithm can be used to test and optimize thousands of potential designs [5]. An evolutionary algorithm is a method where there are three basic iterative steps: evaluation, selection and variation. After a random population is initiated these three iterative steps are applied as many times as necessary. Evaluation is the simple process of determining the most fit individuals (or least costly). Selection is the process of destroying the least fit individuals. And finally, while there are many different possible implementations of variation, the basic goal is to replace the lost population with combinations of the successful organisms with some random variation [6]. As an example of variation, if an organism is represented by a binary number, the first half of one and the second half of another successful organism could be combined. Mutation could be implemented by flipping some number of bits in the new organism. But in all cases, some form of crossover and mutation are part of variation to replace the lost population. The repetition of these three basic steps forms the basis of an evolutionary algorithm.

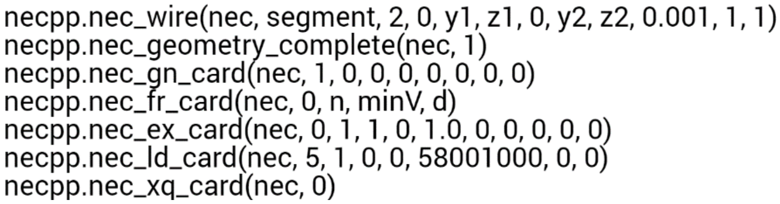
Statement of Problem

Having lower VSWR antennas increases their range and efficiency as more power is transferred to electromagnetic waves. While radio transmission equipment has improved greatly in its ability to transmit at wide frequency ranges while remaining light and small, antenna designs have not kept pace, making the larger frequency range a performance compromise. The US Navy uses F-5 jets for training in Florida and sometimes the US Coast Guard requests their assistance in radioing for in-distress boats at lower maritime communications frequencies [1].

VSWR usually rises quickly outside of designed frequencies, rendering the current antennas largely ineffective at these low wavelengths. The Navy sought a new design that functions at these low frequencies while retaining effectiveness in the ranges that already performed well. The specifications were to have a VSWR of 2.5 or less over the frequencies 108-400MHz. This would provide great benefit to the Coast Guard at no detriment to the Navy. While a tuned antenna would solve the problem, they are harder to manufacture and considerably more expensive. This is because a traditional plate antenna is manufactured from a simple sheet of metal, while a tuned antenna incorporates electronics that modify the shape to optimize the specific broadcast frequency. This new design is a traditional plate antenna with simple manufacturing that also functions well at the broadband frequencies desired.

Data

In the implementation of the evolutionary algorithm an individual is a collection of vertices connected in an order. This defines the outline of the antenna and the wires that are connected to be simulated in the NEC software. The environment is the same for all individuals where a ground plane is present and reasonable (as close as possible to real world environment) cards are used (shown in Fig. 1). In the cards, *segment* is the number of that wire, *y1* and *z1* are the starting y and z of a segment, *y2* and *z2* are the ending y and z of the segment (this card is called for every wire in the outline), *n* is the number of samples, *minV* is the minimum frequency in MHz (108) and *d* is the change from one sample to another (5). The individuals were limited to 10 segments with a 2cm by 1cm



```
necpp.nec_wire(nec, segment, 2, 0, y1, z1, 0, y2, z2, 0.001, 1, 1)
necpp.nec_geometry_complete(nec, 1)
necpp.nec_gn_card(nec, 1, 0, 0, 0, 0, 0, 0, 0)
necpp.nec_fr_card(nec, 0, n, minV, d)
necpp.nec_ex_card(nec, 0, 1, 1, 0, 1.0, 0, 0, 0, 0, 0)
necpp.nec_ld_card(nec, 5, 1, 0, 0, 58001000, 0, 0)
necpp.nec_xq_card(nec, 0)
```

Fig. 1. Card information used in simulations.

triangle at the bottom to guarantee a suitable place to solder a connection (or attach an alligator clip for testing). Random points are chosen for the vertices, and individuals are then subjected to the evolutionary algorithm to optimize a design. Vertices are bounded to the rectangle specified in the constraints (-0.18 to 0.52 on the x-axis and 0.01 to 0.262 on the y-axis, all in meters) apart from the triangle which touches the ground plane at (0,0,0). If an individual returns an error in the NEC simulation, it is artificially given a highly mismatched impedance and thus a high VSWR to guarantee that such organisms are unsuccessful. Because of approximations used, the program can sometimes give erroneous result without returning an error, resulting in a negative VSWR which the program would quickly exploit as it gives a very low cost. To avoid these

$$\text{Relection Coefficient}\,(\Gamma) = \frac{\sqrt{(R - Zo)^2 + j^2}}{\sqrt{(R + Zo)^2 + j^2}} \qquad (1)$$

$$\text{VSWR} = \frac{1 + \Gamma}{1 - \Gamma} \qquad (2)$$

incorrect simulations any antenna with a negative real component to the impedance (and therefore a negative VSWR) is given the same large VSWR as an error. The NEC program can return a list of complex impedances at specified frequencies which using equation (1) and (2), as well as a constant 50Ohms for source impedance, can be used to calculate VSWR.

The cost of an individual was determined by its total VSWR summed at intervals over a range. A weight was added to some of these values so that they would be incentivized to be lower. The points were sampled at every 5MHz from 105 to 400MHz inclusive and given a multiplier of 3 for all samples above 250. This encourages lower VSWR at the higher frequencies which are more important for communications.

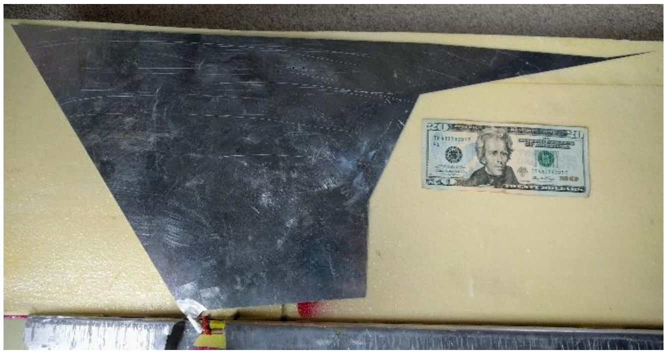


Fig. 2. Picture of the final design cut from aluminum.

The evaluation and selection of the population was done by sorting the individuals by their cost and removing the highest cost half. Variation was achieved by averaging the vertices of three antennas and moving some vertices a random distance and direction. The resulting shape was then bounded to the constraints by simply moving the x and y position of the vertices to be within the parameters. The three antennas to be combined were selected with a preferential bias towards the best individual, this increased the chances of creating a new organism with simple mutations to the best design.

Because of the random nature of an execution, many different runs were performed and the result of each saved. The most promising and lowest cost two were tested and the one that fit the design specifications (shown in Fig. 2) was chosen. Fig. 3 shows the VSWR sweep of

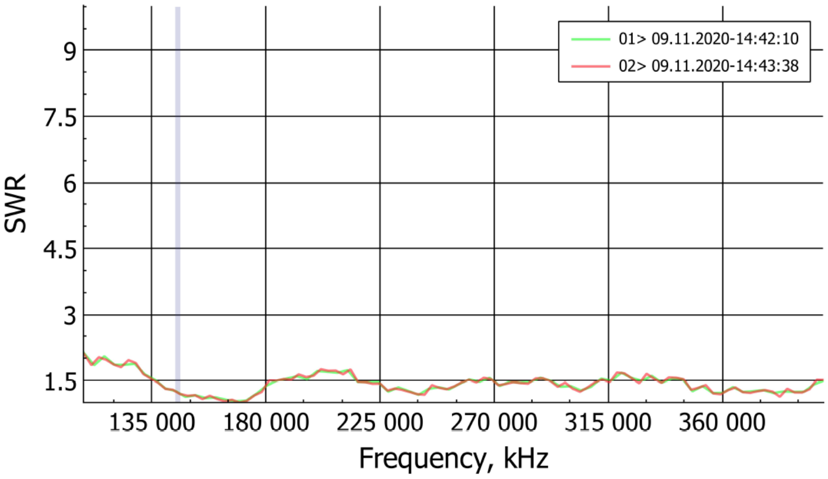


Fig. 3. The VSWR sweep of the final design.

the final design tested on a grounded F5 aircraft in its hangar which offers a near perfect recreation of its final environment. The highest VSWR is just over 2 at 108MHz. Two runs are shown in red and green with nearly identical results. The VSWR is captured using a RigExpert and the AntScope2 software sampled at 100 points, the y-axis is the default for the program. Testing was done with aluminum foil as it is more easily cut out and results in identical VSWR sweeps, the final design was then cut from .032” aluminum plate and retested to assure identical results.

Analysis

The cost of the best individual is guaranteed to always improve or stay the same because the best individual is never discarded. This means that the best organism improves with more generations. Unfortunately, as the design is optimized its gains are incrementally smaller. The algorithm can stall in a local minimum with a mediocre design that the algorithm cannot improve further. This leads to the shape seen in Fig. 4 and Fig. 5 where improvement slows down drastically after just a few generations with some larger breakthroughs or small improvements happening over a long interval. Because some runs are “doomed to fail” by falling into a mediocre local minimum, the algorithm had to be executed multiple times. This problem could have been solved in several ways but was not because a working design was made before the drastic slowdown in improvement was noticed. In many runs the design approaches a nearly optimized result in 10-15 generations and then

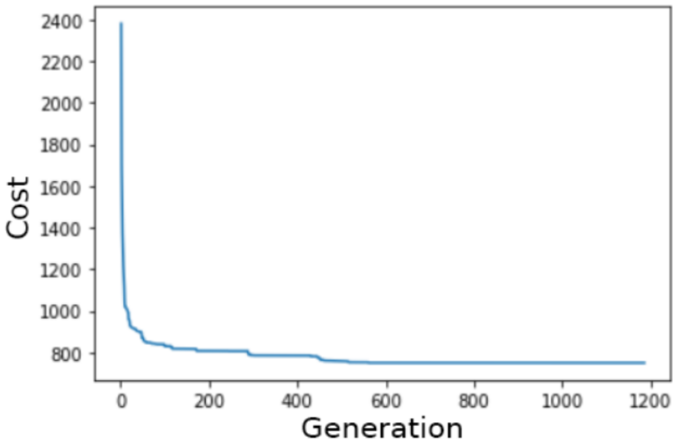


Fig. 4. Best individual’s cost over first 1187 generations (with the first generation removed).

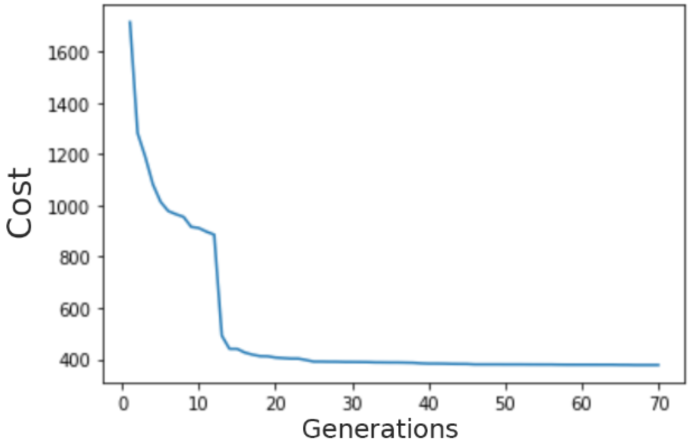


Fig. 5. Best individual's cost over first 70 generations (with the first generation removed).

improves minimally over many more (Fig. 5). Some potential solutions to this issue include adding a "gradient" to the surviving organisms. The best organism would be guaranteed to stay in the population, but any other organism would have a chance of being removed based on its position, the lower its position the more likely to be removed. This could allow for enough large-scale random variation to move outside a local minimum and improve further over many generations. The graphs of the best individual per generation (Fig. 4 and Fig. 5) clearly show slowed improvement over time. In early generations improvement is fast because completely novel designs have a good chance of being better than the previous generation's best individual. As the general shape for the best antenna begins to form, only small improvements from slight shifts in the positions of the vertices improve the cost. The two-step pattern likely happens when a good general shape begins to be optimized and then a completely new shape creates a large improvement in one generation. This leads to a graph that roughly follows an exponential decay or a multi-step exponential decay function. The first-generation cost is removed because it is nearly always a design with an error, this gives it a cost that would dwarf the working antennas and make the graph illegible.

The variation algorithm, while not perfect for the above reasons, had advantages. Large improvements could be made by combining two antennas, potentially drastically changing the positions of the vertices, which is good early in the process where there is lots of room for optimization. Small improvements could be made by having all three averaged antennas be the best individual allowing for small mutations to improve the antenna slightly, which is advantageous late in the process where small improvements to the cost are most likely.

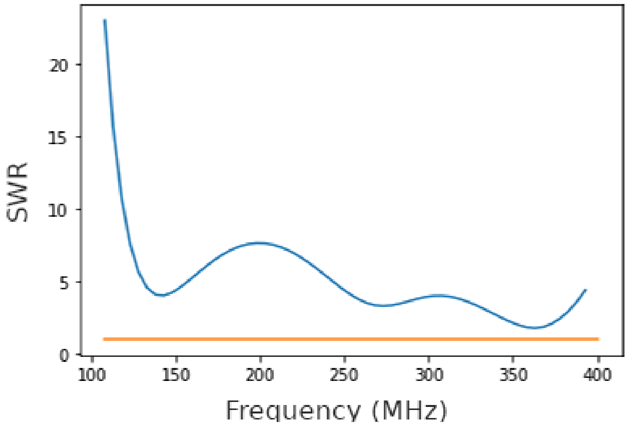


Fig. 6. The final designs simulated VSWR from 108 to 400MHz, the orange line is a VSWR of 1.

The final design's simulated VSWR (Fig. 6) is much higher than the reality but the shape and frequencies are remarkably close. While the local maximums and minimums occur at similar frequencies, the relative heights are not very similar to the real world equivalent. This is likely due to the processing time saving approximations and differences from wire to plate.

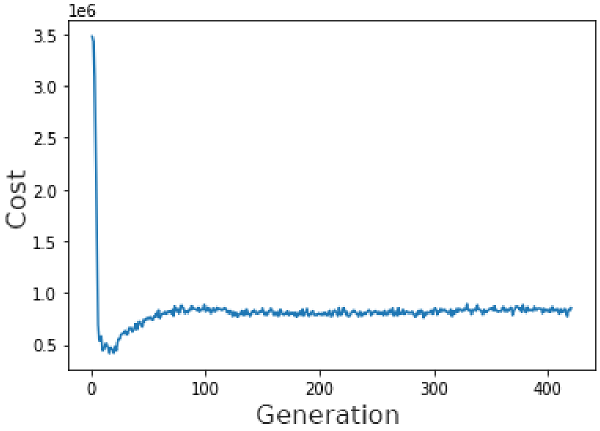


Fig. 7. Average cost over 420 generations.

The average cost of the whole population exhibited some interesting patterns. All runs seem to follow the shape shown in Fig. 7 with a dip in the early generations and then apparent stabilization onto some value with minor random variation. While the initial dip's cause is unknown, the stabilization is likely because of slow improvement to the design. The average after stabilizing is a combination of a random but stable proportion of new individuals that have an error and the current population whose cost is dwarfed in comparison.

Multiple final designs exhibited a final shape of a wide trapezoid with a sharp point seen in Fig. 8 (which is much wider than the graph suggests). The trapezoid part of the antenna is large to fill as much of the available space as possible, this likely helps with lower frequencies with longer wavelengths. The prevalence of spikes in many other results means that it is both effective at lowering cost and easy to evolve. Because only one point needs to be moved far out to create a spike it makes sense that the algorithm could easily find that advantageous design. The spike part of the design may act as a sudo-dipole effectively working at a narrow range of frequencies that the rest of the antenna handles poorly.

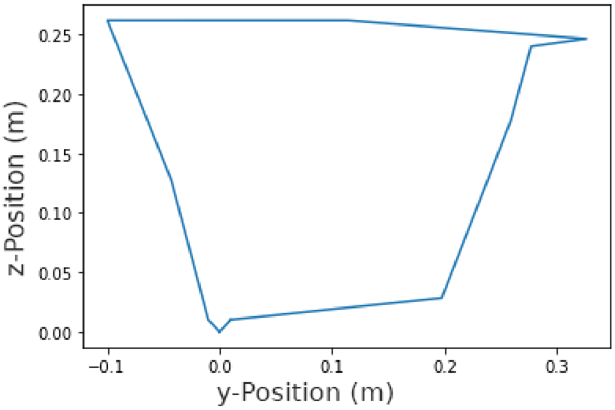


Fig. 8. Outline of a different but very similar design.

Conclusion

Evolutionary Algorithms are an effective method for designing novel, non-obvious antenna designs. Even with considerable approximations, a design fitting the final specifications can be created with limited knowledge in the field and no prior antenna designing experience. The effectiveness of the result is clear in Fig. 3 and Fig. 9. The optimization for the lower frequencies can be achieved with little or no detriment to other frequencies. The previous design had comparable VSWR values in the mid and high frequency range but below 180MHz performed much worse compared to the new design. The ability of the program to test and modify thousands of novel designs allows for unusual but effective shapes unlikely to be designed by a human.

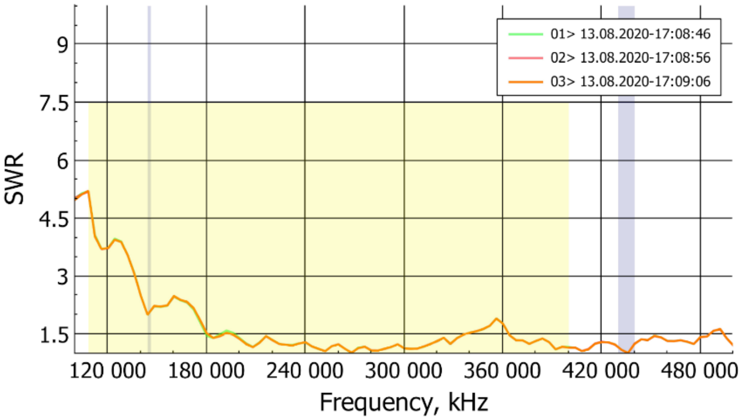


Fig. 9. Sweep of a previous design with the 108MHz to 400MHz frequencies highlighted.

Effective antenna simulation software made it possible to test many antennas quickly enough to achieve good results in under an hour per execution. While there is certainly room for improvement in the algorithm used, running it multiple times, and keeping the most successful results was a quick method for obtaining a viable design.

References

[1] "United States Frequency Allocation Chart," *United States Frequency Allocation Chart | National Telecommunications and Information Administration*, 2016. [Online]. Available: https://www.ntia.doc.gov/page/2011/united-states-frequency-allocation-chart. (retrieved 2020)

[2] Adler, Dick (1993) Information on the History and Availability of NEC-MOM Codes for PC's & Unix *Applied Computational Electromagnetics Society Newsletter: 8–10.*

[3] T. Molteno, "Antenna simulation in python," *PyPI*, (2019). Accessed: 2020 [Online]. Available: https://pypi.org/project/necpp/

[4] G. J. Burke, and A. J. Poggio (1981) Numerical Electromagnetic Code (NEC) Part I: Program Description - Theory *National Technical Reports Library*, 1, _-_

[5] G. S. Hornby, A. Globus, J. D. Lohn, and D. S. Linden, (2006) Automated Antenna Design with Evolutionary Algorithms. *Collection of Technical Papers - Space 2006 Conference*, 1, 1-8.

[6] L. Altenberg, and Richard M. Kliman, (2016) Evolutionary Computation. *Encyclopedia of Evolutionary Biology, Academic Press*, 1, 40-47

[7] W. J. Highton, "Return Loss and Mismatch Loss Calculator." *Chemandy Electronics*. [Online]. Available: https://chemandy.com/calculators/return-loss-and-mismatch-calculator.htm (retrieved 2020)