

Evolutionary Optimization of Quadrifilar Helical and Yagi-Uda Antennas

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Abstract: - We present optimization results obtained for two type of antennas using evolutionary algorithms. A quadrifilar helical UHF antenna is currently flying aboard NASA's Mars Odyssey spacecraft and is due to reach final Martian orbit insertion in January, 2002. Using this antenna as a benchmark, we ran experiments employing a coevolutionary genetic algorithm to evolve a quadrifilar helical design *in-situ* - i.e., in the presence of a surrounding structure. Results show a 93% improvement at 400 MHz and a 48% improvement at 438 MHz in the average gain. The evolved antenna is also one-fourth the size. Yagi-Uda antennas are known to be difficult to design and optimize due to their sensitivity at high gain and the inclusion of numerous parasitic elements. Our fitness calculation allows the implicit relationship between power gain and sidelobe/backlobe loss to emerge naturally, a technique that is less complex than previous approaches. Our results include Yagi-Uda antennas that have excellent bandwidth and gain properties with very good impedance characteristics. Results exceeded previous Yagi-Uda antennas produced via evolutionary algorithms by at least 7.8% in mainlobe gain.

Keywords: - antenna, optimization, evolvable hardware, coevolution.

1 Introduction

Automated antenna synthesis via evolutionary design has recently garnered much attention in the research literature [13]. Underlying this enthusiasm is an issue that many designers readily acknowledge - good antenna design requires not only knowledge and intelligence, but experience and artistry. Thus automated design techniques and tools have been lacking. Evolutionary algorithms show promise because, among search algorithms, they are able to effectively search large, unknown design spaces.

NASA's Mars Odyssey spacecraft is due to reach

final Martian orbit insertion in January, 2002. Onboard the spacecraft is a quadrifilar helical antenna that provides telecommunications in the UHF band with landed assets, such as robotic rovers. This antenna can be seen in Fig. 1. It consists of four wires that spiral around a center axis to form helices. Each helix is driven by the same signal which is phase-delayed in 90° increments. A small ground plane is provided at the base. It is designed to operate in the frequency band of 400-438 MHz.

Based on encouraging previous results in automated antenna design using evolutionary search, we wanted to see whether such techniques could

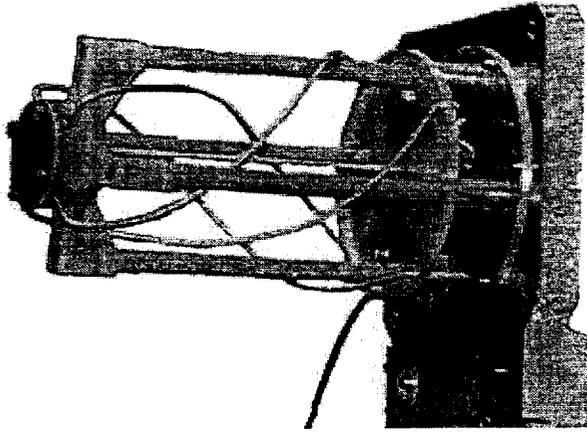


Figure 1: Photograph of the quadrifilar helical UHF antenna deployed on the Mars Odyssey spacecraft.

improve upon Mars Odyssey antenna design. Specifically, a coevolutionary genetic algorithm is applied to optimize the gain and size of the quadrifilar helical antenna.

A significant aspect of our optimization was that it was performed *in-situ* – in the presence of a neighboring spacecraft structure. On the spacecraft, a large aluminum fuel tank is adjacent to the antenna. Since this fuel tank can dramatically affect the antenna's performance, we leave it to the evolutionary process to see if it can exploit the fuel tank's properties advantageously. A similar approach was taken in [9] with good results.

Optimizing in the presence of surrounding structures would be quite difficult for human antenna designers, and thus the actual antenna was designed for free space (with a small ground plane). In fact, when flying on the spacecraft, surrounding structures that are moveable (e.g., solar panels) may be moved during the mission in order to improve the antenna's performance.

The Yagi-Uda was first proposed in 1926 [15]. We chose this type of antenna because it presents difficult design and optimization challenges, and because it was previously studied with respect to evolutionary design [7]. The Yagi-Uda antenna is comprised of a set of parallel elements with one reflector element, one driven element (driven from its center), and one or more director elements (see Fig. 2). The highest gain can be achieved along the axis and on the side with the directors. The reflector element reflects power forwards and thus

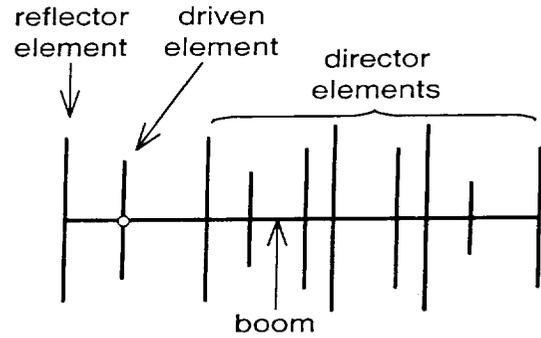


Figure 2: Typical Yagi-Uda antenna.

acts like a small ground plane. The design parameters consist of element lengths, inter-element spacings, and element diameters.

The Yagi-Uda application that we use is taken from [7]. It involves designing a special feed for the Arecibo 305-meter spherical reflector in Puerto Rico [3]. The antenna was to be used to search for primeval hydrogen having a redshift of approximately 5. Neutral hydrogen line emission is at a frequency of 1420 MHz; thus the frequency region of interest was about 235 MHz. Preliminary studies indicated that the band from 219 to 251 MHz was of the greatest interest, particularly from 223 to 243 MHz. The most important design goal was for the feed to have sidelobes/backlobes at least 25 dB down from the mainbeam gain in the region from $70^\circ < \phi < 290^\circ$, due to the interference which came from surrounding radio and TV towers. Of lesser importance was that the E-plane (the plane parallel to the plane of the antenna) and H-plane (perpendicular to the E-plane) beamwidths be about 50° .

Voltage Standing Wave Ratio, or VSWR, is a way to quantify reflected-wave interference, and thus the amount of impedance mismatch at the junction. VSWR is the ratio between the highest voltage and the lowest voltage in the signal envelope along a transmission line [14]. The VSWR was desired to be less than 3 and the gain was to be maximized, limited by the wide beamwidth. The feed would be mounted over a 1.17 meter square ground plane—that is, a ground plane only 0.92λ in size.

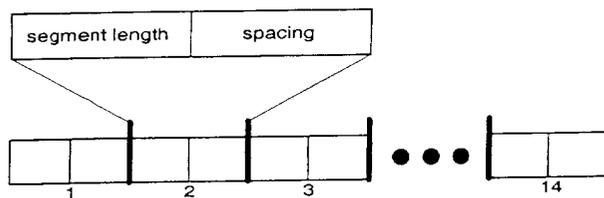


Figure 3: Genetic representation of a 14-element Yagi-Uda antenna.

2 Antenna Representation and Operators

The representational scheme used for the Mars UHF antenna parameterized a generic quadrifilar helical antenna, and was specified as follows. An array of byte-encoded floating point numbers represented the number of wire segments, number of turns, wire thickness, bottom diameter, top diameter, and height.

The representational scheme used for the Yagi-Uda antenna is similar to that taken from [7]. As shown in Fig. 3, this scheme is comprised of 14 elements, each one encoding a length and spacing value. Each floating point value was encoded as three bytes, yielding a resolution of $1/2^{24}$ per value. The first pair of values encoded the reflector element, the second pair encoded the driven element, and the remaining 12 pairs encoded the directors. One point crossover was used with cut points allowed between bytes. Mutation was applied on individual bytes.

Radius values were constrained to 2, 3, 4, 5, or 6 mm. All elements within a given individual were assigned the same radius value. Element lengths were constrained to be symmetric around the x -axis and between 0 and 1.5λ . Elements having zero length were removed from the antenna; as a consequence, a constructed antenna could have less than 14 elements. Spacing between adjacent elements (along the z axis) was constrained to be between 0.05λ and 0.75λ . The wavelength λ was 1.195 meters, the wavelength of 235 MHz.

3 Experimental Setup

Experiments were set up as follows. The NEC simulation program [4] was used to evaluate all antenna designs. We used a parallel master/slave generational genetic algorithm with a population

size of 6000. One point crossover across byte boundaries was used at a rate of 80%. Mutation was uniform across bytes at a rate of 1%. Runs were executed on 32-node and 64-node Beowulf computing clusters [12].

The wire geometry encoded by each individual chromosome was first translated into a NEC input deck, which was subsequently sent to the NEC simulator. The segment size for all elements was fixed at 0.1λ , where λ was the wavelength corresponding to 235 MHz. For the Yagi-Uda antenna, the source element for excitation was specified to be the middle segment of the driven element. The z location of the reflector element was always set to 0. The antenna was analyzed in free space.

For the quadrifilar helical runs, a coarse model of the neighboring fuel tank was used in the simulations. Its size and position was calculated based on engineering drawings of the spacecraft. To compare our results to the spacecraft antenna, we modeled that antenna with the best data we had at the time¹.

A coevolutionary genetic algorithm was applied to the quadrifilar helical antenna optimization. The algorithm used is similar to that presented in [10]. Two populations are used: one consisting of antenna designs, and one consisting of target vectors. The fundamental idea is that the target vectors encapsulate level-of-difficulty. Then, under the control of the genetic algorithm, the target vectors evolve from easy to difficult based on the level of proficiency of the antenna population.

Each target vector consists of a set of objectives that must be met in order for a target vector to be "solved." A target vector consisting of two values: the average gain (in dB), VSWR, and antenna volume. A target vector was considered to be solved by a given antenna if the antenna exceeds the performance thresholds of all target.

Values for target gain ranged between -50 dB (easy) and 8 dB (difficult). Target VSWR values ranged between 100 (easy) and 20 (difficult). Target antenna volumes ranged from $100,000 \text{ cm}^3$ (easy) to 100 cm^3 (difficult). Target vectors are represented as a list of floating point values that are mutated individually by randomly adding or subtracting a small amount (5% of the largest legal value). Single point crossover was used, and

¹We are in the process of obtaining more accurate specifications from the company that designed the antenna.

crossover points were chosen between the values.

The general form of the fitness calculations are from [10]. In summary, antennas are rewarded for solving difficult target vectors. The most difficult target vector is defined to be the target vector that only one antenna can solve. Such a target vector garners the highest fitness score. Target vectors that are unsolvable, or are very easy to solve by the current antenna population, are given low fitness scores.

For the Yagi-Uda runs, the simulator was instructed to sample the radiation pattern of each individual at three different frequency values: 219, 235, and 251 MHz, representing a 13.6% bandwidth. Each radiation pattern was calculated at ϕ set to 0° and θ varying between 0° and 355° , the latter sampled at 5° increments. VSWR values were also calculated for each of the three frequencies.

Fitness was expressed as a cost function to be minimized. The calculation was as follows:

$$F = -G_L + \sum (C * V_i) \quad (1)$$

where: G_L = lowest gain of all frequencies measured at $\theta = 0^\circ$ and $\phi = 0^\circ$, V_i = VSWR at the i th frequency, and

$$C = \begin{cases} 0.1 & \text{if } V_i \leq 3 \\ 1 & \text{if } V_i > 3 \end{cases}$$

Lacking from this calculation was a term involving sidelobe/backlobe attenuation. We chose not include such a term because we reasoned that as the mainlobe gain increased, the sidelobes/backlobes would decrease in size.

4 Experimental Results

For the quadrifilar helical antenna, a set of five runs were executed using the algorithm described above. Only one of the runs found an antenna design that exceeded that benchmark antenna. Fig. 4 shows the gain plots for both the evolved and actual Mars UHF antennas. Fig. 5 shows the antennas, structures, and radiation patterns of actual Mars Odyssey UHF and evolved antenna. The evolved antenna measures $6\text{cm} \times 6\text{cm} \times 16\text{cm}$ which is approximately four times as small volume-wise as the benchmark (roughly $10\text{cm} \times 10\text{cm} \times 25\text{cm}$). At 400 MHz, the average gain of the

evolved antenna was 3.77 dB and 1.95 for the benchmark antenna. At 438 MHz, the average gain of the evolved antenna was 2.82 dB and 1.90 for the benchmark antenna. This represents a 93% improvement at 400 MHz and a 48% improvement at 438 MHz in the average gain.

Given that our model of the actual spacecraft antenna was reasonable, though imprecise, it had relatively poor VSWR values: 76.76 to 103.51. The VSWR of the evolved antenna ranged from 4.92 to 20.00 which is an improvement, though VSWR values less than or equal to 2.0 are specified as design constraints.

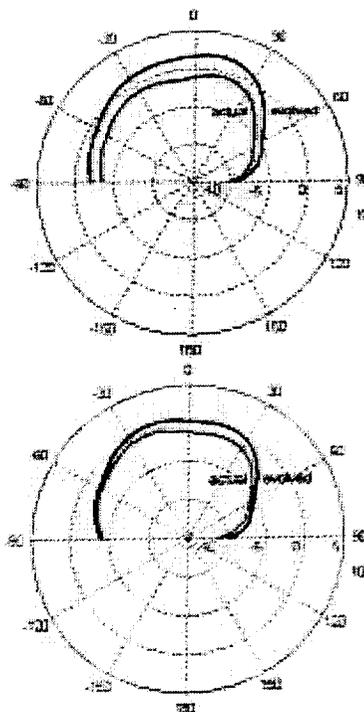


Figure 4: Gain plots for 400 MHz (top) and 438 MHz (bottom). In each case, the evolved antenna maintains a higher gain than the actual Mars Odyssey antenna. Plots take into account circular polarization.

For the Yagi-Uda antenna, thirteen runs were executed under differing random number streams for comparison purposes. Table 1 summarizes the run data for the best antenna found in each run of 100 generations. Fig. 6 shows the radiation pattern from the best antenna found (run 13). It exhibits 10.58 dB and has a VSWR of 2.02 at its center frequency. Its sidelobe/backlobe gain at this frequency is 3.07 dB. Fig. 7 shows a diagram of

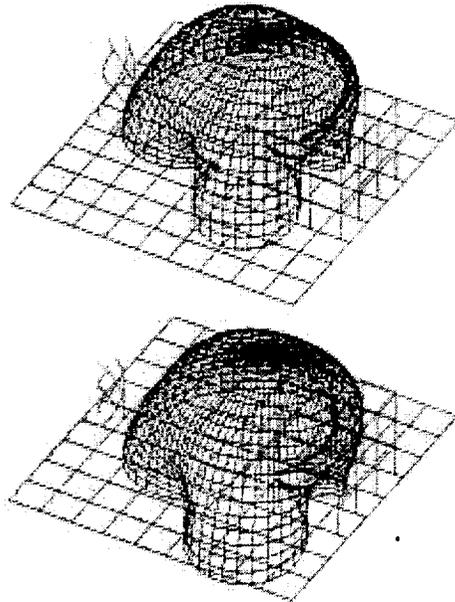


Figure 5: Antennas, structures, and radiation patterns of actual Mars Odyssey UHF (top) and evolved antenna (bottom). The antennas can be seen in the upper left and the fuel tanks in the lower right of each diagram.

the antenna's physical structure.

To increase simulation speed, the evolved Yagi-Uda antennas were produced without the presence of a ground plane – an idealized setting. Adding a ground plane thus simulates more realistic conditions. We removed the reflector element and simulated the best antennas found over a ground plane of 1.17 meters [7]. We found the performance increased – at the center frequency the mainlobe gain was 12.52 dB and the VSWR was 2.39. At 291 MHz, the gain was 11.33 dB, and at 251 MHz, the gain was 11.15 dB. In contrast, the antenna produced in [7] exhibits gains of 10.36, 10.91, 10.34 dB at 219, 235, and 251 dB, respectively. Thus the antenna from run 13 has a minimum performance increase of 7.8% as compared to the previously reported antenna.

5 Discussion

An improved version of the quadrifilar antenna currently flying on Mars Odyssey was presented. The evolutionary algorithm allowed the antenna to be designed in the presence of the surrounding structure, whereas the human-designed antenna

	Length (meters)	Distance above Ground Plane (meters)
—	0.59	5.75
—	0.45	5.08
—	0.37	4.58
—	0.27	4.10
—	0.54	3.24
—	0.48	2.90
—	0.54	2.08
—	0.40	1.80
—	0.34	1.11
—	0.51	0.93
—	0.54	0.70
—	0.53	0.46
—	0.59	0.31
—	0.86	0.00

Figure 7: The best Yagi-Uda antenna from run 13. The radius of all elements was 3 mm.

was designed for free-space. Results showed a 93% improvement at 400 MHz and a 48% improvement at 438 MHz in the average gain. The evolved antenna was also one-fourth the size of the actual antenna on the spacecraft, which is important because of the scarcity of area on spacecraft.

Small improvements in antenna performance can be significant in many applications. Because of their numerous design variables, complex behavior, and sensitivity to parameters, Yagi-Uda antennas are notoriously difficult to optimize. Our experiments produced several excellent antennas in a relatively small number of generations. When simulated over a finite ground plane, the highest performance antenna found exhibiting a mainlobe gain that was 7.8% higher than a previously-reported antenna.

Previous work has explicitly included a side-lobe/backlobe term in the fitness function in order to minimize radiation outside of the desired direction [7]. We did not include an explicit side-lobe/backlobe term but rather relied on the fact that the radiation pattern of an antenna is a zero sum quantity - increasing the intensity in one direction will implicitly reduce the amount of radiation in other directions.

For human antenna designers, designing an antenna to be synergistic with its surrounding structures is typically a daunting task. The results from the quadrifilar helical antenna provide encourag-

Run	219 MHz		235 MHz		251 MHz	
	dB	VSWR	dB	VSWR	dB	VSWR
1	9.63	2.33	9.64	1.67	10.20	2.99
2	9.49	2.23	9.08	1.85	9.20	1.58
3	9.23	2.89	10.04	1.11	9.62	2.60
4	9.24	2.47	9.23	1.35	9.37	2.83
5	8.73	2.83	8.79	1.51	9.22	2.60
6	9.35	2.87	9.51	1.73	9.28	2.00
7	9.87	2.64	9.82	1.99	9.46	1.98
8	9.04	2.35	9.02	1.64	9.08	2.92
9	9.44	2.96	9.46	1.87	9.51	2.39
10	9.02	1.25	9.12	2.42	9.02	1.41
11	10.01	1.95	9.81	1.97	10.11	1.66
12	9.37	2.55	9.17	1.70	9.41	2.47
13	10.34	2.57	10.58	2.02	10.51	1.70

Table 1: Results from the best Yagi-Uda design after 100 generations for each of the 13 runs (dB is measured at $\phi = 0^\circ$, $\theta = 0^\circ$).

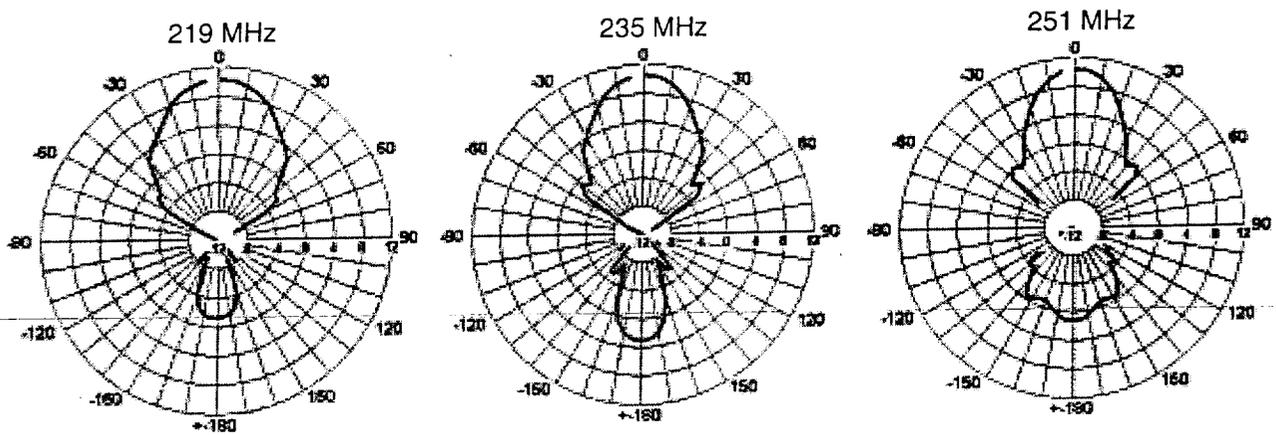


Figure 6: Radiation pattern of the best evolved Yagi-Uda antenna without a ground plane, measured at $0^\circ \leq \theta < 360^\circ$, $\phi = 0^\circ$, for 219, 235, and 251 MHz, respectively. (The scale is 2 dB per division. Inner ring is -12 db, outer ring is 12 dB.)

ing evidence that evolution can exploit those structures to give increased antenna performance.

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