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Tools for Automated Antenna Design and Optimization

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Current methods of designing and optimizing antennas by hand are time and labor intensive, limit complexity, and require significant expertise and experience. Evolutionary design techniques can overcome these limitations by searching the design space and automatically finding effective solutions that would ordinarily not be found. In recent years, evolutionary algorithms have shown great promise in finding practical solutions in large, complex design spaces. We present automated antenna design and optimization methods based on evolutionary algorithms. We have evolved efficient antennas for a variety of aerospace applications, and here we describe one proof-of-concept study and one project that produced flight antennas that flew on NASA's Space Technology 5 (ST5) mission. We discuss the software tools we developed to automate the design of these evolved antennas which are the first ever artificially-evolved objects to fly in space.

Nomenclature

EA	Evolutionary Algorithm
GA	Genetic Algorithm
ST5	Space Technology 5
NEC	Numerical Electromagnetics Code

I. Introduction

EVOLVABLE hardware is an emerging technology that is based on using advanced search algorithms to automatically design, reconfigure, adapt, or otherwise manipulate hardware or software models of hardware. Evolutionary algorithms (EAs) are one of the key search techniques used in the field.

EAs are stochastic search methods that mimic the metaphor of natural biological evolution. Evolutionary algorithms operate on a population of potential solutions applying the principle of survival of the fittest to produce better and better approximations to a solution. At each generation, a new set of approximations is created by the process of selecting individuals according to their level of fitness in the problem domain and breeding them together using operators borrowed from natural genetics. This process leads to the evolution of populations of individuals that are better suited to their environment than the individuals that they were created from. Evolutionary algorithms model natural processes, such as selection, recombination, mutation, migration, locality and neighborhood. Fig. 1 shows the

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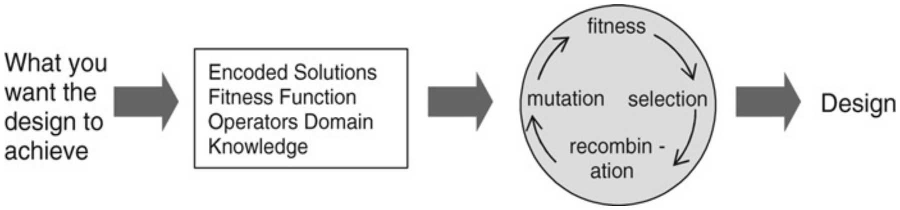

Fig. 1 Automated design process using an evolutionary algorithm.

structure of a simple evolutionary algorithm in an automated design flow. By operating on a population of solutions, evolutionary algorithms perform their search in a parallel manner.

II. Mars Odyssey Antenna

Automated antenna synthesis via evolutionary design has recently garnered much attention in the research literature.[1] Evolutionary algorithms show promise because, among search algorithms, they are able to effectively search large, unknown design spaces.

NASA's Mars Odyssey spacecraft is currently in Martian orbit. 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. 2. 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 improve upon Mars Odyssey antenna design. Specifically, a coevolutionary genetic algorithm is applied to optimize the gain and size of the quadrifilar helical antenna.

The optimization was performed *in-situ* – in the presence of a neighboring spacecraft structure.[2] 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. In other words, we do not give the algorithm information about how to exploit the environment, it must determine that during the evolutionary process. Clearly the more of the surrounding environment one is able to model, the more the algorithm will be able to exploit nearby radiating structures, hopefully for a performance gain. However this places greater computational loads and we determined empirically that simulation of the fuel tank by itself was the most we could accomplish.

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 re-positioned during the mission in order to improve the antenna's performance.

A. Experiments and Results

Experiments were set up as follows. The Numerical Electromagnetics Code, Version 4 (NEC4)[3] was used to evaluate all antenna designs. NEC4 is a high-fidelity, method of moments electromagnetics simulator. We used a parallel master/slave generational genetic algorithm with a population size of 6000. A master/slave algorithm is simply one in which a master program deals out work to a collection of worker programs running on separate computers. 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. Typical antenna simulation times were a few seconds, and complete runs finished after 10–20 hours.

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.

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 time of this writing.

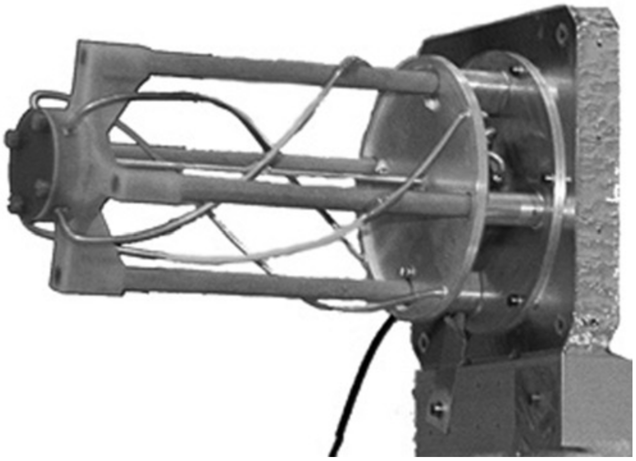

Fig. 2 Photograph of the quadrifilar helical UHF antenna deployed on the Mars Odyssey spacecraft.

A coevolutionary genetic algorithm was applied to the quadrifilar helical antenna optimization. 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. Coevolutionary algorithms as a class, have shown great promise in a variety of applications and we wantd to gain experience in using them in evoltionary design.

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. The algorithm terminates when target vectors that represent the mission requirements are solved.

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 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 crossover points were chosen between the values.

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.

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

$$F = -G_L + \sum (C * V_i) \quad C = \begin{cases} 0.1 & \text{if } V_i \leq 3 \\ 1 & \text{if } V_i > 3 \end{cases}$$

where: G_L = lowest gain of all frequencies measured at $\theta = 0°$ and $\phi = 0°$, V_i = VSWR at the ith frequency. 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.

A set of five runs were executed using the algorithm described above. Only one of the runs found an antenna design that exceed that benchmark antenna. Fig. 3 show the antennas, structures, and radiation patterns of actual Mars Odyssey UHF and evolved antenna. The evolved antenna measures 6 cm × 6 cm × 16 cm which approximately four times as small volumewise as the benchmark (roughly 10 cm × 10 cm × 25 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 represent a 93% improvement at 400 MHz and a 48% improvement at 438 MHz in the average gain.

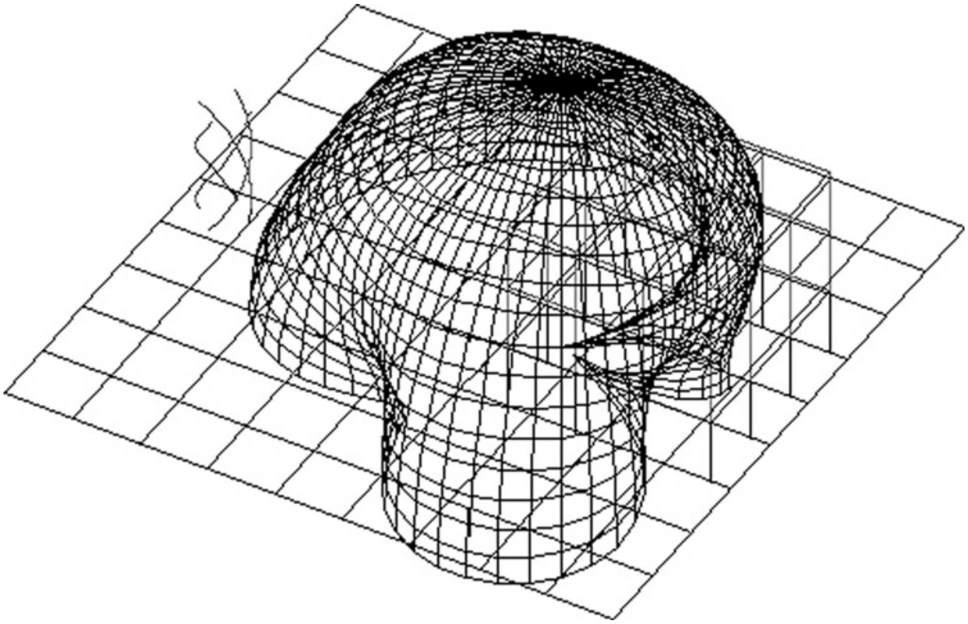

Fig. 3 Radiation pattern of the evolved antenna. The antenna can be seen in the upper left and the fuel tank in the lower right.

B. 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 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.

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

III. Space Technology 5 X-Band Antenna

The ST5 mission consists of three spacecraft which will orbit at close separations in a highly elliptical geosynchronous transfer orbit and will communicate with a 34 meter ground-based dish antenna. Each spacecraft (see Fig. 4) will have two antennas attached, one on each side of the spacecraft, Fig. 5. Initially the spacecraft were to fly approximately 35,000 km above Earth and the requirements for the communications antenna were for a gain pattern of ≥ 0 dBic from 40°–80° from zenith. With the change in launch vehicle and the new, lower orbit this necessitated the addition of a new requirement on the gain pattern of ≥ -5 dBic from 0°40° from zenith. The complete set of requirements for the antennas on the ST5 Mission are summarized in Table 1. VSWR is a way to quantify reflected-wave interference, a measure of the impedance mismatch. It is the ratio between the highest voltage and the lowest voltage in the signal envelope along a transmission line, with a ratio of 1 being perfect VSWR.

One of the challenges in engineering design is responding to a change in design requirements. We used the techniques described in this paper to automatically design a first set of X-band antennas for NASA's Space Technology 5 (ST5) spacecraft. One of these evolved antennas is shown in Fig. 6. Since our original evolutionary runs and the fabrication and testing of this first set of antennas, the launch vehicle for the ST5 spacecraft changed resulting in a lower orbit and different antenna requirements. With traditional engineering design such a change in requirements would necessitate redoing much of the design work with a near doubling of design costs. In contrast, with an

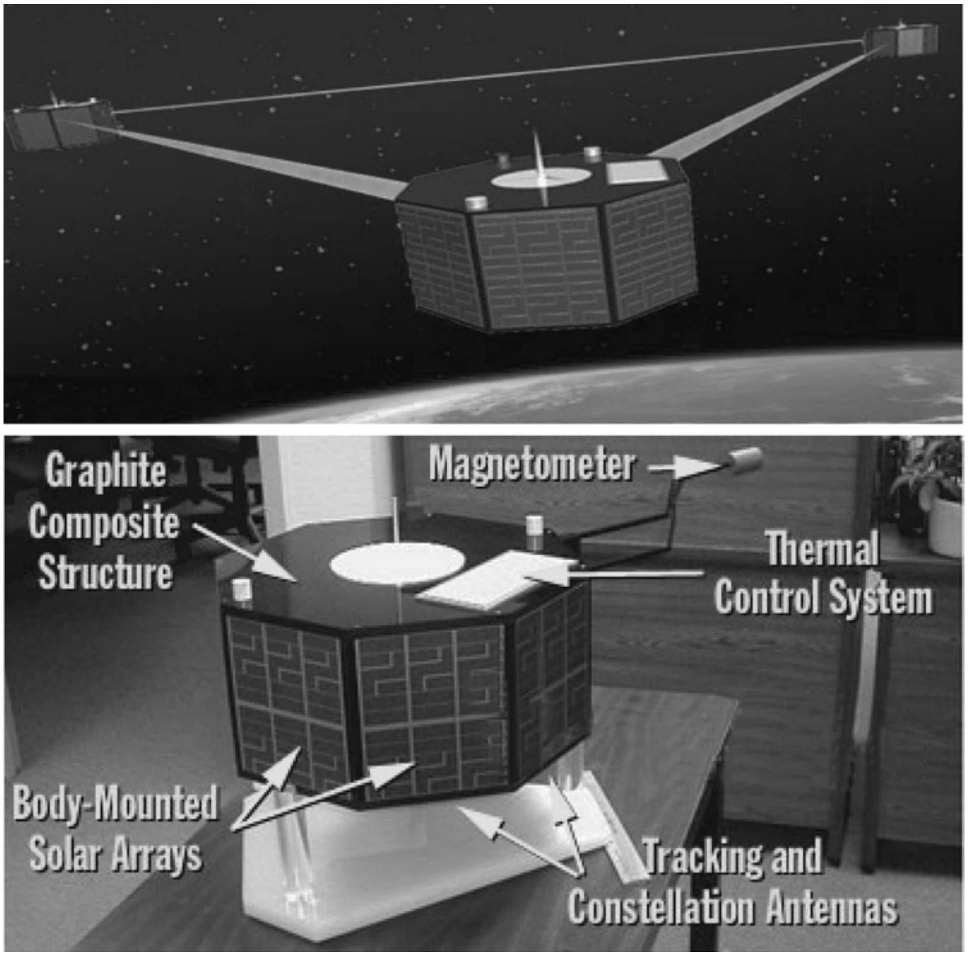

Fig. 4 Artist's depiction of the ST5 mission (top), satellite model (bottom). The mission consists of multiple miniaturized satellites, called nanosats or small-sats, flying in the test track of Earth's magnetosphere. The nanosats are 54.2 cm across and 28.6 cm high. When fully fueled they will weigh approximately 47 pounds. Flying clusters of multiple spacecraft reduces the risk of an entire mission failing if one system or one instrument fails. Each satellite will have two antennas, centered on the top and bottom of each spacecraft.

evolutionary design system for automatically creating antennas once the software has been developed, modifying it to produce antennas for a similar design problem requires only a minimal amount of human effort to implement the change a re-evolve new antennas with minimal additional cost.

As with the Mars Odyssey application, our goal is to find mission-compliant antenna designs, not necessarily optimal designs. Like traditional antenna design, a set of design assumptions is required, and while those assumptions may impede the ability to find optimal solutions, they are needed to fully specify the problem.

In the rest of this section we describe the evolutionary design software we used for evolving the initial antennas for this mission and the changes we made to them to address the change in mission requirements. We then present the performance of the new antenna designs, both from simulation and from fabricated units. One of our newly evolved antennas, ST5-33.142.7, meets the new mission requirements and has successfully passed environmental testing. Three of these antennas are scheduled to be launched in 2006 and will be the first evolved hardware in space and the first evolved antennas to be fielded.

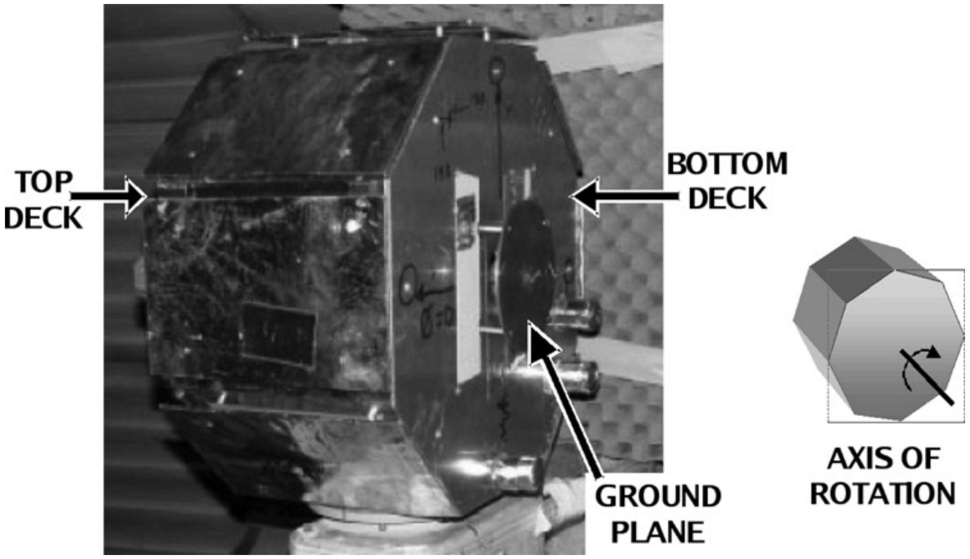

Fig. 5 Photograph of the ST5 mock-up with antennas mounted (only the antenna on the top deck is visible).

Table 1 Key ST5 antenna requirements.

Property	Specification
Transmit frequency	8470 MHz
Receive frequency	7209.125 MHz
VSWR	<1.2:1 at Transmit freq <1.5:1 at Receive freq
Original gain pattern	≥ 0 dBic, $40^\circ \leq \theta \leq 80^\circ$, $0^\circ \leq \phi \leq 360^\circ$
Additional gain pattern requirement	≥ -5 dBic, $0^\circ \leq \theta \leq 40^\circ$, $0^\circ \leq \phi \leq 360^\circ$
Input impedance	50 Ω
Diameter	<15.24 cm
Height	<15.24 cm
Antenna mass	<165 g

A. Evolutionary Antenna Design Software

As a result of the new ST5 mission requirements we needed to change both the type of antenna we were evolving and the fitness function. The original antennas we evolved were constrained to a monopole wire antenna with four identical arms, with each arm rotated 90° from its neighbors. There the EA evolved genotypes that specified the design for one arm and the phenotype consisted of four copies of the evolved arm. Because of symmetry, the previous four-arm design has a null at zenith that is built into the design and is unacceptable for the revised mission. To achieve an antenna that meets the new mission requirements the new antenna designs were configured to produce a single arm. In addition, because of the difficulties we experienced in fabricating branching antennas to the required precision, here we constrained our antenna designs to non-branching antennas. In the remainder of this section we describe the two evolutionary algorithms we used to evolve antennas for the ST5 mission and how we changed them to address the new requirements.

B. Parameterized EA for Non-Branching Designs

The first EA was used in our previous work in evolutionary antenna design[4] and it is a standard genetic algorithm (GA) that evolves non-branching wire forms. With this EA the design space used a vector of real-valued triplets that specify the X, Y and Z locations of segment end-points. The fitness function for this EA used pattern quality scores at 7.2 GHz and 8.47 GHz. Unlike the second EA, VSWR was not explicitly used in this fitness calculation, rather it

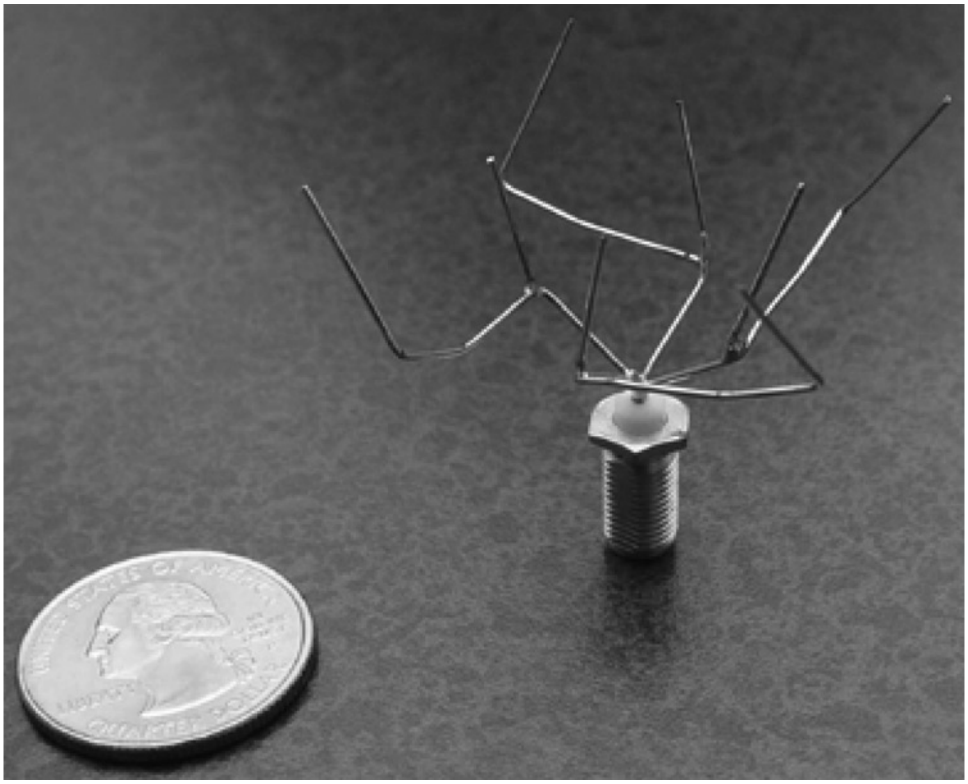

Fig. 6 Photograph of the evolved antenna.

is included implicitly by how it affects the gain pattern. To quantify the pattern quality at a single frequency, PQ_f, the following formula was used:

$$\mathrm{PQ}_f = \sum_{\substack{0^\circ \leq \phi < 360^\circ \\ 0^\circ \leq \theta \leq 80^\circ}} (\mathrm{gain}_{\phi,\theta} - T)^2 \quad \text{if } \mathrm{gain}_{\phi,\theta} < T$$

where $\mathrm{gain}_{\phi,\theta}$ is the gain of the antenna in dBic (right-hand polarization) at a particular angle, T is the target gain (3 dBic was used in this case), ϕ is the azimuth, and θ is the elevation. To compute the overall fitness of an antenna design, the pattern quality measures at the transmit and receive frequencies were summed, lower values corresponding to better antennas:

$$F = \mathrm{PQ}_{7.2} + \mathrm{PQ}_{8.47}$$

Modifying this evolutionary design system to produce antennas for the new orbit consisted of changing the fitness function to check angles $0^\circ \leq \theta < 40^\circ$ as well the original range of $40^\circ \leq \theta \leq 80^\circ$. This fitness function is fairly easy to modify by a non-expert as it merely requires changing two sets of parameters: the frequencies of interest, here it is set to 7.2 GHz and 8.47 GHz; and the angles of interest, in this case it is from 40° to 80°.

C. Open-Ended EA

The second EA uses an open-ended, variable-length representation in which elements of the genotype specify how to construct the antenna. Each node in the tree-structured representation is an antenna-construction operator and an antenna is created by executing the operators at each node in the tree, starting with the root node. In constructing an antenna the current state (location and orientation) is maintained and operators add wires or change the current state. The operators are as follows:

- `forward(length, radius)` – add a wire with the given length and radius extending from the current location and then change the current state location to the end of the new wire.
- `rotate-x(angle)` – change the orientation by rotating it by the specified amount (in radians) about the x-axis.
- `rotate-y(angle)` – change the orientation by rotating it by the specified amount (in radians) about the y-axis.
- `rotate-z(angle)` – change the orientation by rotating it by the specified amount (in radians) about the z-axis.

Since we constrained antennas to a single, bent wire with no branching each node in the genotype has at most one child. This constructive representation for encoding antennas is an extension of our previous work in using a linear-representation for encoding rod-based robots.[5] Aside from restricting antennas to not having branches, the only changes made to this evolutionary design system to address the new mission requirements were to change the fitness function.

The fitness function used to evaluate antennas is a function of the VSWR and gain values on the transmit and receive frequencies. These three components are multiplied together to produce the overall fitness score of an antenna design:

$$F = vswr \times gain \times standard\ deviation$$

The objective of the EA is to produce antenna designs that minimize F.

The VSWR component of the fitness function is constructed to put strong pressure to evolving antennas with receive and transmit VSWR values below the required amounts of 1.2 and 1.5, reduced pressure at a value below these requirements (1.15 and 1.25) and then no pressure to go below 1.1:

$$v_r = \text{VSWR at receive frequency}$$

$$v_r' = \begin{cases} v_r + 2.0(v_r - 1.25) & \text{if } v_r > 1.25 \\ v_r & \text{if } 1.25 > v_r > 1.1 \\ 1.1 & \text{if } v_r < 1.1 \end{cases}$$

$$v_t = \text{VSWR at transmit frequency}$$

$$v_t' = \begin{cases} v_t + 2.0(v_t - 1.15) & \text{if } v_t > 1.15 \\ v_t & \text{if } 1.15 > v_t > 1.1 \\ 1.1 & \text{if } v_t < 1.1 \end{cases}$$

$$vswr = v_r' v_t'$$

The gain-penalty component of the fitness function uses the gain (in decibels) in 5° increments about the angles of interest: from $0° \leq \theta \leq 90°$ and $0° \leq \phi \leq 360°$. For each angle, the calculated gain score from simulation is compared against the target gain for that elevation and the outlier gain, which is the minimum gain value beyond which lower gain values receive a greater penalty. Gain penalty values are further adjusted based on the importance of the elevation:

```
gain_penalty (i, j):
        gain = calculated gain at $\theta = 5° i$ , $\phi = 5° j$;
        if (gain ≥ target[i]) {
                penalty := 0.0;
        } else if ((target[i] > gain) and (gain ≥ outlier[i])) {
                penalty := (target[i] - gain);
        } else { /* outlier[i] > gain */
                penalty := (target[i]-outlier[i]) + 3.0 * (outlier[i] - gain));
```

```
}
return penalty * weight[i];
```

Target gain values at a given elevation are stored in the array `target[]` and are 2.0 dBic for i equal from 0 to 16 and are -3.0 dBic for i equal to 17 and 18. Outlier gain values for each elevation are stored in the array `outlier[]` and are 0.0 dBic for i equal from 0 to 16 and are -5.0 dBic for i equal to 17 and 18. Each gain penalty is scaled by values scored in the array `weight[]`. For the low band the values of `weight[]` are 0.1 for i equal to 0 through 7; values 1.0 for i equal to 8 through 16; and 0.05 for i equal to 17 and 18. For the high band the values of `weight[]` are 0.4 for i equal to 0 through 7; values 3.0 for i equal to 8 through 12; 3.5 for i equal to 13; 4.0 for i equal to 14; 3.5 for i equal to 15; 3.0 for i equal to 16; and 0.2 for i equal to 17 and 18. The final gain component of the fitness score of an antenna is the sum of gain penalties for all angles.

To put evolutionary pressure on producing antennas with smooth gain patterns around each elevation, the third component in scoring an antenna is based on the standard deviation of gain values. This score is a weighted sum of the standard deviation of the gain values for each elevation θ. The weight value used for a given elevation is the same as is used in calculating the gain penalty.

This fitness function differs from the one we used previously[6] in the fidelity to which the desired gain pattern can be specified and in explicitly rewarding for a smooth pattern. Our previous fitness function with the constructive EA had one target gain value for all elevations and weighted all elevations equal. With the new fitness function different target gain values can be set for different elevation angles and also the importance of achieving the desired gain at a given angle is specified through setting the weight value for a given elevation. The other difference with this fitness function is that previously there was a separate penalty for "outlier" gain values whereas in the new fitness function this is included in the gain component of the fitness score and a new component that measures pattern smoothness is included.

While this second fitness function appears to require a significant amount of expertise to modify so as to evolve antennas for a different gain pattern, in fact only a few parameters need to be set. First, the desired frequencies, along with their corresponding VSWR values, are set. Then the desired minimum and maximum gain at each elevation is set, with 5° increments between each elevation. Next, a weight value is set for each elevation to indicate how important that elevation is.

IV. Evolved Antennas

To re-evolve antennas for the new ST5 mission requirements we used the same EA setup as in our initial set of evolutionary runs, however, we did not seed the first generation with previously evolved antenna designs. For the non-branching EA, a population of fifty individuals was used, 50% of which is kept from generation to generation. The mutation rate was 1%, with the Gaussian mutation standard deviation of 10% of the value range. The non-branching EA was halted after one hundred generations had been completed, the EA's best score was stagnant for forty generations, or EA's average score was stagnant for ten generations. For the branching EA, a population size of two hundred individuals was evolved with a generational EA. Parents were selected with remainder stochastic sampling based on rank, using exponential scaling. New individuals were created with an equal probability of using mutation or recombination. As before, NEC4 was used to simulate all antenna designs.

The best antennas evolved by the two EAs were then evaluated on a second antenna simulation package, WIPL-D, with the addition of a 6" ground plane to determine which designs to fabricate and test on the ST5 mock-up. The best antenna design from each EA was selected for fabrication and these are shown in Fig. 7. For these runs a single antenna evaluation took a few seconds of wall-clock time to simulate and an entire run took approximately six to ten hours.

A. Simulated Results

Both antenna designs have excellent simulated RHCP patterns, as shown in Fig. 8 for the transmit frequency. The antennas also have good circular polarization purity across a wide range of angles, as shown in Fig. 9 for ST5-104.33. To the best of our knowledge, this quality has never been seen before in this form of antenna.

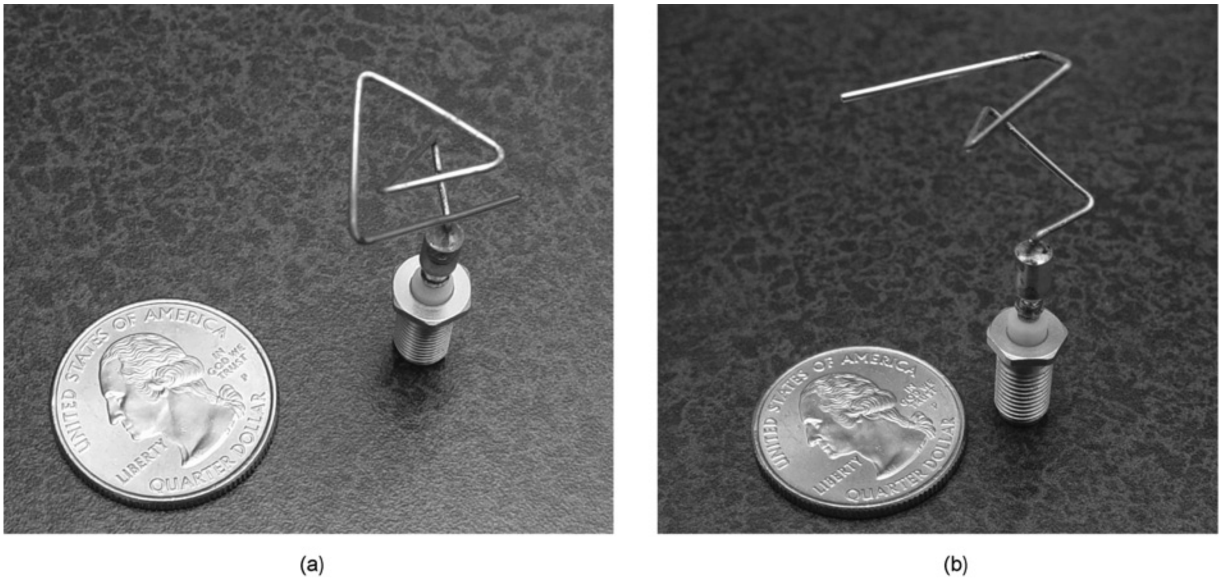

Fig. 7 Evolved antenna designs: (a) evolved using a vector of parameters, named ST5-104.33; and (b) evolved using a constructive process, named ST5-33.142.7.

B. Measured Results

The antennas were measured on the ST5 mock-up (Fig. 5), and the results are shown in Fig. 10. Because each spacecraft has two antennas, one on each side of the spacecraft, of interest is the performance of pairs of antennas on the spacecraft. The evolved antennas were arrayed with a Quadrafilar Helix Antenna (QHA) developed by New Mexico State University's Physical Science Laboratory that was the original antenna for this mission. This figure shows plots of two QHA antennas together, and a QHA and an ST5-104.33 antenna. Results are similar for ST5-33.142.7, which is the design that has been selected for use on the ST5 mission. Compared to using two QHAs together, the evolved antennas have much greater gain across the angles of interest.

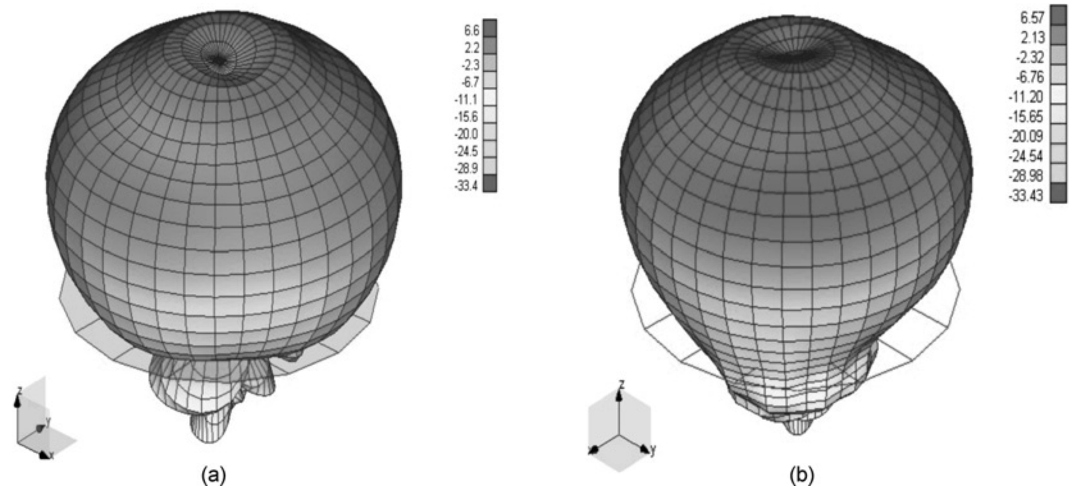

Fig. 8 Simulated 3D patterns for ST5-104.33 and ST5-33.142.7 on 6" ground plane at 8470 MHz for RHCP polarization. Simulation performed by WIPL-D. Patterns are similar for 7209 MHz.

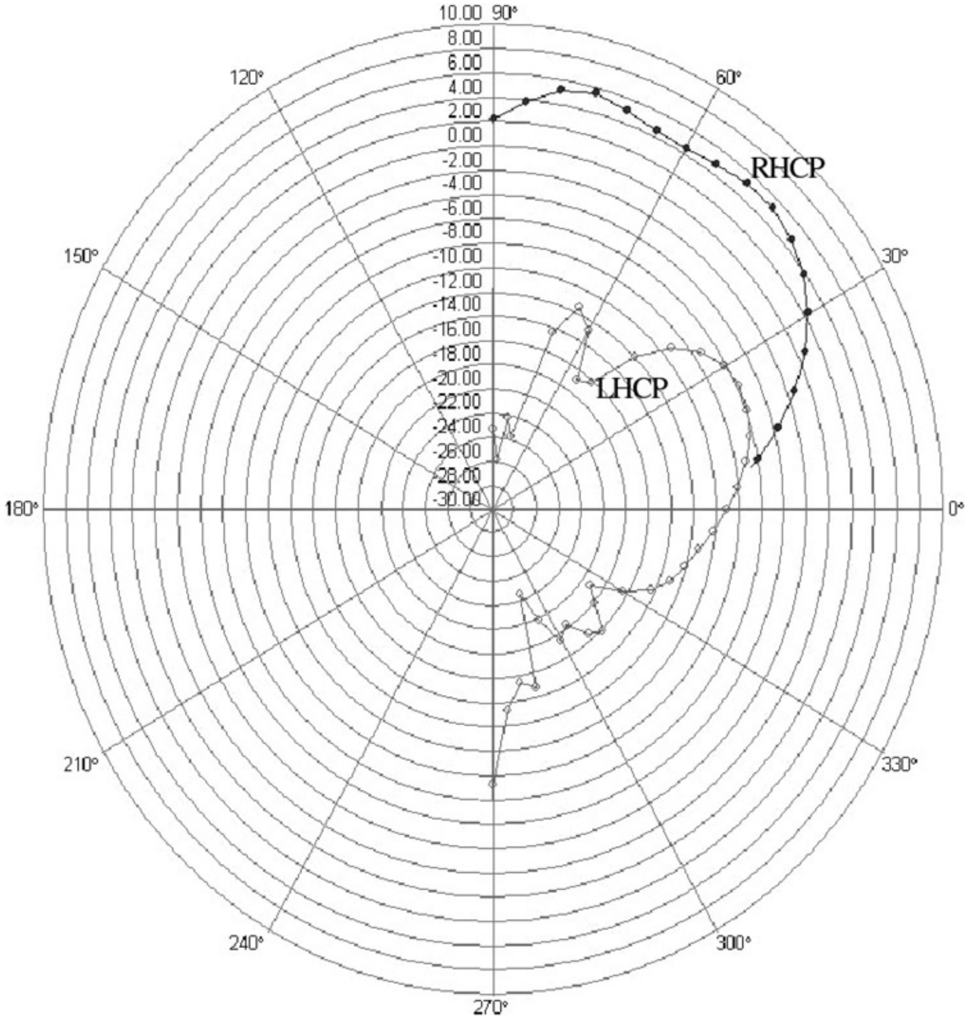

Fig. 9 RHCP vs LHCP performance of ST5-104.33. Plot has 2 dB/division.

V. Discussion

We have presented our software tools that were used to design antennas for two NASA missions. While the Mars Odyssey application was a proof-of-concept study, the ST5 X-band evolved antennas were fabricated and flew on the mission. While the first set of evolved antennas were mission compliant, a change in launch vehicle resulted in a change in orbit for the ST5 spacecraft and a change in requirements for their communication antennas. In response to this change in requirements we reconfigured our evolutionary design systems and in under four weeks we were able to evolve new antenna designs that were acceptable to ST5 mission planners.

Because evolved antennas are a relatively new technology (we are not aware of any deployed/fielded evolved antennas to date) convincing the mission management team to fly the evolved antennas aboard the ST5 mission was something of a challenge. The ST5 mission was a technology validation mission, a fact that made it easier to accept the evolved antennas. However, because antennas are a single of point of failure, it is harder to justify a technology validation compared to a new scientific instrument. In the end, both traditional (quadrifilar helix) and evolved antennas were flown, one of each per spacecraft.

Compared to the conventionally-designed antennas, the evolved antennas have a number of advantages in regard to power consumption, fabrication time and complexity, and performance. Lower power requirements result from

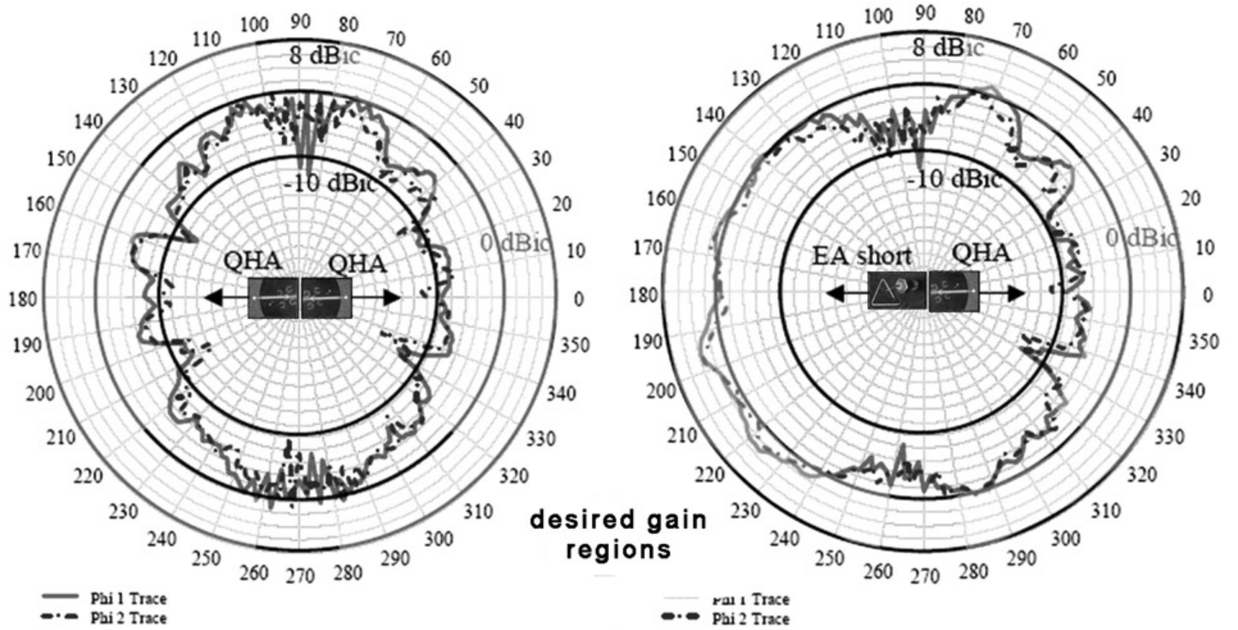

Fig. 10 Measured patterns on ST-5 mock-up of QHA antenna and ST5-104.33 plus QHA antenna. $\phi_1 = 0°, \phi_2 = 90°$.

achieving high gain across a wider range of elevation angles, thus allowing a broader range of angles over which maximum data throughput can be achieved. Since the evolved antenna does not require a phasing circuit, less design and fabrication work is required. In terms of overall work, the evolved antenna required approximately three person-months to design and fabricate whereas the conventional antenna required about five. Lastly, the evolved antenna has more uniform coverage in that it has a uniform pattern with small ripples in the elevations of greatest interest $(40° - 80°)$. This allows for reliable performance as the elevation angle relative to the ground changes.

The evolved ST5 antennas represent the first antennas to be fielded with an evolved design topology, and the first artificially evolved object to fly in space.

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