GECCO-2005

Evolutionary Computation in Practice

Evolutionary Computation for the Automated Design of Space Systems

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Evolutionary Computation Technologies for the Automated Design of Space Systems

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ABSTRACT

The Evolvable Computation Group, at NASA's Jet Propulsion Laboratory, is tasked with demonstrating the utility of computational engineering and computer optimized design for complex space systems. The group is comprised of researchers over a broad range of disciplines including biology, genetics, robotics, physics, computer science and system design, and employs biologically inspired evolutionary computational techniques to design and optimize complex systems. Over the past two years we have developed tools using genetic algorithms, simulated annealing and other optimizers to improve on human design of space systems. We have further demonstrated that the same tools used for computer-aided design and design evaluation can be used for automated innovation and design. These powerful techniques also serve to reduce redesign costs and schedules.

Computationally derived evolutionary designs have shown competitive advantages over human created designs in complexity, creativity and robustness. Our group has demonstrated this in the areas of power system design, low-thrust trajectory optimization, robotic arm deployment path finding, MEMS micro-gyro calibration, mission planning and scheduling, neural network design, and avionics architecture design. We have also developed a framework for the rapid introduction and parallelization of optimization problems in an evolutionary environment using computer clusters.

Four areas, described in this paper, demonstrate human competitive performance. Optimizations and designs using evolutionary techniques result in designs matching or exceeding the performance of those derived from traditional means by human designers. Metrics used for this performance evaluation include design time, robustness and fault-tolerance, cost, and comparison to accepted and flown designs. The areas described in this paper are the automatic design of power systems, robotic arm deployment path planning, the design of low-thrust trajectories and the automatic tuning of MEMS micro-gyroscopes. We expect that future work will lead to further advances in computational engineering and in the development of Computer Optimized Design (COD).

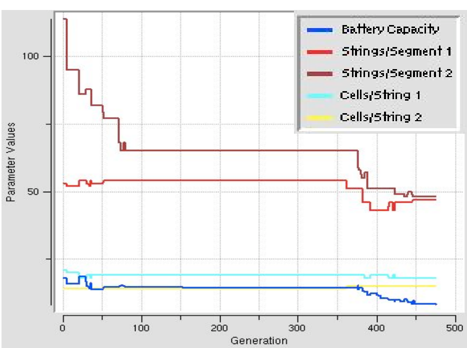
Background

PROJECT OVERVIEW

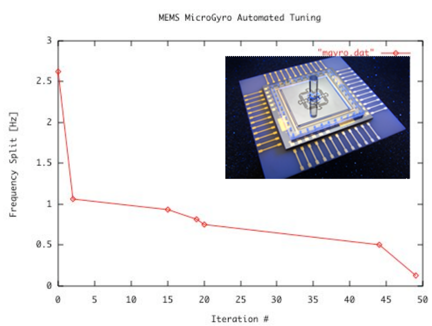
Evolutionary Computation and Automated Design

The Evolvable Computation Group, lead by Dr. Rich Terrile, is tasked with developing the tools and infrastructure to allow computational engineering and computer optimized design of complex space systems at JPL. The group is comprised of highly skilled researchers over a broad range of disciplines including biology, genetics, robotics, physics, computer science and system design. We use biologically inspired evolutionary techniques to design and optimize complex systems. Over the past two years we have demonstrated that these techniques greatly amplify the power of system engineers in several areas relevant to the design of space systems.

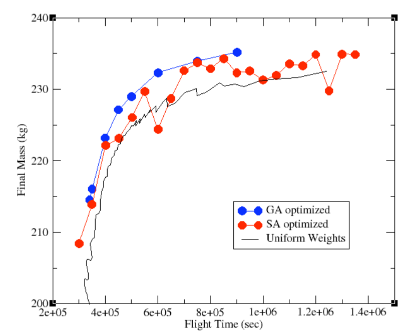
<u>Portfolio of Human Competitive Successes</u>



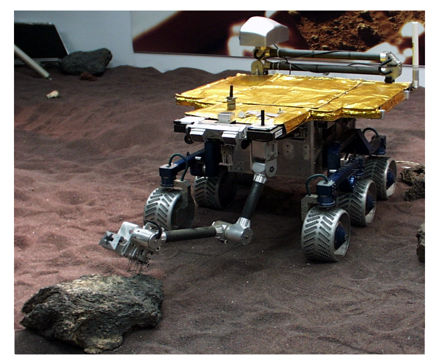
Power System Design



MEMS Gyro Tuning



Low Thrust Trajectory Optimization



Robotic Arm Path Planning

Task Disciplines

- Biology and Evolutionary/Developmental Systems
- Genetics
- Computer Science
- Avionics Architecture
- Sequence Generation
- Evolvable Hardware
- Robotics and Biology
- Advanced Robotics
- Multi-Mission Design Tools
- Low-Thrust Trajectory Optimization
- Nanoelectronics
- Evolutionary Frameworks

Vision

The *vision* of this Center is to develop the tools and infrastructure to enable computational engineering and computer optimized design of complex space systems at JPL and to incorporate their general use in flight projects.

- The Center is an extension of the Evolutionary Computation Group which is comprised of researchers over a broad range of disciplines including biology, genetics, robotics, physics, computer science and system design, and employs biologically inspired evolutionary computational techniques to design and optimize complex systems.
- Over the past 2.5 years we have developed tools using genetic algorithms, simulated annealing and other optimization techniques to improve on human design of space systems.
- We have further demonstrated that the same tools currently used for computer-aided design and design evaluation can be incorporated into an evolutionary framework and used for automated innovation and design.
- These powerful techniques greatly amplify the performance of a system engineer and also serve to reduce redesign costs and schedules.
- Improvements over human designed tasks routinely exceed 10-20%.

The *long term vision* is to couple the level of complexity in evolutionary computational systems to Moore's Law increases in computational power. This will lead to the eventual evolution of software and hardware systems which are innovative and robust.

- To accomplish this we will derive about 25% of our funding from R&TD to fund research tasks designed to utilize future levels of advanced computing with a range of more complex applications, i.e., learning neural networks, machine written software, software verification, etc.

Evolutionary Computation

Design Rules and Complexity

Sandstone to Cities

Hardware Design Rules

Design Rules Based on Knowledge of Physical Laws
Physics, Chemistry, Material Science, etc.

Large Library of Codified Design Rules
Based on Mathematics and Experience

Standards and Tools

Results: Cities, Aircraft and Computers

Code to Operating Systems

Software Design Rules?

Partially-Codified Design Rules Based on
Individual Experience

Design Rules Individually or
Institutionally Derived

Results: Windows, Air Traffic Control, Nasdaq

Molecules to Minds

Nature's Design Rules

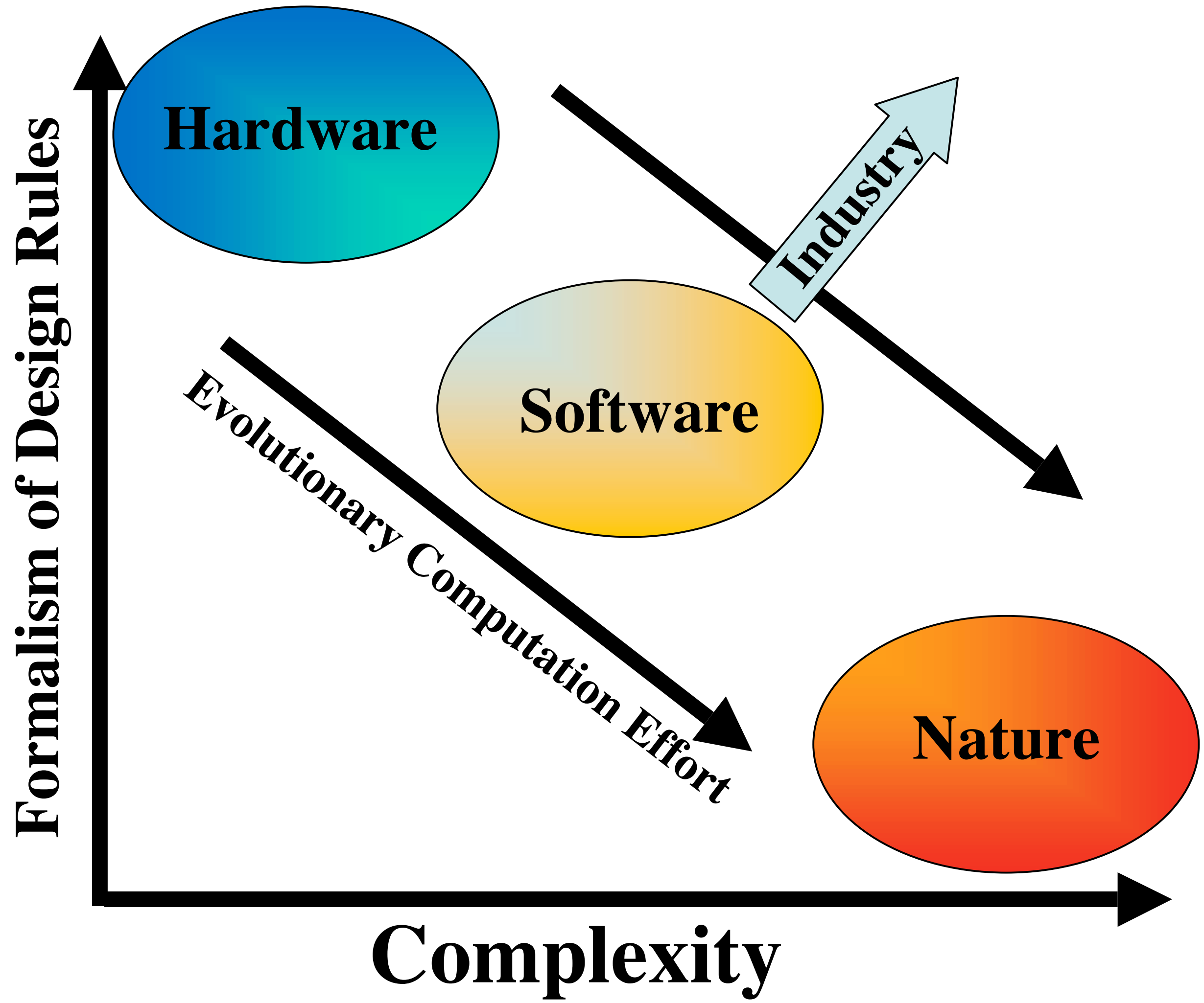
Begin with an Information System

Rule 1: Random Variation

Rule 2: Selection

Repeat

Results: Life, the Human Brain and Mind



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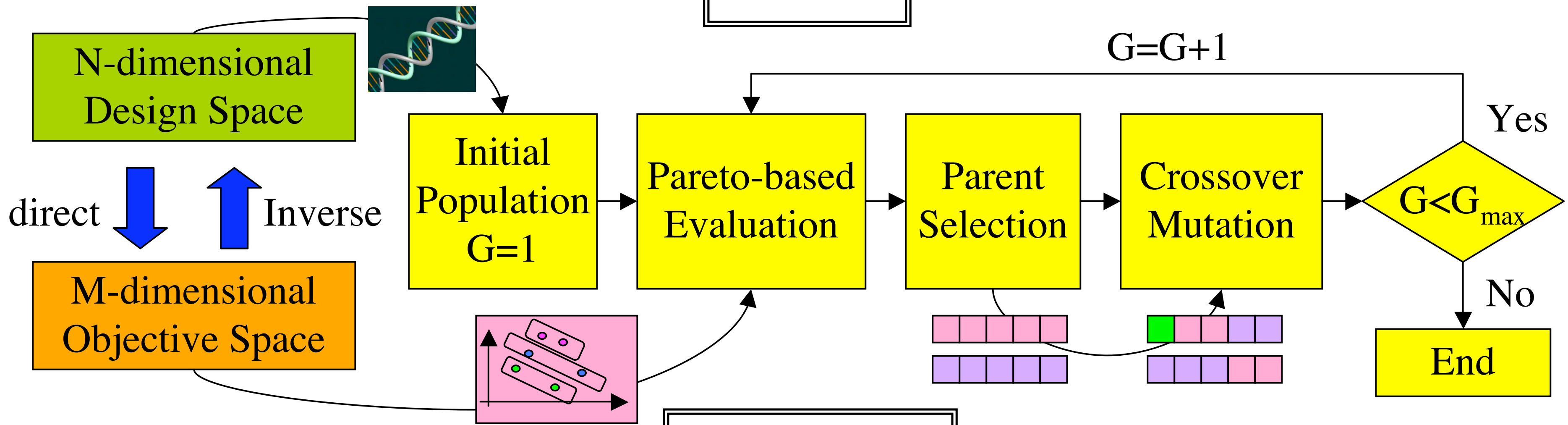
Design Optimization with Genetic Algorithms

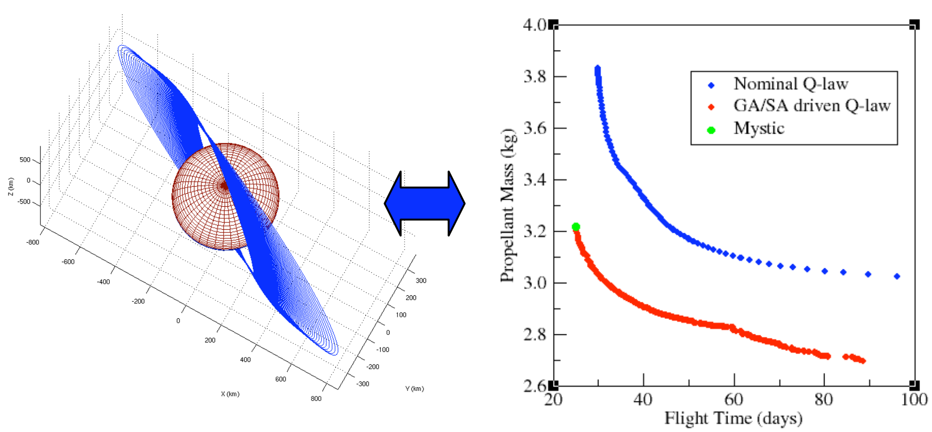
Method



Application

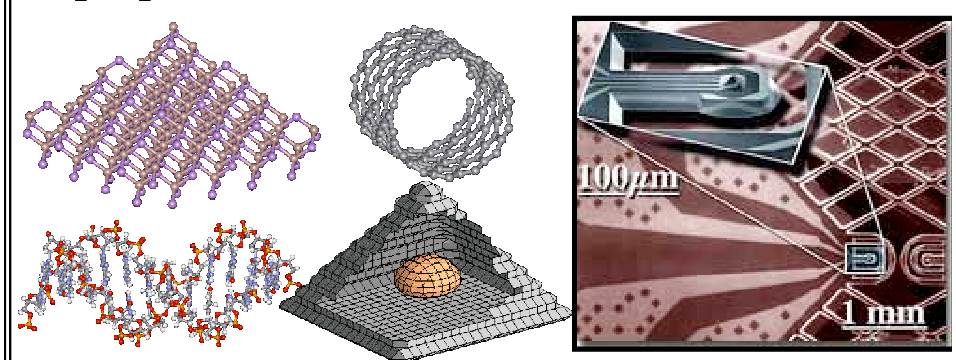
Trajectory Design

- Design parameters: thrust sequence
- Objective parameters: flight time, consumed propellant mass



Material/Device Design

- Design parameters: atomic structure, nanostructure geometry.
- Objective parameters:material/device properties



Elements of Computer Optimized Design

Design + **Computational Model** + **Evolutionary Framework**

Design

Single design based on expertise of human designer

↓

Traditional Design

Allows only one point of design space to be examined

Computational Model

Predicts and evaluates the outcome (design) of variable sets of input parameters

↓

Computer Aided Design (CAD)

Allows rapid exploration of alternative designs by human designer

Evolutionary Framework

Competes a population of variable input parameters over many generations

↓

Computer Optimized Design (COD)

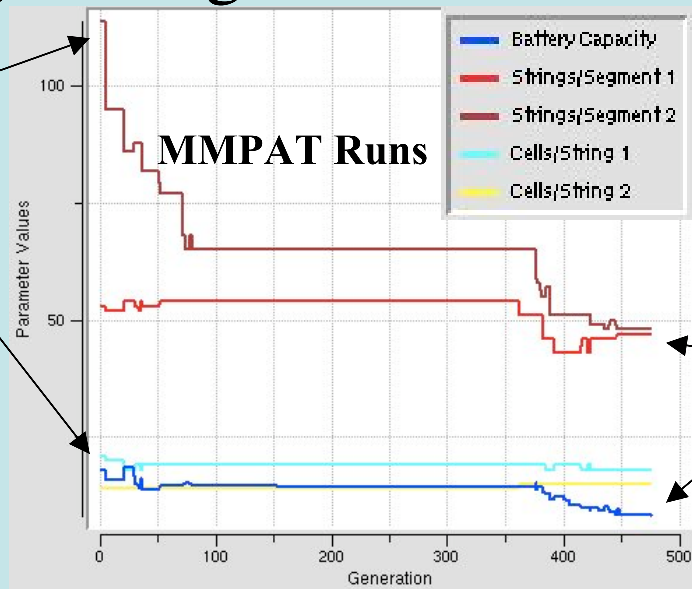
Allows automatic exploration and optimization of designs over huge volumes of design space

Evolutionary Computation

Automated Design Using JPL Multi-Mission Design Tools

Optimization started with Deep Impact design parameters

Optimization statistically weighted to consider cost and mass



Optimization used Deep Impact cruise activity sequence

For this sequence, requirements could be met with smaller battery and smaller solar array

Approach:

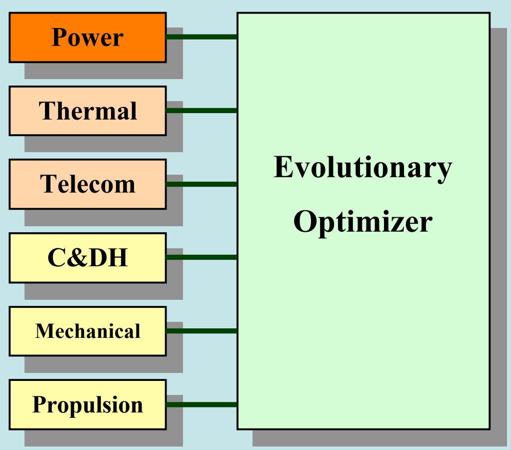
- Integrate existing S/C resource and performance analysis simulations into an optimization infrastructure

Results:

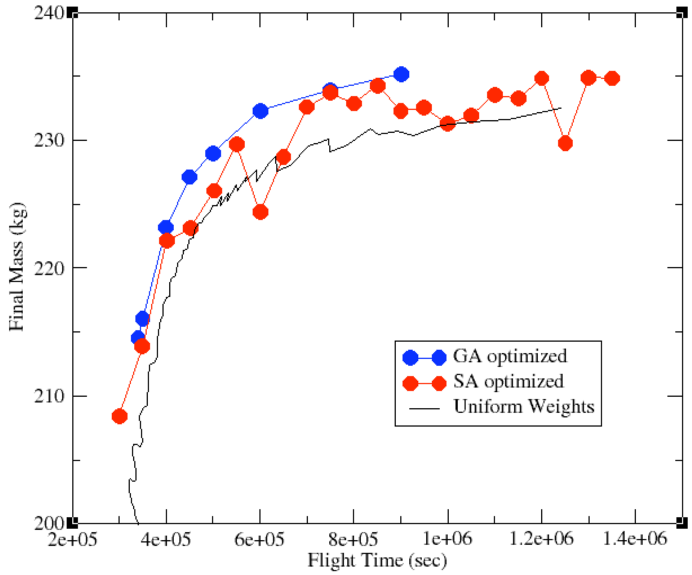
- Performed search and evaluation of more than 20,000 continuously improving subsystem design solutions for both cruise and surface operations **in one day**
- Automated Design of S/C subsystems works!

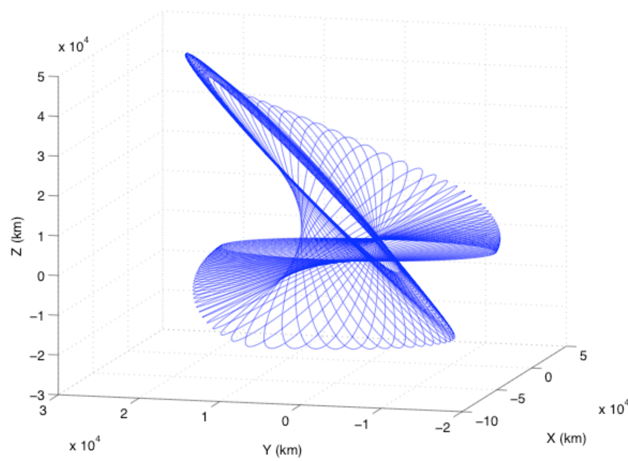
Future:

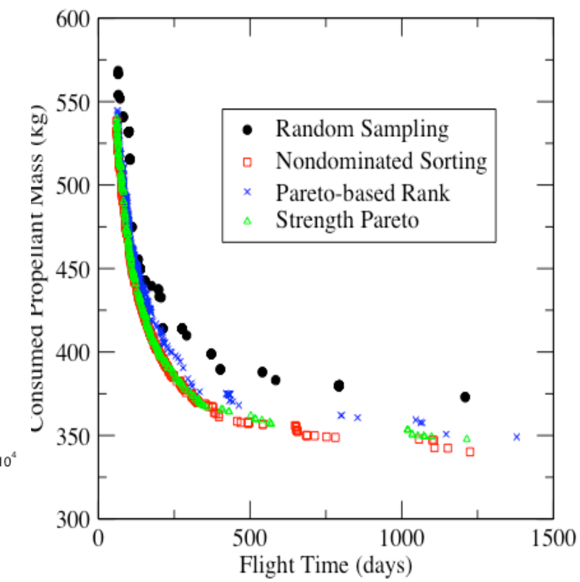
- Integrate more subsystems: thermal, telecom, etc. for a complete S/C solution



Low Thrust Trajectory Task







Our low-thrust trajectory effort has delivered a tool capable of quickly optimizing the parameters of a state-of-the-art control law for orbit transfers around a central body, yielding a 10-15% propellant savings over the nominal control law and matching the performance of full trajectory optimization techniques which can take days to run. We are extending our work to more general low thrust trajectories and using direct optimizations (without any assumptions beyond the physical models). We will also examine the sensitivity and error budget of the trajectory designs. Exploration of chaotic transfer regions will also allow us to map out the so called interplanetary highway of low energy transfers.

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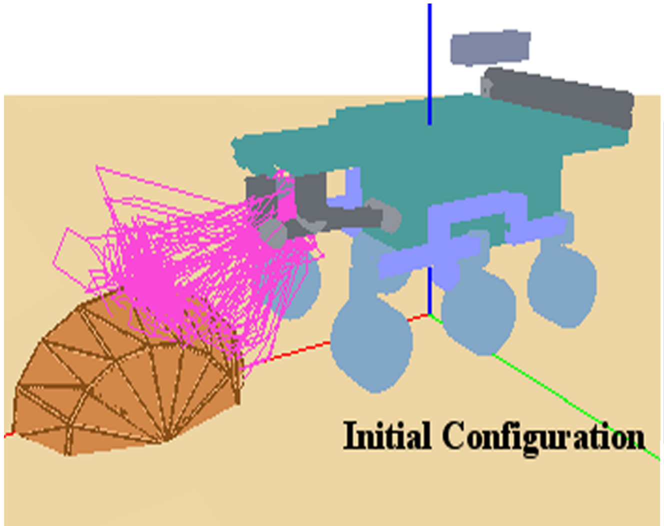
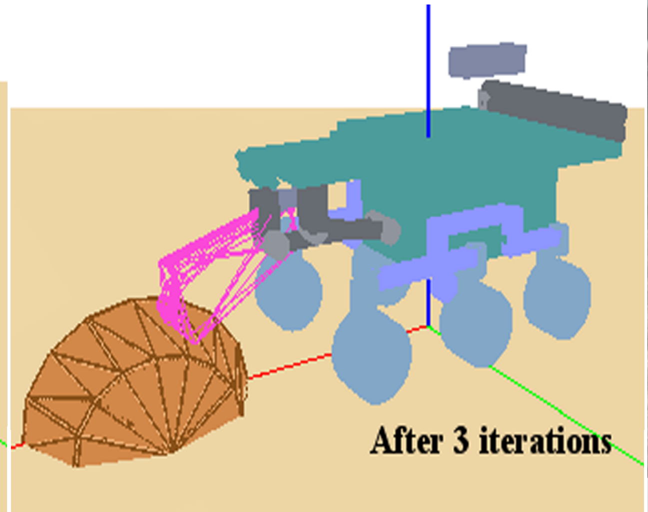
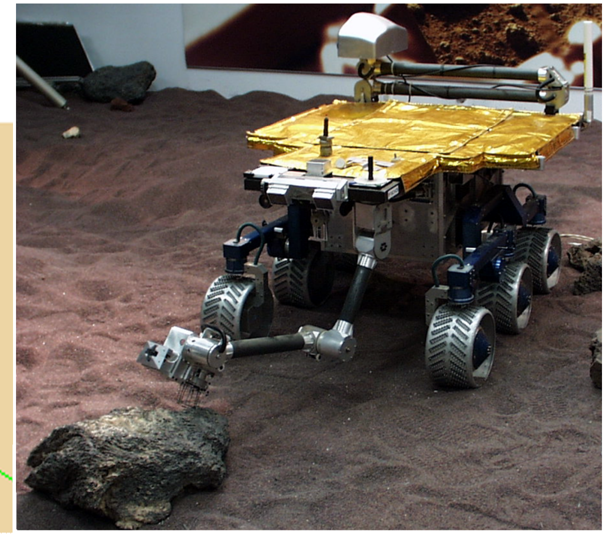
Evolvable Computation

MER Robotic Arm Path Planning Task





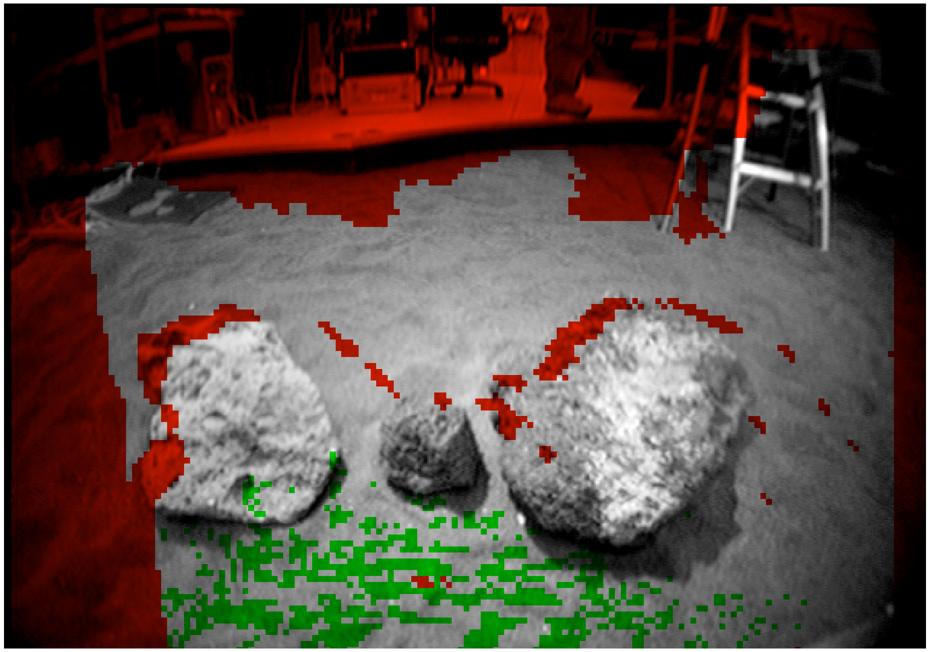


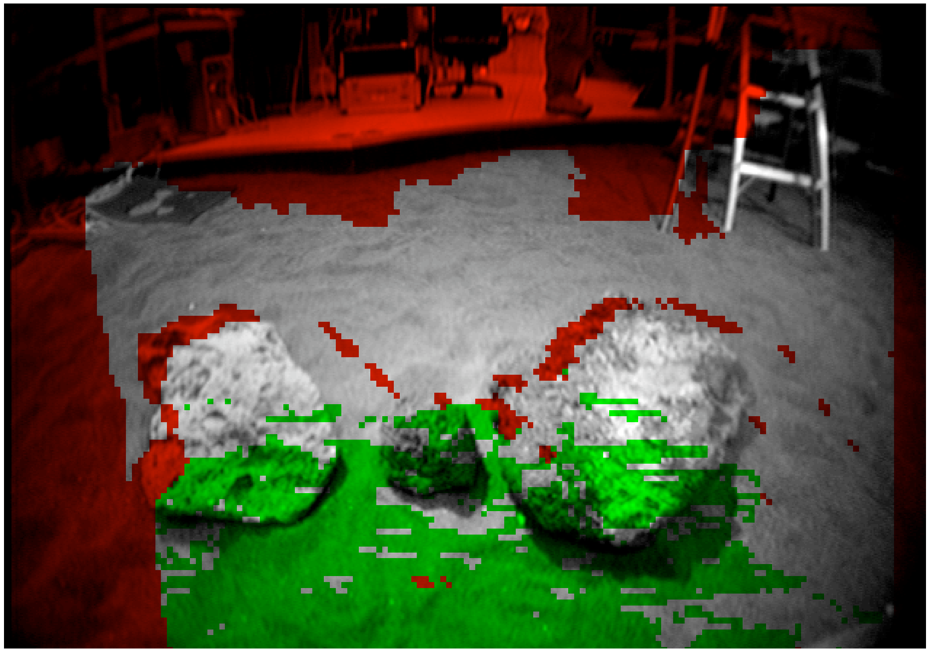
The left two images are from the Genetic Algorithm (GA) for arm control being developed by Hrand Aghazarian. They are taken directly from the simulation environment that is used for testing the FIDO rover algorithms (same GA object code running on rover as that in the simulation). As can be seen, after three iterations the populations of possible paths are converging to multiple methods. The right image shows a GA arm deployment on the FIDO Rover. We propose to extend the algorithms to dual manipulators (for MSL) with higher degrees of freedom for doing other tasks such as digging.

This path finding algorithm can potentially save MER hours of surface operations per sol by providing a very fast plan for acquiring any surface target. The algorithm takes less than one second to determine an optimal safe path. Traditional flight software can only find paths to a limited sub-set of targets and only after several hours of design effort. The potential saving to MER (or to applications on the Mars Science Laboratory (MSL)) could be in the tens of millions of dollars.

Evolvable Computation

MER Robotic Arm Path Planning Task





Comparison of digital terrain maps showing reachability of targets with the FIDO robotic arm. Green areas are reachable with arm path solutions. Grey areas are not reachable and red areas indicate no data available for a solution. Left image is default elbow up reachability derived from the FIDO arm path algorithm. This algorithm derives an un-optimized safe path to each target. The right image is the same terrain map analyzed with a genetic algorithm to find the safest paths to targets. The larger green or reachable area of the genetic algorithm is an indication of the power of the technique in not only providing a greater number of targets, but also in providing the fittest arm path solutions with respect to safety from arm (self and terrain) collisions. Additionally, the genetic algorithm is efficient enough to run on the rover computer without the need for ground interaction.

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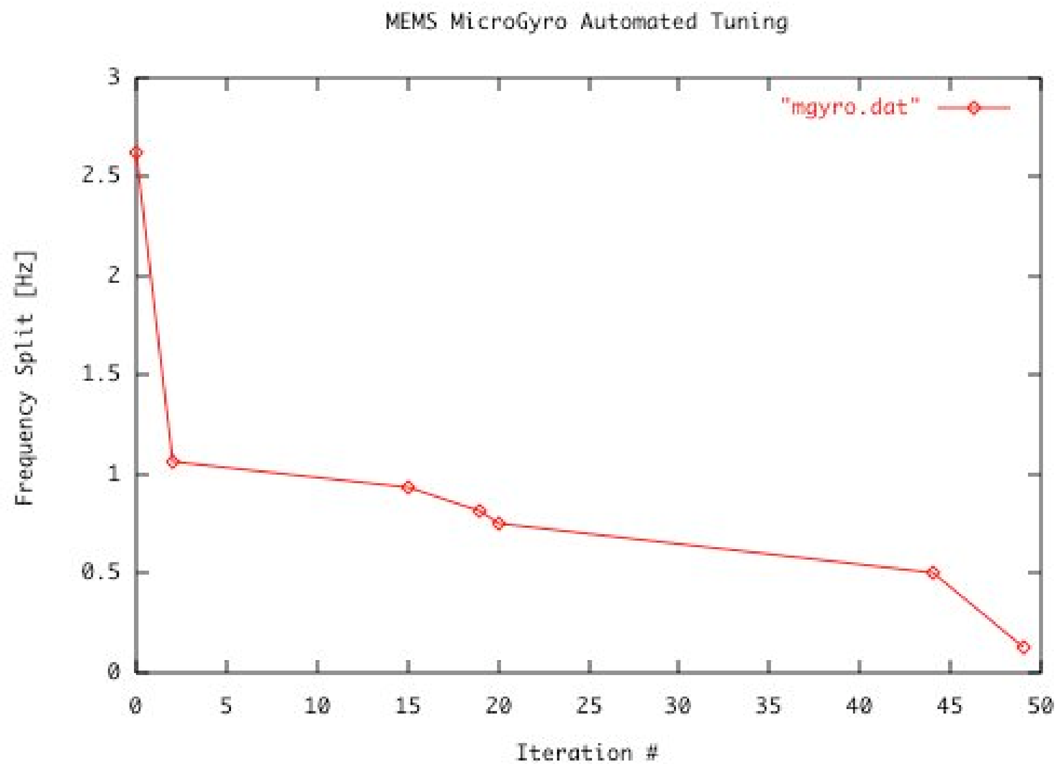
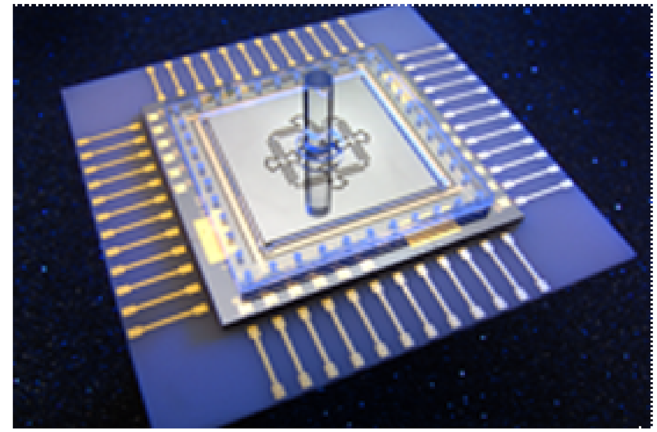
Evolvable Computation

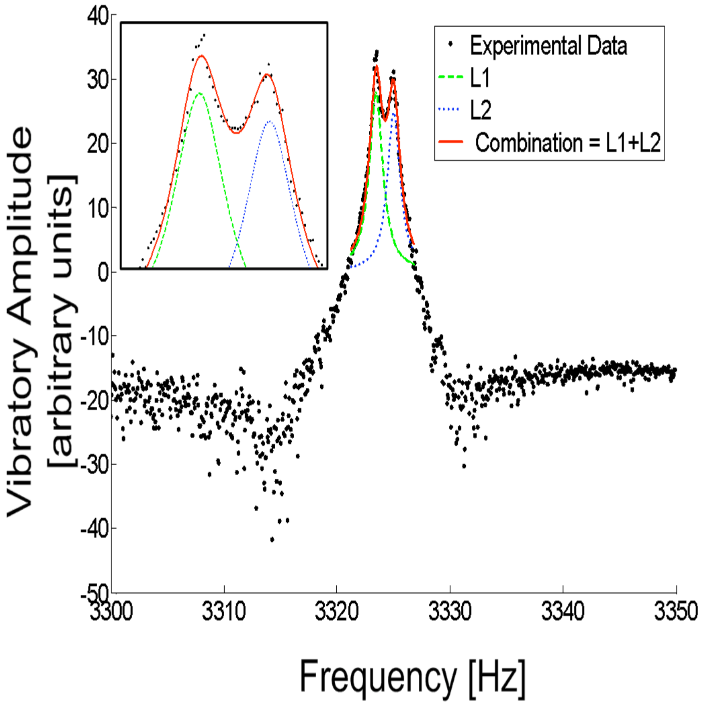
Project: Tuning of MEMS Micro-gyro

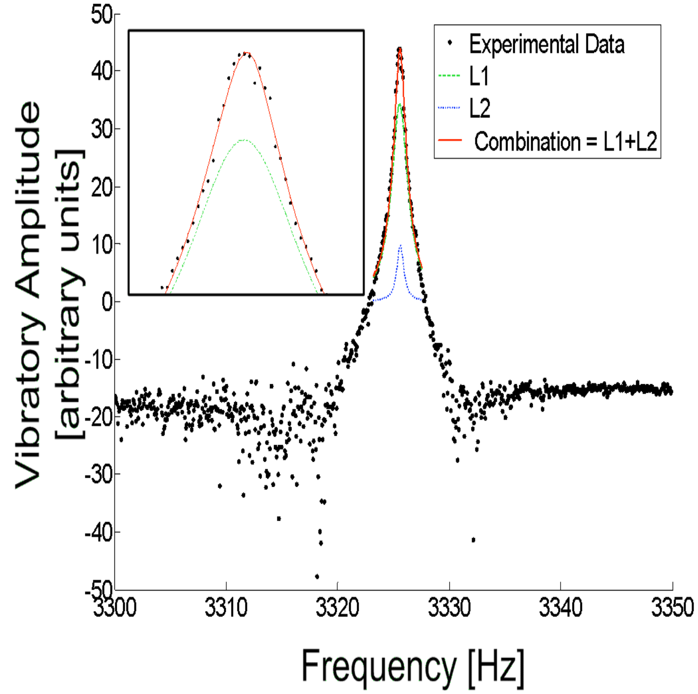




We demonstrated automatic tuning of MEMS Micro-gyros to frequency splits of less that 0.125 Hz in one hour. Smaller splits are better and compare to 0.2 Hz for humans in several hours. In FY05 we will look at defining the necessary components for integrating the tuning into the MEMS gyro. This will allow the development of a MEMS gyro with a fraction of the mass and power of existing units.

Project: Tuning of MEMS Micro-gyro





The frequency split before tuning. The two Lorentzian fitting curves are shown, as dashed and dotted lines below the solid line indicating the sum of the curves. The inset shows the details of the peak data points with a frequency split of 1.6Hz.

The frequency split after tuning is shown, reduced to approximately 0.05Hz.

Summary

- The Evolutionary Computation Group was selected as one of the R&TD program's success stories.
- Evolution works
  - Demonstrated automatic optimization of complex design problems.
  - Demonstrated human competitive performance in several JPL related areas of design.
  - Demonstrated feasibility, application and advantage.
- Recognized Progress
  - In two years we have developed an externally recognized group in the field of Evolutionary Computation.
  - Over ten publications in the last year.
  - NTRs and winning proposals from NASA Office of Exploration
- Future challenge
  - Incorporating evolutionary techniques into the flight projects.
  - Establishing computational engineering as a standard practice at JPL.
  - Maintaining the Evolutionary Computation Group at JPL.
    - Creation of the Center for Evolutionary Computation and Automated Design

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