Evolutionary Computing for Spacecraft Power Subsystem Design Search and Optimization

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Agenda

- Evolution
- Evolutionary Computing
- Trade Studies and the Spacecraft Lifecycle
- Multi-Mission Power Analysis Tool
- PERSON Evolutionary Computing Environment
- Objective Fitness Function – Weighted Sum Approach
- Deep Impact Test Cases
- MER Test Cases
- New Objective Fitness Function – Niched Elitist
- Future Work

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  MMPAT-EC Originator and Task Lead

What is Evolution?

Evolution is a process of change over time.

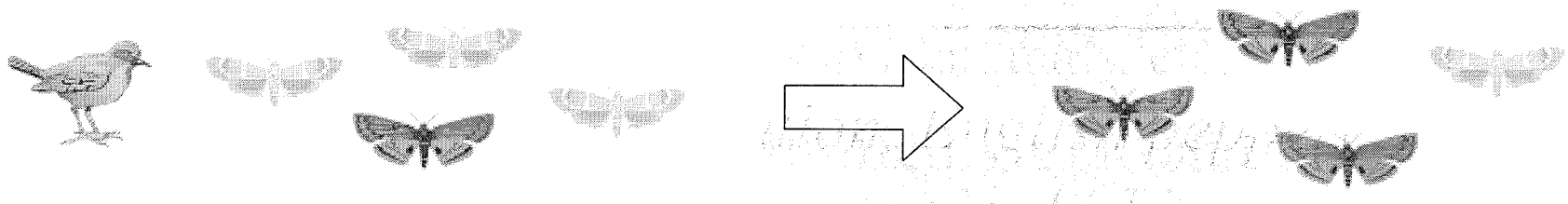
1. **Microevolution** refers to limited variation that takes place in a type or family. Change happens within a group, but the descendant is clearly of the same type as the ancestor.
   - Artificial Selection of Dogs, Horses, Cows, Beets, etc.
   - Natural Selection of Peppered Moths,"Super Germs", etc.

2. **Macroevolution** refers to major evolutionary changes such as the development of new types from previously existing, but different, types.
   - Dinosaurs to Birds, Reptiles to Mammals, etc.

Microevolution Example

During the industrial revolution, English peppered moth evolved from a light spotted color to dark grey color as birch trees became darker with soot.

- Diverse moth population (Random Variation)
- Darker trees made light moths easier for birds to see (Selection Pressure)
- Dark grey moth genes dominated the population (Reproductive Advantage)



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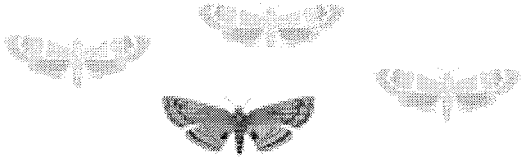
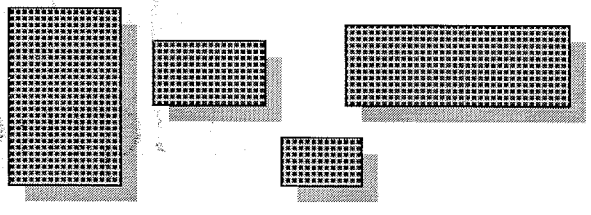
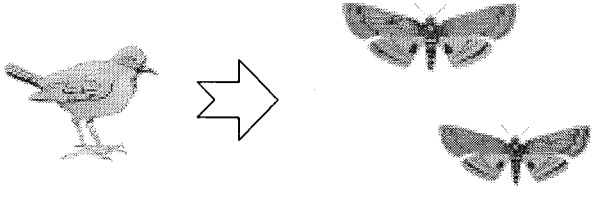
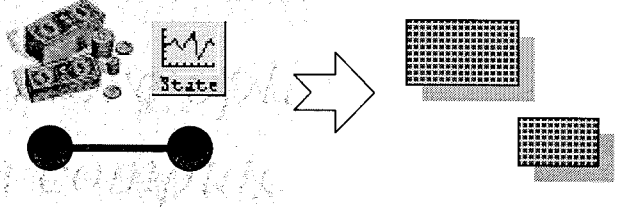
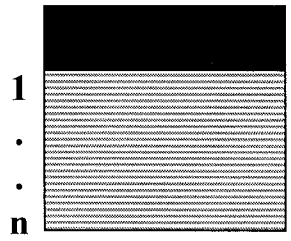
What is Evolutionary Computing?

Evolutionary Computing seeks one or more optimal solutions for a given system by using a computer program to simulate the biological processes of natural selection

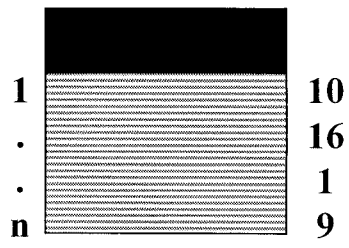
Evolution	**vs.**	**Evolutionary Computing**
	Genetic Coding	Type solar_array { int cell_type int num_strings int num_cell_per_string }
	Population Generation	
	Survival of the Fittest	

Evolutionary Computing
Classical Approach

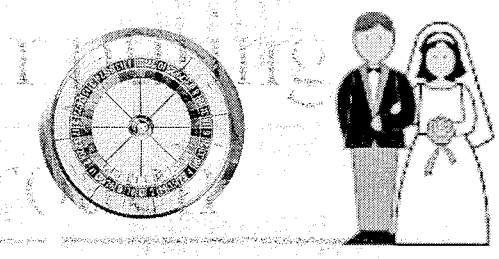
0. Start with a randomly distributed population of "parent" solutions



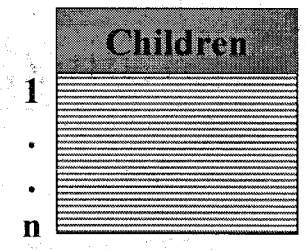
1. Assign a fitness value to each parent

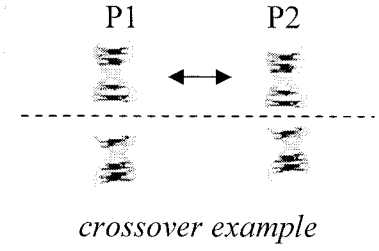


2. Randomly select two parents to reproduce



3. Create children by combining parent parameters (crossover). Possibly randomly mutate the child's parameters.





4. Children now become parents.

Note: the more fit parents should have a higher probability of being selected to reproduce

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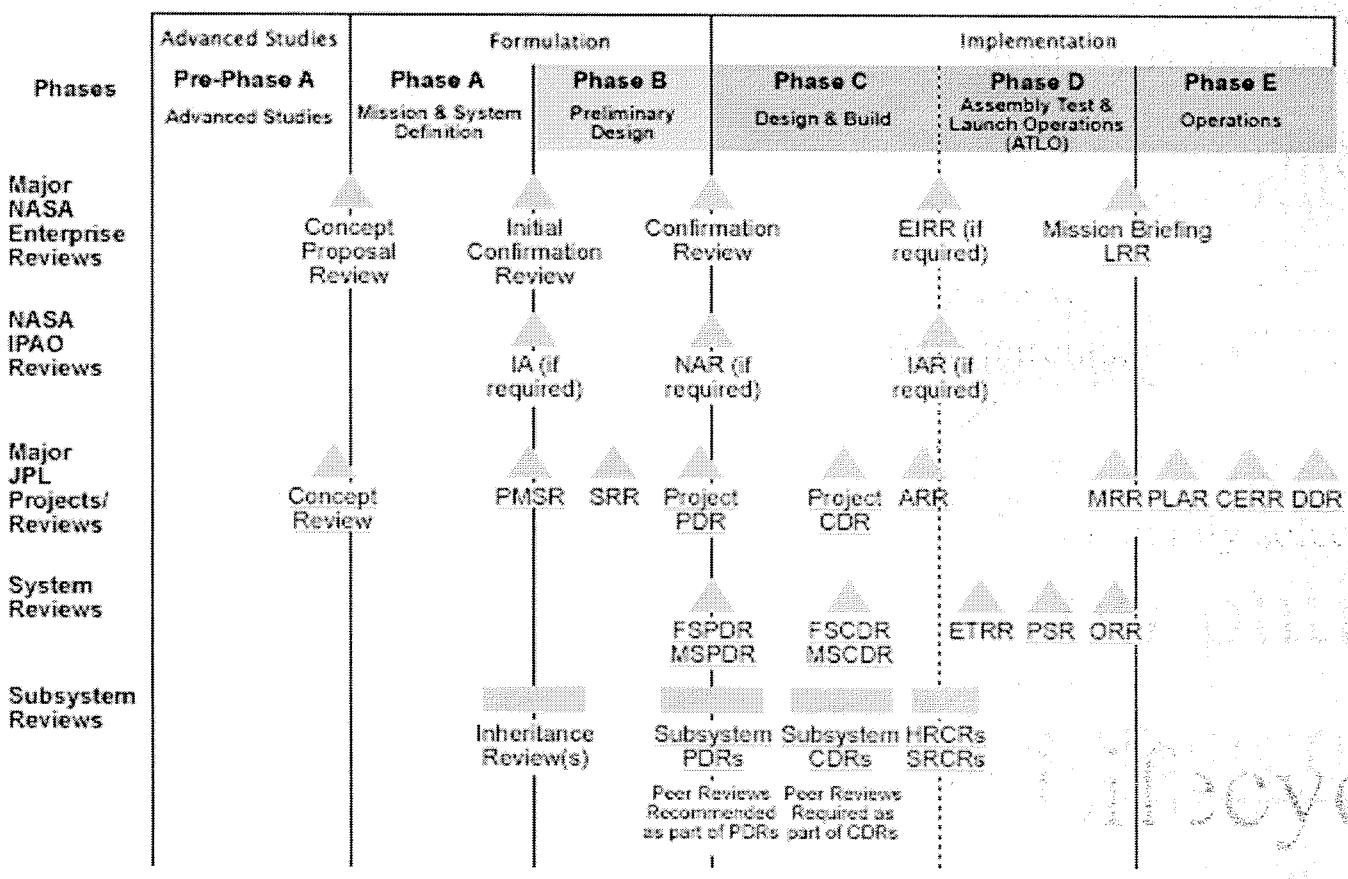
JPL Project Lifecycle



Reviews:

ARR - Assembly,Test and Launch Operations Readiness Review
CDR - Critical Design Review
CERR - Critical Event Readiness Review
DDR - Data Delivery Review
EIRR - External Independent Readiness Review
ETRR - Environmental Test Readiness Review
FSCDR - Flight System Critical Design Review
FSPDR - Flight System Preliminary Design Review
HRCR - Hardware Requirements/Certification Review
IA - Independent Assessment
IAR - Independent Annual Review
LRR - Launch Readiness Review
MSCDR - Mission System Critical Design Review
MSPDR - Mission System Preliminary Design Review
MRR - Mission Readiness Review
NAR - Non Advocate Review
ORR - Operations Readiness Review
PDR - Preliminary Design Review
PLAR - Post Launch Assessment Review
PMSR - Preliminary Mission and Systems Review
PSR - Pre Ship Review
SRCR - Software Requirements/Certification Review
SRR - System Requirements Reviews

Products	Study Concept	Preliminary Design Project Plan Sizing Costing *What to Build* *Trajectory* *Launch Date* *Who Does Work*	Requirements Schedules Specifications	Flight System, Instruments Designed & Built	Assemble Test Launch	Science Data

**from PSO, EC Approved Life Cycle Chart Dec. 2001*

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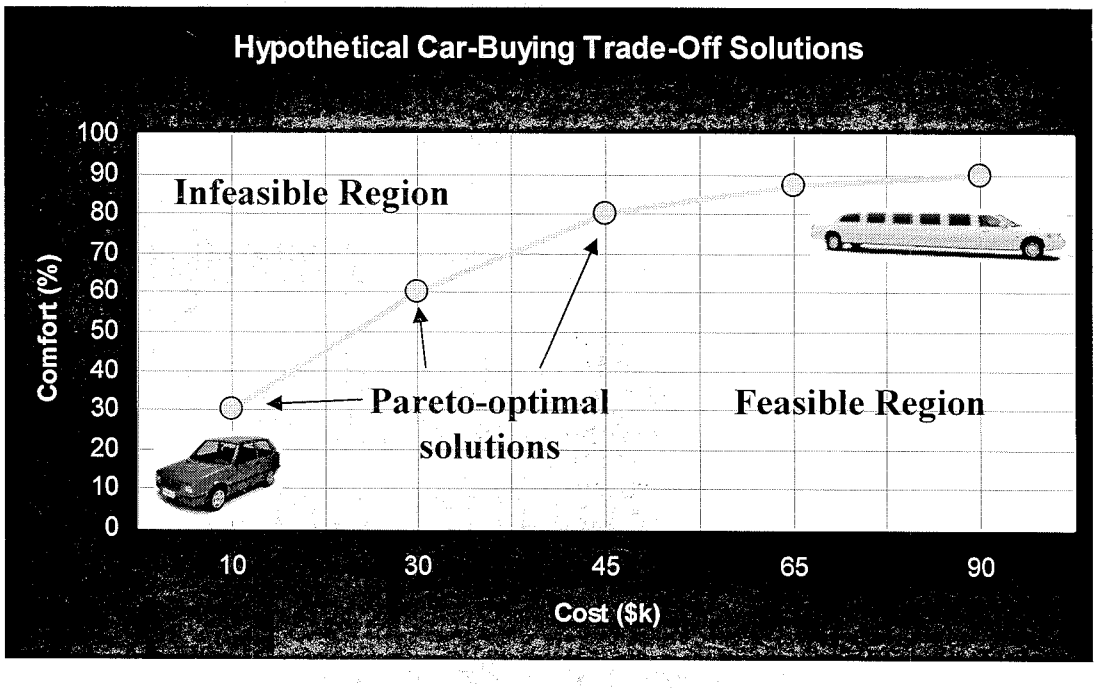
Trade Studies

Trade Studies are conducted by flight projects to create mission concepts with different trade-off solutions for mass, cost, performance and risk.

Ideally, these solutions are evenly distributed along the Pareto-optimal front. In practice this is very difficult to achieve particularly when there are non-linear functions.

Ultimately, project management will use higher level information to select one of the solutions.

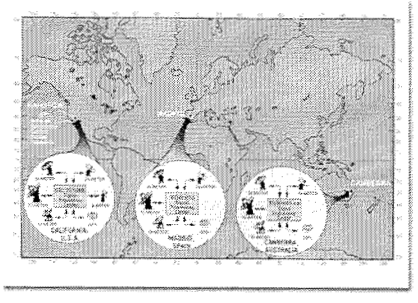


Multi-Objective Optimization involves finding one or more optimal solutions when there is more than one conflicting objective. This means that a solution that is better in one objective compromises, or trades-off, other objectives.

**adapted from Multi-Objective Optimization using Evolutionary Algorithms, K. Deb, pg 2, Wiley 2001*

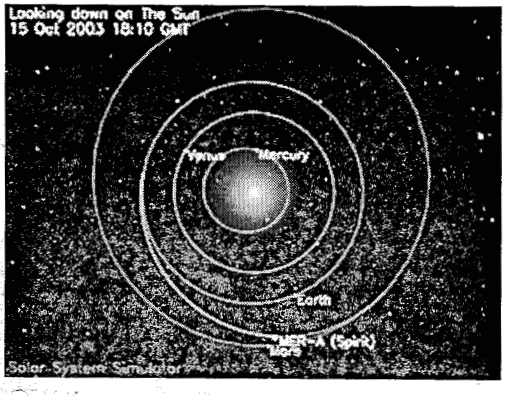
Space Mission Architecture

Command, Control, and Communications Architecture



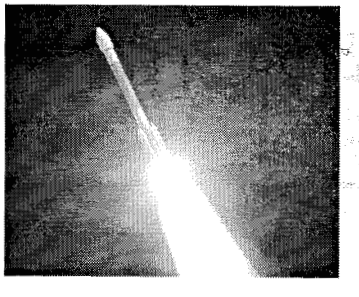
Subject

Orbit and Constellation

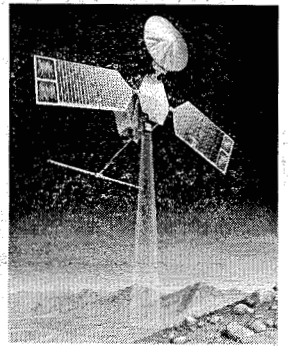


Mission Operations

Mission Concept



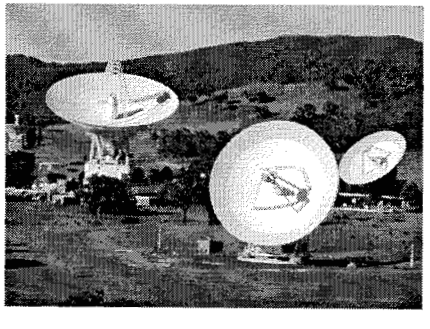
Launch Element



Payload

Flight System

Ground Element



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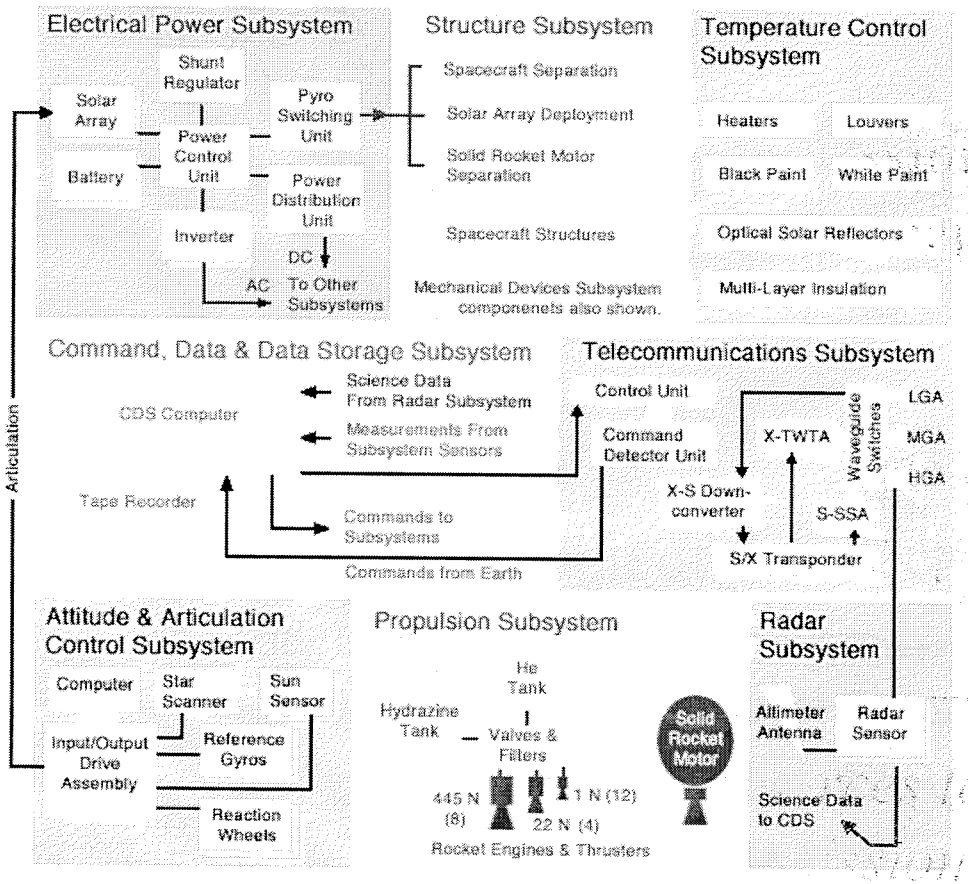
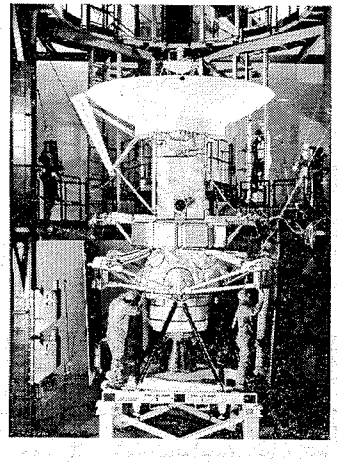
*adapted from Space Mission Analysis and Design, James Wertz, pg 11, 1999

Flight System

The Flight System provides resources to the payload to accomplish the mission





System

Subsystem

Assembly

Typical Flight System Subsystems:

- Power
- Command & Data Handling
- Telecommunications
- Propulsion
- Mechanical
- Thermal
- Guidance, Navigation and Control
- Flight Software

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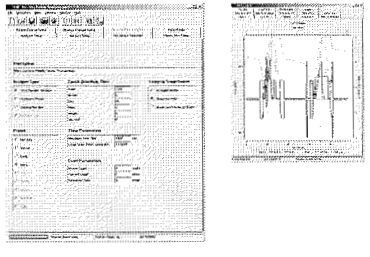
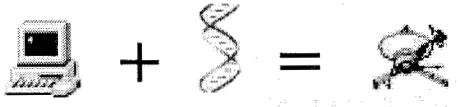
Task Overview

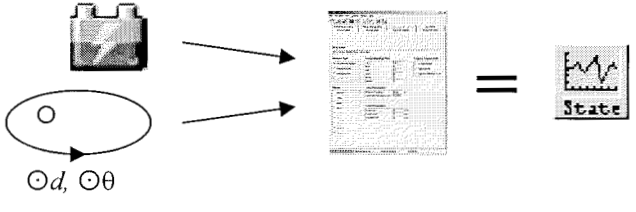
1. MMPAT is a variable fidelity software simulation of the Electrical Power Subsystem used in flight operations



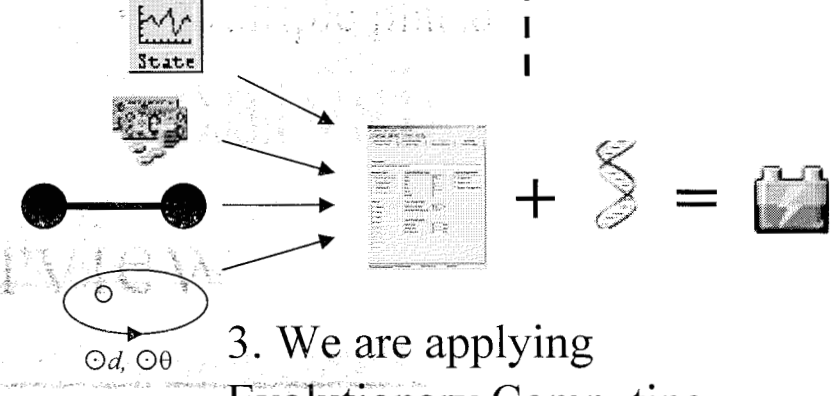


This approach can be applied to other subsystems as well (thermal, propulsion, etc.)

2. Given S/C trajectory, activity plan, PEL and power subsystem sizes, MMPAT can quickly and accurately determine the state of power subsystem



4. Mission Designers and Engineers will be able to *automatically* size components and select technologies quickly *based on anticipated performance* of the subsystem *rather than on worst case estimates*



3. We are applying Evolutionary Computing algorithms to MMPAT to help design & optimize the power subsystem design parameters

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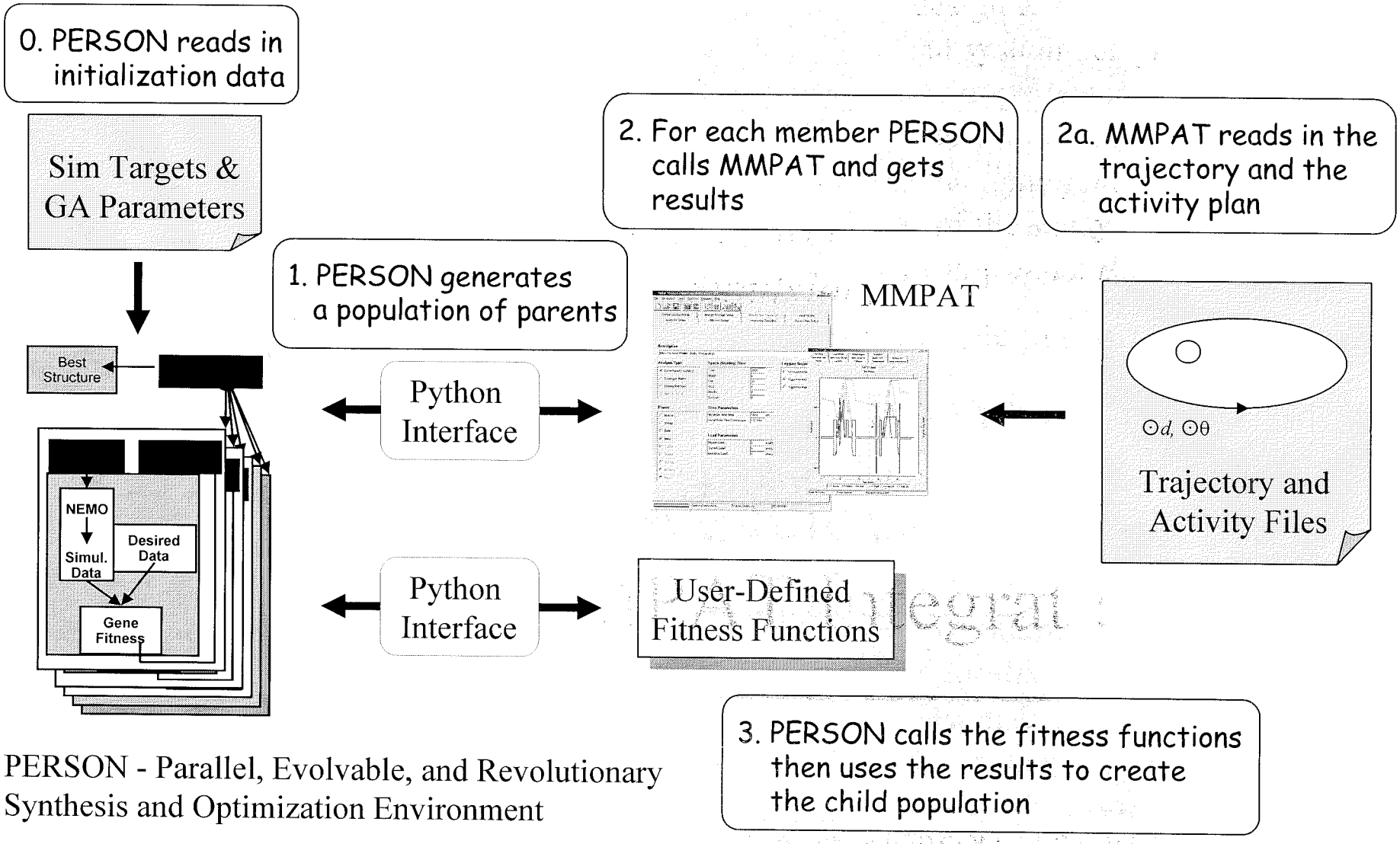
PERSON/MMPAT Integration



PERSON - Parallel, Evolvable, and Revolutionary Synthesis and Optimization Environment

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Objective Fitness Function For Power Subsystem

For this prototype the objective fitness function took into account three factors:

Cost – Cost of solar cells and of battery watt-hours

Mass – Mass of solar cells and of battery watt-hours

Performance – Battery SOC should not drop below some user-defined minimum.

Battery should charge to some user-defined value but not be rewarded for charging to 100% (wastes energy)

**** this requires a multi-objective fitness function***

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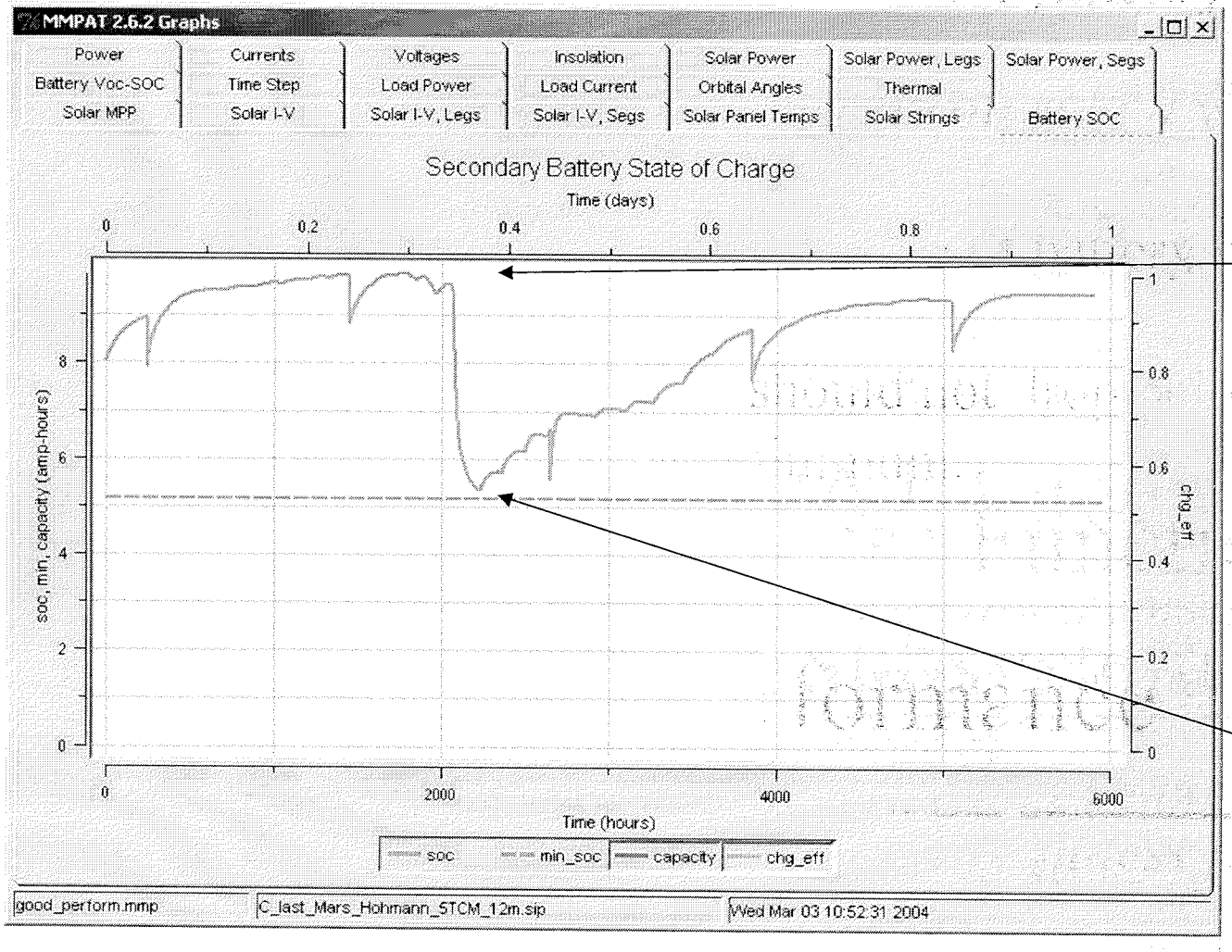
Good Performance



Highest point is close to maximum

Lowest point is close to user defined minimum

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Objective Fitness Function
Weighted Sum Approach

$$f_k(a_i) \longrightarrow \sum_{K=1}^{n} w_k f_k(a_i)$$

The n objectives $f_1, \ldots, f_n$ are weighted by user-defined, positive coefficients $w_1, \ldots, w_n$ and added together to obtain a scalar cost for each population member.

So in our case:

$$\begin{aligned}\text{Fitness} = {} & w_{bc}\,(\text{Cost}_b * \text{amphr})^2 + w_{sc}\,(\text{Cost}_s * \text{cells})^2 + \\ & w_{bm}(\text{Mass}_b * \text{amphr})^2 + w_{sm}\,(\text{Mass}_s * \text{cells})^2 + \\ & w_{min}(\text{SOC}_{min} - \text{SOC}_{minallowed})^2 + \\ & w_{tgt}(\text{AvgSOC} - \text{FracSOC})^2\end{aligned}$$

**from Evolutionary Computation2 -Advanced Algorithms and Operations, T. Back, D.B. Fogel, Z. Michalewicz, pg 26, IOP Publishing 2000*

Objective Fitness Function Test Cases

		Weighted Sum Approach
Deep Impact	Weighted Toward Cost & Mass	Test Case 1
	Weighted Toward Performance	Test Case 2
MER	Weighted Toward Cost & Mass	Test Case 3
	Weighted Toward Performance	Test Case 4

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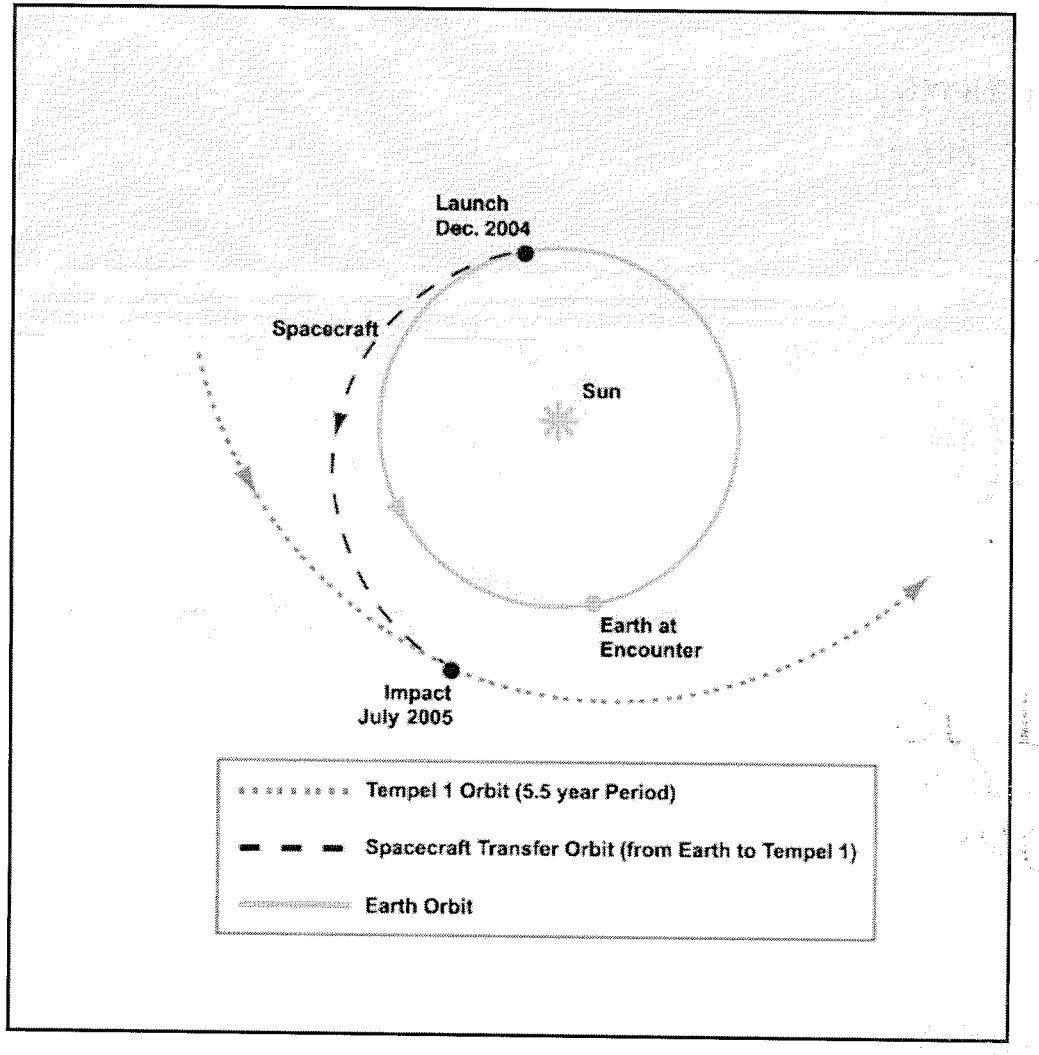
Deep Impact Test Case Mission Description



Deep Impact is a two-part spacecraft (S/C). The larger "flyby S/C carries the smaller "impactor" S/C to Tempel 1 and releases it into the comet's path for a planned collision on the sunlit side.

After the release of the impactor the flyby S/C maneuvers within 500km to observe and record: the impact, the ejected material blasted from the crater, and the structure and composition of the crater's interior.

*from Deep Impact Web Site, JPL, Oct. 2003

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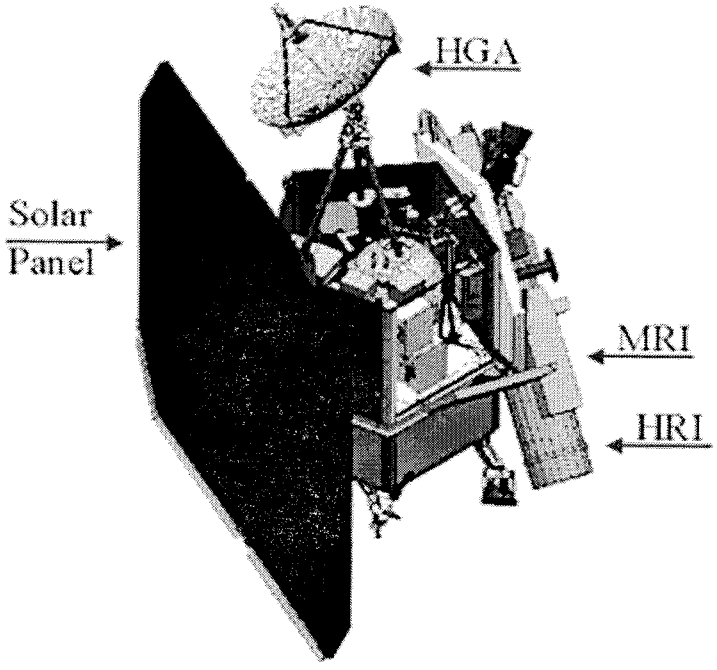
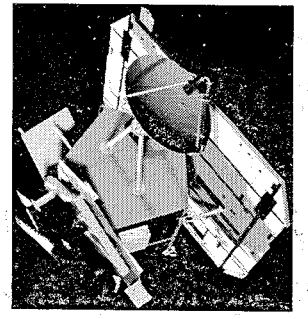
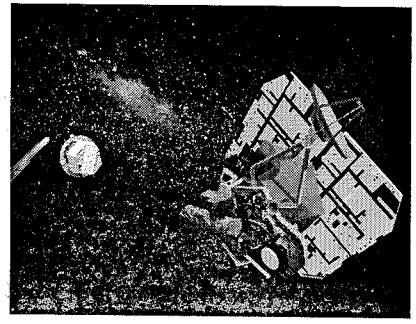
Deep Impact Test Case
Flyby Spacecraft Description

Deep Impact flyby spacecraft is about the size of a Ford Explorer, the flyby spacecraft is three-axis stabilized and uses a fixed solar array and a small NiH_2 battery for its power system.



Deep Impact Flyby Spacecraft





The structure is aluminum and aluminum honeycomb construction. Blankets, surface radiators, finishes, and heaters passively control the temperature.

The propulsion system employs a simple blowdown hydrazine design that provides 190 m/s of delta V. The flyby spacecraft mass is 650 kg with a total mass of 1020 kg.

**from Deep Impact Web Site, JPL, Oct. 2003*

Deep Impact Test Case
Test Case Description

Trajectory – Cruise. Start from Earth to 1.5 AU in 8.3 months

Activity Plan – Constant load of 400 watts with solar panels tilted 23 deg. off normal.

Simulated 5 trajectory correction maneuvers by turning the solar array edge-on to the Sun for about 3 ½ minutes every 50 days.

Evolution Parameters - Population size of 200 for 500 generations

Deep Impact Test Case
Test 1 – Weighted Sum Approach

Weighted toward (prioritizing) cost and mass

Solar Array & Battery Capacity:

- Cells/string in segment 1: 22
- Strings/segment in segment 1: 44
- Cells/string in segment 2: 16
- Strings/segment in segment 2: 122
- Battery capacity in amp-hr: 16.0

Cost & Mass Values:

- Solar cell cost: $0.832k
- Solar cell mass: 0.01 kg/cell
- Battery cost: $15.9k/amp-hr
- Battery mass: 0.01667 kg/watt-hr

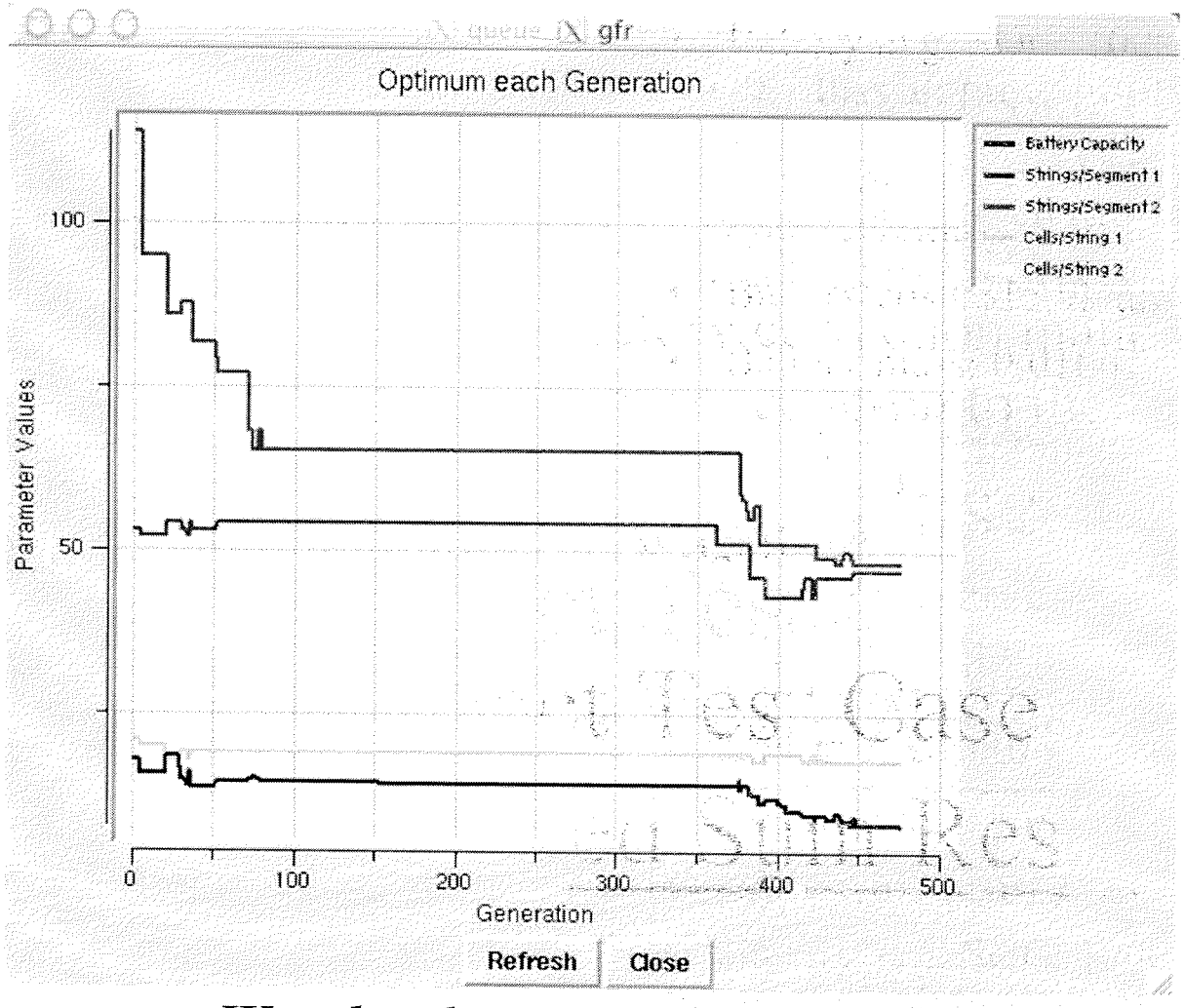
Optimization Intervals:

- Cells/string in segment 1: [1, 50]
- Strings/segment in segment 1: [1, 100]
- Cells/string in segment 2: [1,40]
- Strings/segment in segment 2: [1,200]
- Battery capacity in amp-hr: [8.0, 40.0]

Weightings:

- Solar array cost: 1.0
- Solar array mass: 1.0
- Battery cost: 1.0
- Battery mass: 1.0
- Battery SOC min.: 1000.0
- Battery avg. SOC: 1000.0

Deep Impact Test Case
Test 1 – Weighted Sum Results



Weighted toward cost and mass

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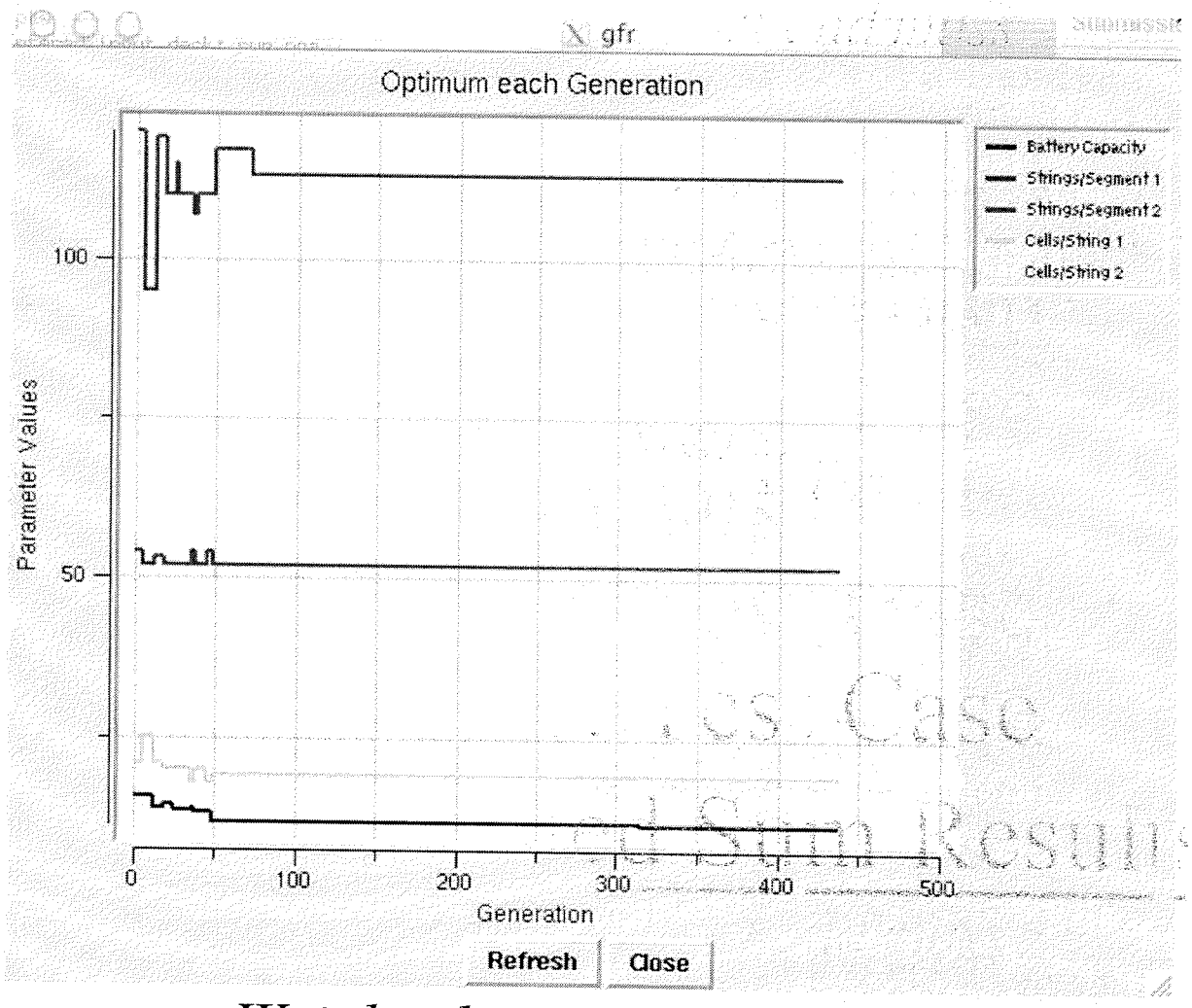
Deep Impact Test Case
Test 2 – Weighted Sum Results



Weighted toward performance

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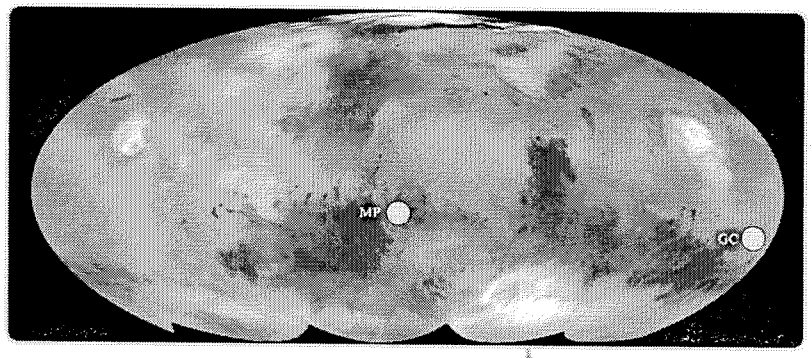
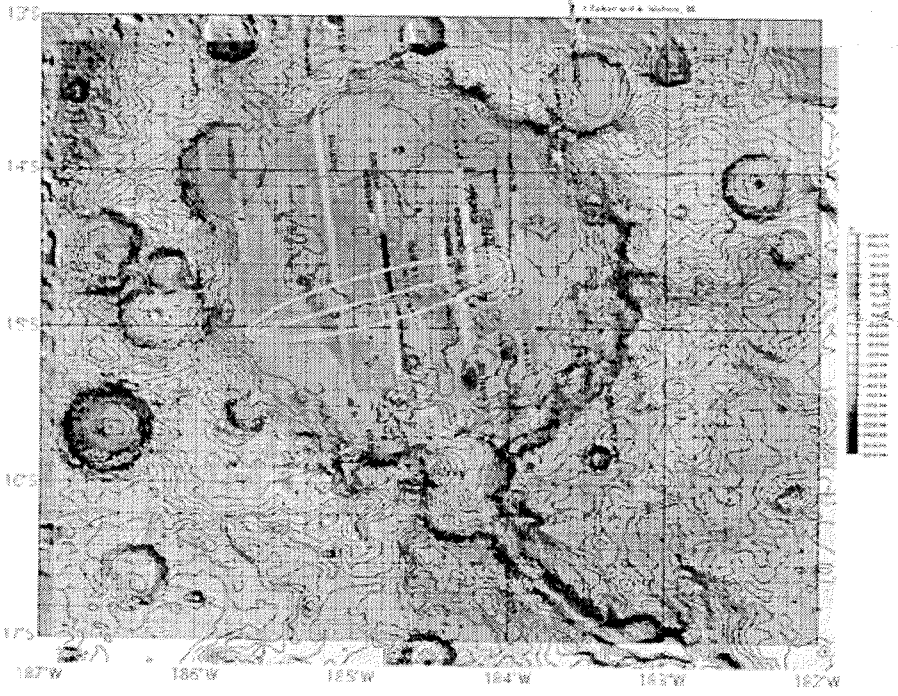
Mars Exploration Rover (MER) Mission Description



Gusev Crater Site (TCM-5 DeltaDOR, -2Day:
MER-A; Open of window=dashed, Close=solid)



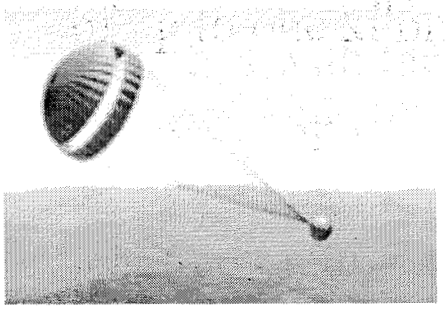
The **Mars Exploration Rover** mission consists of two separate launches with the two rovers, MER-A "Spirit" and MER-B "Opportunity", being delivered in a landing craft to separate sites, Gusev Crater and Meridiani Planum, on Mars in January 2004.

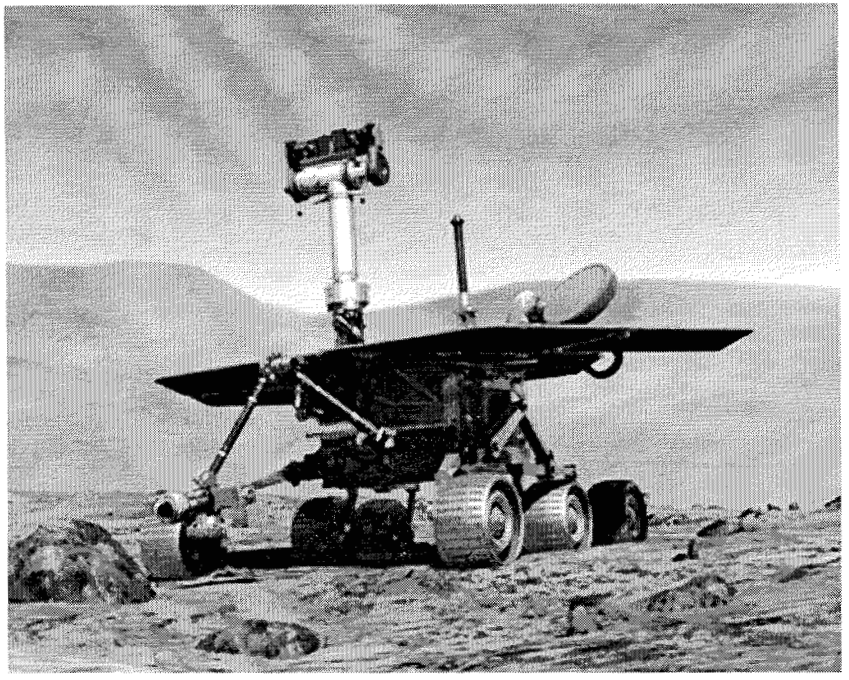
The primary mission goal is to search for and characterize a wide range of rocks and soils that hold clues to past water activity on Mars. A goal for the rover is to drive up to 40 meters (about 44 yards) in a single day, for a total of up to one kilometer.

**from MER Web Site, JPL, Oct. 2003*

MER Test Case
Rover Description

MER is 1.5m (4.9ft) high by 2.3m (7.5ft) wide by 1.6m (5.2ft) long. Two Li-Ion rechargeable batteries provide energy for the rover at night. Over time, these batteries will degrade.





Mars Exploration Rover

The main source of power for each rover comes from a multi-panel solar array. When fully illuminated, the rover solar arrays generate about 140 watts of power for up to four hours per sol (a Martian day). By the end of the 90-sol mission, the capability of the solar arrays to generate power will likely be reduced to about 50 watts of power due to anticipated dust coverage on the solar arrays.

**from MER Web Site, JPL, Oct. 2003*

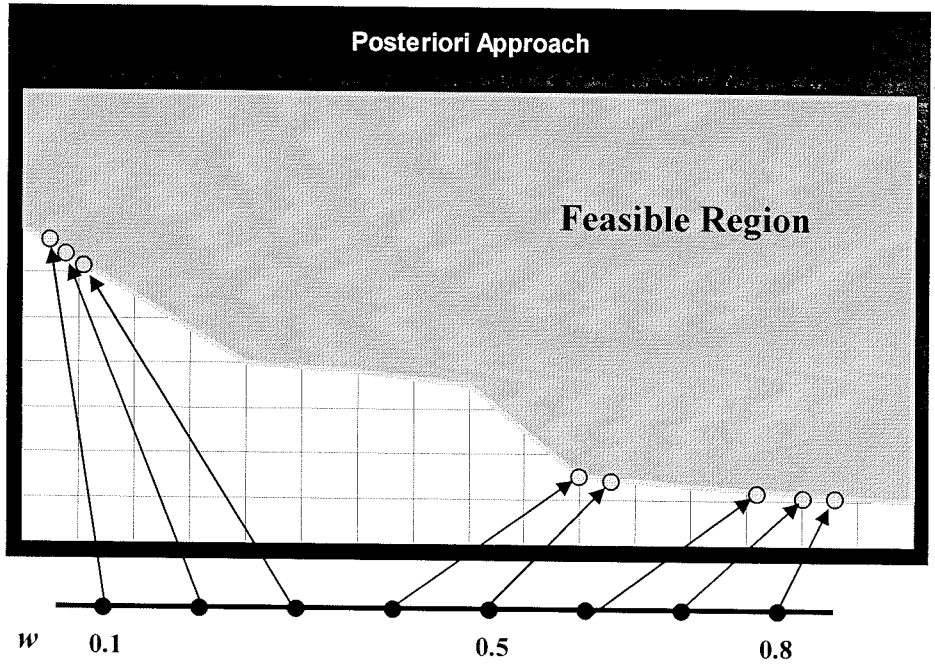
MER Test Case
Test Case Description

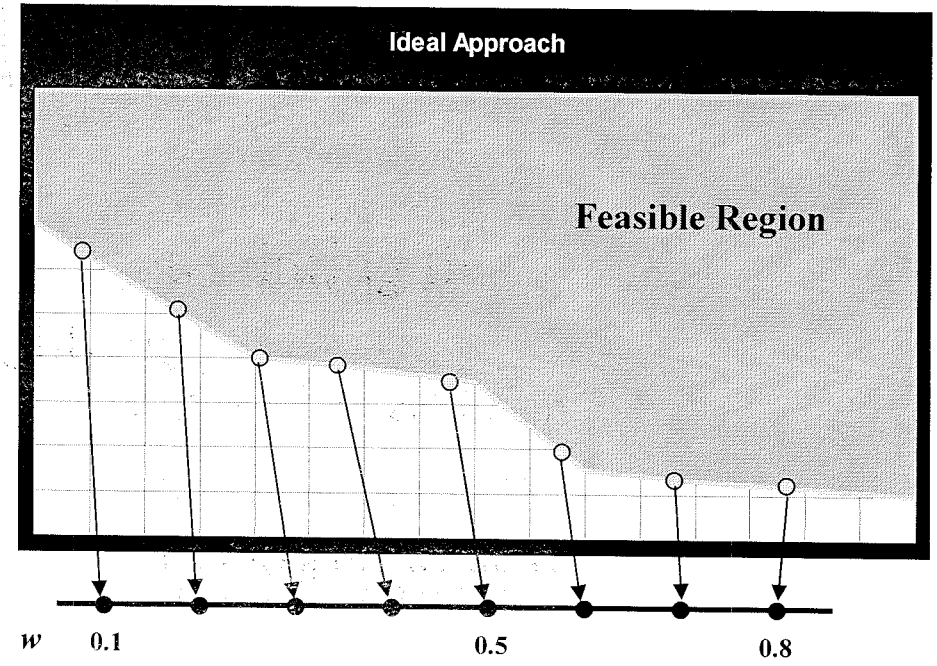
Trajectory – Mars Surface. 14.95 South Latitude for 90 sol, simulating MER-A at Gusev Crater

Activity Plan – Constant load of 50 watts during the 6 hour day and 8 watts at night.

Evolution Parameters - Population size of 200 for 500 generations

Weighted Sum Approach - Disadvantages





Disadvantages

- Must call single optimization multiple times
- Weighting may not be evenly distributed
- Since GA is stochastic it may not preserve the best solution

Ideally

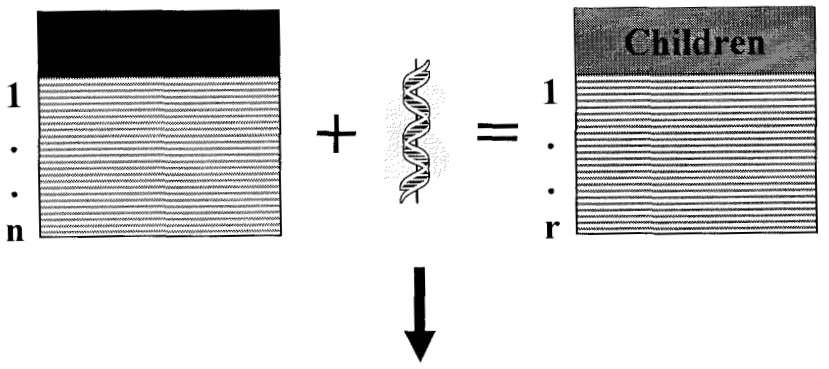
- Generate all solution in one pass
- Evenly distribute the solutions first then map to weightings
- Always preserve the best solution from both the parent and child populations

**adapted from Multi-Objective Optimization using Evolutionary Algorithms, K. Deb, pg 173, Wiley 2001*

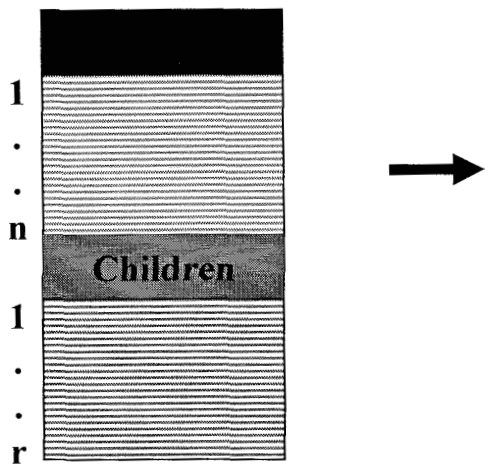
M.Kordon

Niched-Elitist Approach

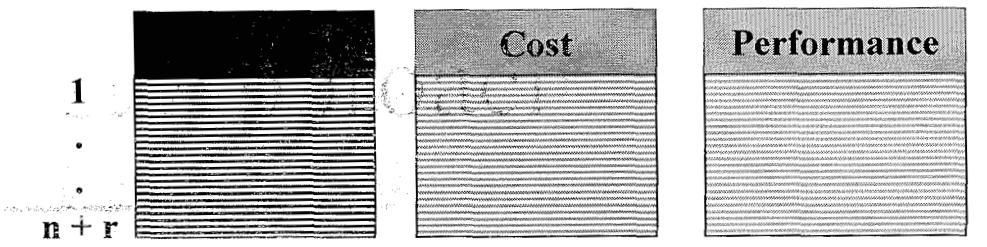
1. Use crossover and mutation to form a child population from the parent



2. Combine the parent and child populations

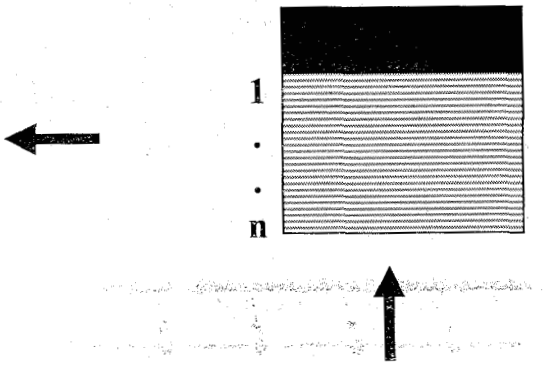


3. Rank the combined population from best to worst in each subpopulation category



Note: Should also have combination categories such as Mass/Cost and Cost/Performance

4. Create new parents by selecting the top ranked solutions from each category until pop. = n



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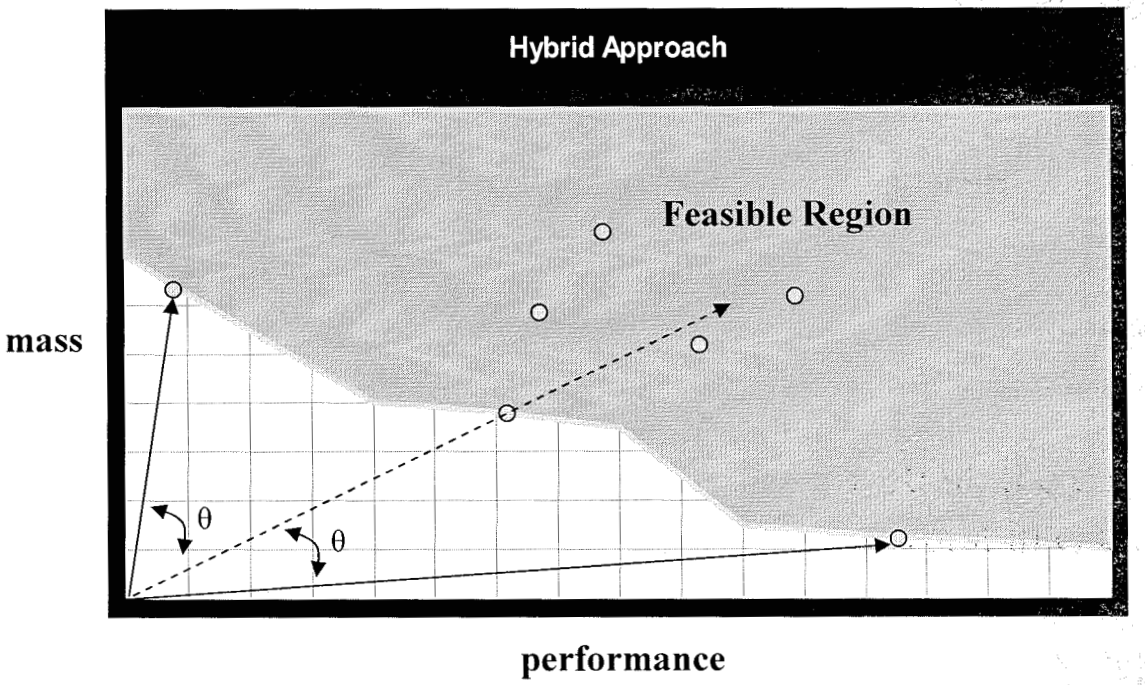
Niched – Elitist Hybrid Solutions



Niched-Elitist Solutions

- Best Cost
- Best Mass
- Best Performance
- Best Cost/Mass
- Best Cost/Performance
- Best Mass/Performance
- Best Cost/Mass/Performance

Hybrid Procedure

1. Get the best 'single' solutions of hybrid (e.g. Best Cost)
2. Find the angle midway between 'single' solutions and project a line through solution space
3. Get the solution closest to the line then closest to origin

Future Work

Known Optimal – Use known optimal test case to test our results

Non-Linear Cost Model – Costs are currently linear

Lifecycle Cost – Cost is only for hardware components. May want to include cost for design, integration, test and workforce lifecycle costs.

Structural Mass – Mass is only for hardware components. May want to include mass of mounting hardware as well.

Future Work (cont)

More Parameters – Include more design parameters such as battery technology

Risk – Incorporate risk in the objective functions

More Subsystems – Apply Evolutionary computing to additional subsystems

Integrated Subsystems – Integrate subsystems together for system solutions.

Backup Slides

Deep Impact Test Case
Test 1 – Weighted Sum Approach

Weighted toward (prioritizing) cost and mass

Solar Array & Battery Capacity:

- Cells/string in segment 1: 22
- Strings/segment in segment 1: 44
- Cells/string in segment 2: 16
- Strings/segment in segment 2: 122
- Battery capacity in amp-hr: 16.0

Cost & Mass Values:

- Solar cell cost: $0.832k
- Solar cell mass: 0.01 kg/cell
- Battery cost: $15.9k/amp-hr
- Battery mass: 0.01667 kg/watt-hr

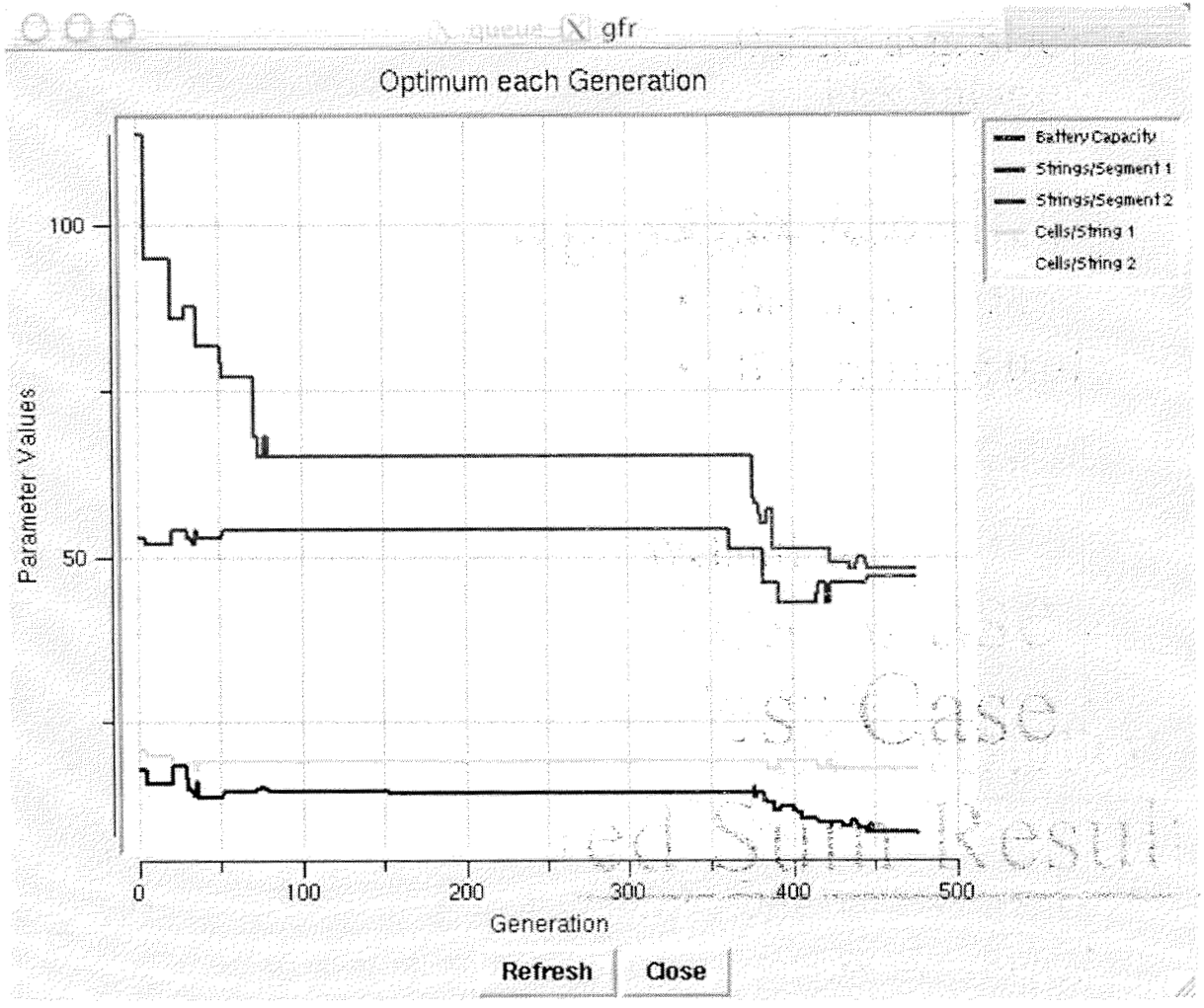
Optimization Intervals:

- Cells/string in segment 1: [1, 50]
- Strings/segment in segment 1: [1, 100]
- Cells/string in segment 2: [1,40]
- Strings/segment in segment 2: [1,200]
- Battery capacity in amp-hr: [8.0, 40.0]

Weightings:

- Solar array cost: 1.0
- Solar array mass: 1.0
- Battery cost: 1.0
- Battery mass: 1.0
- Battery SOC min.: 1000.0
- Battery avg. SOC: 1000.0

Deep Impact Test Case
Test 1 – Weighted Sum Results



Weighted toward cost and mass

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Deep Impact Test Case
Test 2 – Weighted Sum Approach

Weighted toward performance

Solar Array & Battery Capacity:

- Cells/string in segment 1: 22
- Strings/segment in segment 1: 44
- Cells/string in segment 2: 16
- Strings/segment in segment 2: 122
- Battery capacity in amp-hr: 16.0

Cost & Mass Values:

- Solar cell cost: $0.832k
- Solar cell mass: 0.01 kg/cell
- Battery cost: $15.9k/amp-hr
- Battery mass: 0.01667 kg/watt-hr

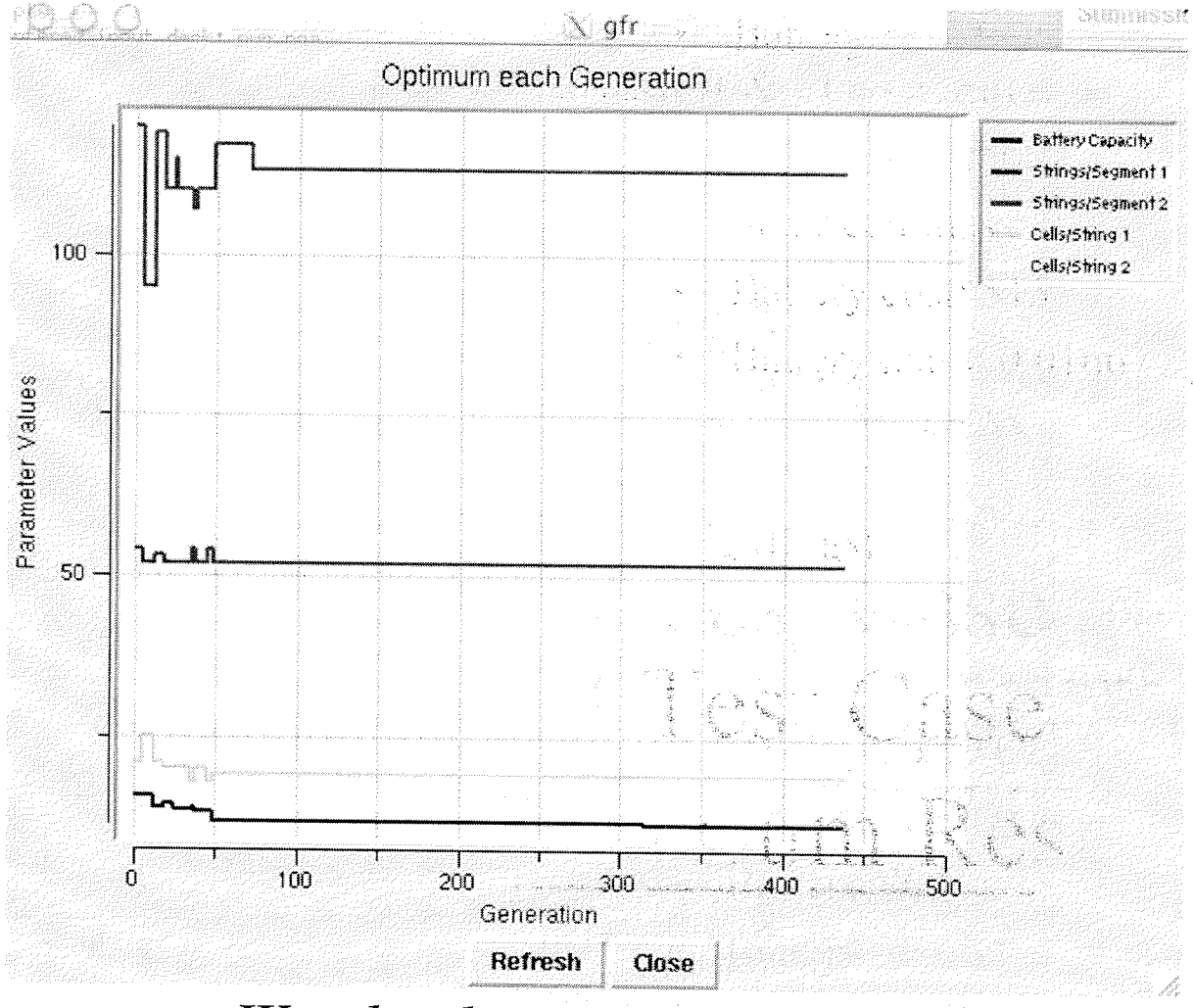
Optimization Intervals:

- Cells/string in segment 1: [1, 50]
- Strings/segment in segment 1: [1, 100]
- Cells/string in segment 2: [1,40]
- Strings/segment in segment 2: [1,200]
- Battery capacity in amp-hr: [8.0, 40.0]

Weightings:

- Solar array cost: 0.000001
- Solar array mass: 0.000001
- Battery cost: 0.1
- Battery mass: 0.1
- Battery SOC min.: 1000000.0
- Battery avg. SOC: 1000000.0

Deep Impact Test Case
Test 2 – Weighted Sum Results



Weighted toward performance

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MER Test Case
Test 3 – Weighted Sum Approach

Weighted toward cost and mass

Solar Array & Battery Capacity:

- Cells/string in all segments: 16
- Strings/segment in segment 1: 4
- Strings/segment in segment 2 & 3: 5
- Strings/segment in segment 5 & 6: 5
- Battery capacity in amp-hr: 8.0

Cost & Mass Values:

- Solar cell cost: $0.832k
- Solar cell mass: 0.01 kg/cell
- Battery cost: $19.3k/amp-hr
- Battery mass: 0.01667 kg/watt-hr

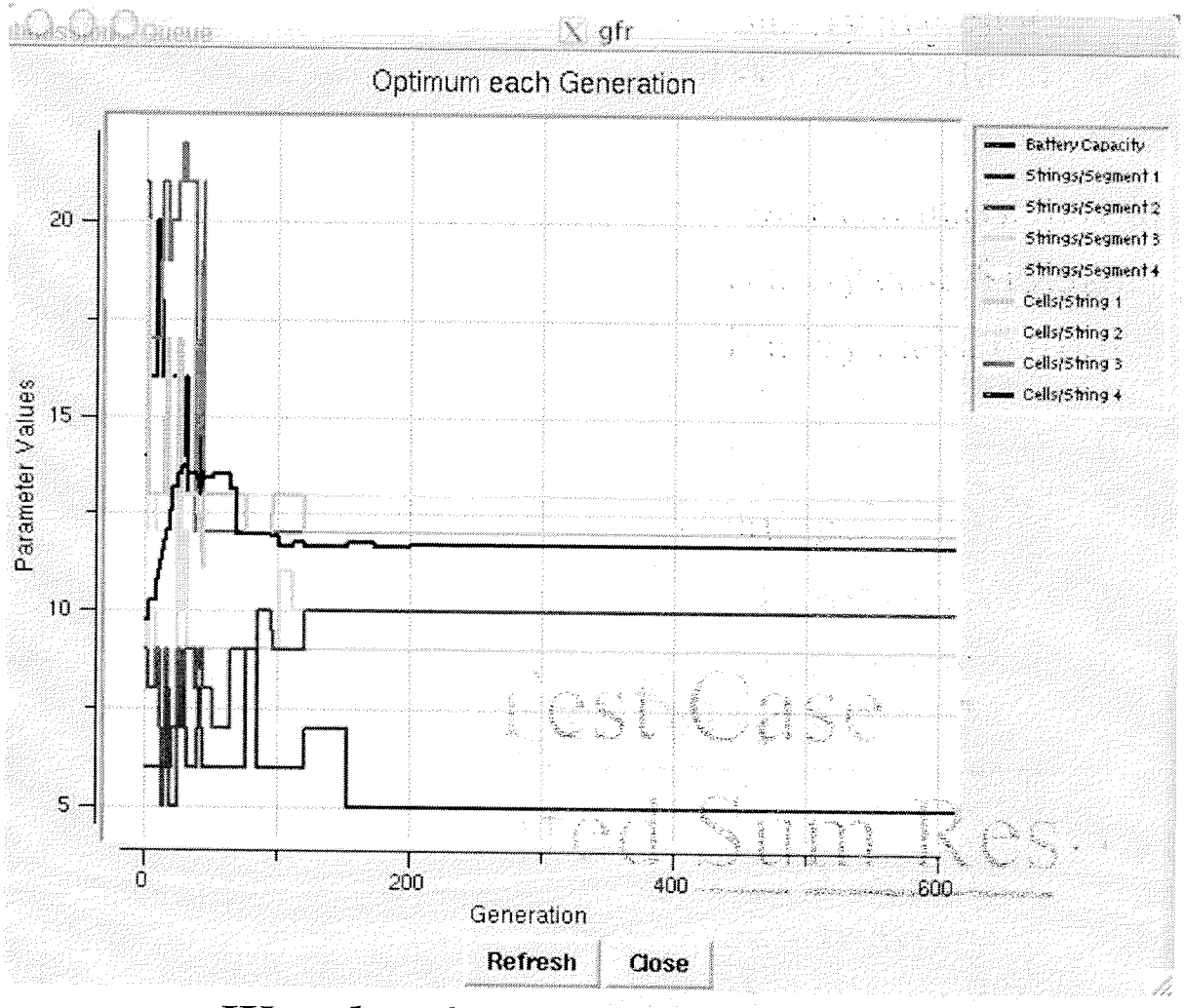
Optimization Intervals:

- Cells/string in all segments: [1, 40]
- Strings/segment in all segments: [1, 20]
- Battery capacity in amp-hr: [4.0, 16.0]

Weightings:

- Solar array cost: 1.0
- Solar array mass: 1.0
- Battery cost: 1.0
- Battery mass: 1.0
- Battery SOC min.: 1000.0
- Battery avg. SOC: 1000.0

MER Test Case
Test 3 – Weighted Sum Results



Weighted toward cost and mass

M.Kordon

MER Test Case
Test 4 – Weighted Sum Approach

Weighted toward performance

Solar Array & Battery Capacity:

- Cells/string in all segments: 16
- Strings/segment in segment 1: 4
- Strings/segment in segment 2 & 3: 5
- Strings/segment in segment 5 & 6: 5
- Battery capacity in amp-hr: 8.0

Cost & Mass Values:

- Solar cell cost: $0.832k
- Solar cell mass: 0.01 kg/cell
- Battery cost: $19.3k/amp-hr
- Battery mass: 0.01667 kg/watt-hr

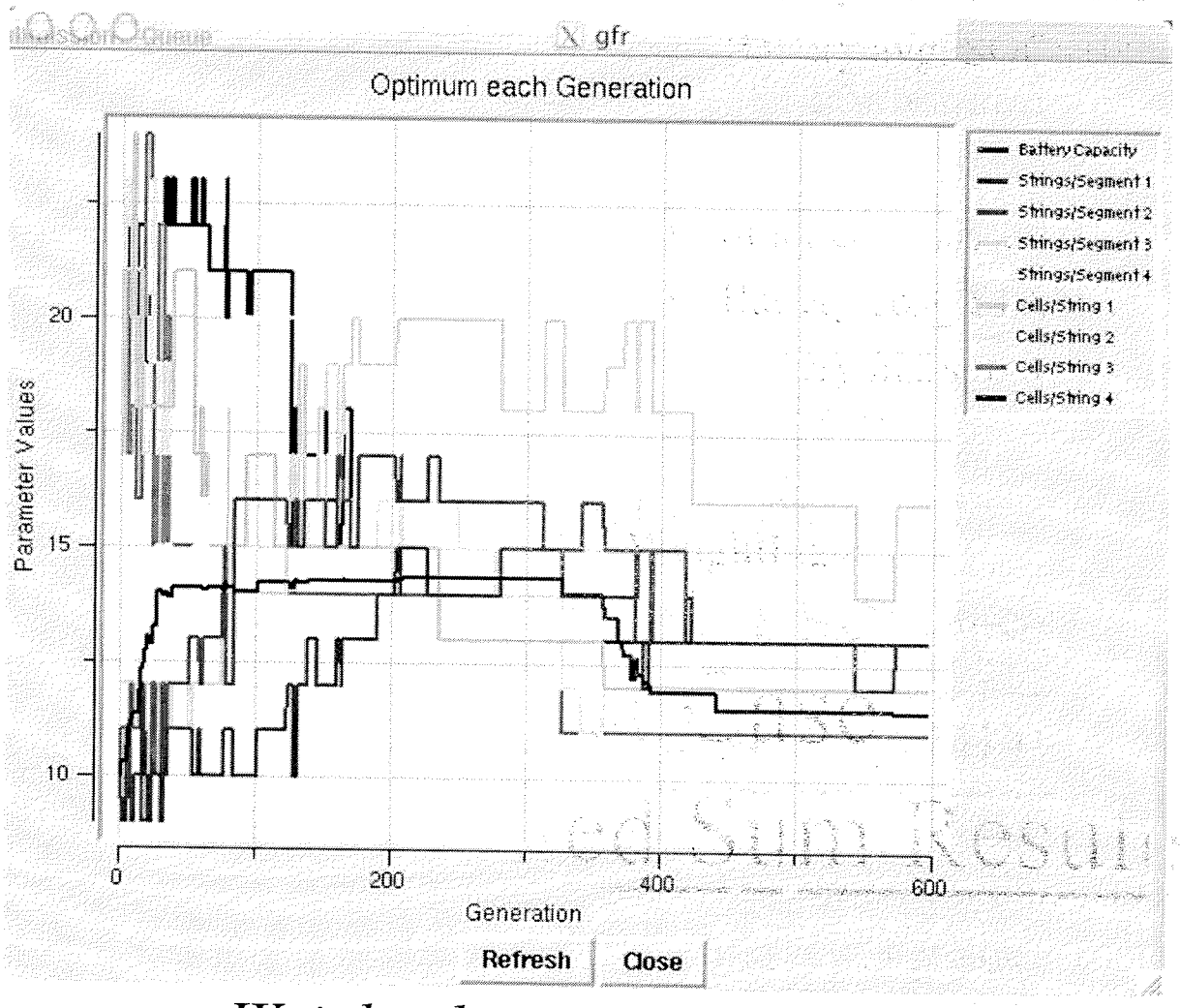
Optimization Intervals:

- Cells/string in all segments: [1, 40]
- Strings/segment in all segments: [1, 20]
- Battery capacity in amp-hr: [4.0, 16.0]

Weightings:

- Solar array cost: 0.000001
- Solar array mass: 0.000001
- Battery cost: 0.1
- Battery mass: 0.1
- Battery SOC min.: 1000000.0
- Battery avg. SOC: 1000000.0

MER Test Case
Test 4 – Weighted Sum Results



Weighted toward performance

M.Kordon