

STAIF Draft Paper

## **Nuclear Electric Vehicle Optimization Toolset (NEVOT): Integrated System Design Using Genetic Algorithms**

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The Nuclear Electric Vehicle Optimization Toolset (NEVOT) optimizes the design of all major Nuclear Electric Propulsion (NEP) vehicle subsystems for a defined mission within constraints and optimization parameters chosen by a user. The tool uses a Genetic Algorithm (GA) search technique to combine subsystem designs and evaluate the fitness of the integrated design to fulfill a mission. The fitness of an individual is used within the GA to determine its probability of survival through successive generations in which the designs with low fitness are eliminated and replaced with combinations or mutations of designs with higher fitness. The program can find optimal solutions for different sets of fitness metrics without modification and can create and evaluate vehicle designs that might never be conceived of through traditional design techniques. It is anticipated that the flexible optimization methodology will expand present knowledge of the design trade-offs inherent in designing nuclear powered space vehicles and lead to improved NEP designs.

### **Introduction**

The integration issues associated with using reactor power for actual space science missions have received little attention to date and the design trade-offs that must occur on a reactor-powered space vehicle are not fully known. The Nuclear Electric Vehicle Optimization Toolset (NEVOT) is designed to uncover the unknown trades so they can be studied and understood. NEVOT is a Nuclear Electric Propulsion (NEP) vehicle optimization algorithm based on a Genetic Algorithm (GA) search technique. The tool searches for the optimal vehicle subsystem combinations to perform user defined missions.

Traditional methods of multi-disciplinary system design are sequential in nature. A subsystem is selected and designed, and inputs from the first subsystem design are passed to the "next" subsystem, which is sized or designed to be compatible with the first subsystem. The process is repeated until all of the subsystems are designed. The entire system is then compared to known constraints and compromises are made between subsystems to meet those constraints. Once a base design is complete, the system is perturbed in an effort to optimize it for a desired result, such as minimizing mass or cost. Automated sequential multi-disciplinary design efforts typically mimic human designers and are sequential in nature. The resulting configurations are a strong function of the information design logic built into them.

NEVOT attempts to remove potentially limiting foreknowledge from the design process in order to create subsystem arrangements that might never result from traditional design methods, whether automated or not. By removing the trends that are inherently designed into complex multi-disciplinary systems we can hopefully uncover new trends that will lead to improved designs.

The tool allows for the combination of tens of thousands of subsystem designs without regard to their compatibility or combined ability to meet the mission requirements. The ability of each combination of subsystems to perform a mission is evaluated after they are created and assigned a figure of merit, called "fitness". The fitness of each vehicle is used within a genetic algorithm to search the possible combinations to find the best vehicles to perform the mission.

Genetic algorithms comprise a type of non-gradient-based search technique that mimics biological adaptation and reproduction to produce improvement in designs from generation to generation, until the fittest solutions are produced. The basic idea behind the genetic algorithm is to define a representation of the system, sometimes referred to as a chromosome. Each chromosome is a collection of variables, or genes, that describe the vehicle. Each gene is allowed to vary within a range representing legitimate engineering choices. The type of information encoded into a gene can include the type or material of a component, the number of the components, the size or rating of components, the operating temperature of a component, among others.

Within the GA, the first generation of vehicles is created by combining randomly-created subsystems. The fitness of each vehicle to meet the mission requirements is then evaluated. Vehicle designs with higher fitness values are allowed to remain in the population and the remaining designs are removed from the population. The population is returned to its original size by (1) adding combinations (children or offspring) of the more fit designs, (2) adding new designs created from fit designs with a single characteristic altered (mutations), and (3) adding new designs that are "clones" of the better designs. Through successive generations, the fittest population of vehicles within the solution space will remain. By including optimization parameters, such as mass or cost, in the fitness evaluation, the vehicles that meet the mission requirements (constraints) while minimizing or maximizing the parameter(s) of interest can be found.

The independent creation of subsystem designs can lead to combinations of subsystems that simply do not make sense. These combinations will have a low fitness and will be eliminated from the population. However, the concept of independent creation also leads to combinations that have never been thought of before, or are precluded by logic encoded within a sequential design process. By studying the surviving specimens, the design trade-offs that occur within the population to make better designs can be observed and understood. Evaluation of the common characteristics of the optimal solutions can lead to (a) identification of those characteristics most important to the mission objectives and (b) understanding of interactions of the characteristics to produce more optimal solutions.

## **Vehicle Component Modeling**

In NEVOT, a space reactor power system (SRPS) is combined with a truss structure module, a spacecraft geometry module, an electric propulsion (EP) module and a trajectory module. The modules are used to take the limited vehicle description contained in the chromosome, complete the vehicle design, and evaluate the vehicle's ability to perform a defined mission. The reference mission is defined by the destination, time on station, target mission duration and payload. Each subsystem design module is to take a limited set of input variables (some varied by the GA and others fixed), finish a more detailed design of the subsystem (if necessary) and return as output (1) information required to evaluate the subsystem's ability to work with other subsystems, (2) information required of all subsystems to evaluate the system and (3) an estimation of parameters of interest that are to be optimized by the algorithm (such as mass).

## **Reference Mission to the Asteroids (4 AU)**

### **Subsystem Module Development**

The development of subsystem modules was initially limited to allow the methodology and interfaces to be developed. A liquid-metal-cooled reactor and an indirect Rankine power conversion system with potassium as the working fluid were chosen for initial development and a limited shield configuration was defined.

Truss module

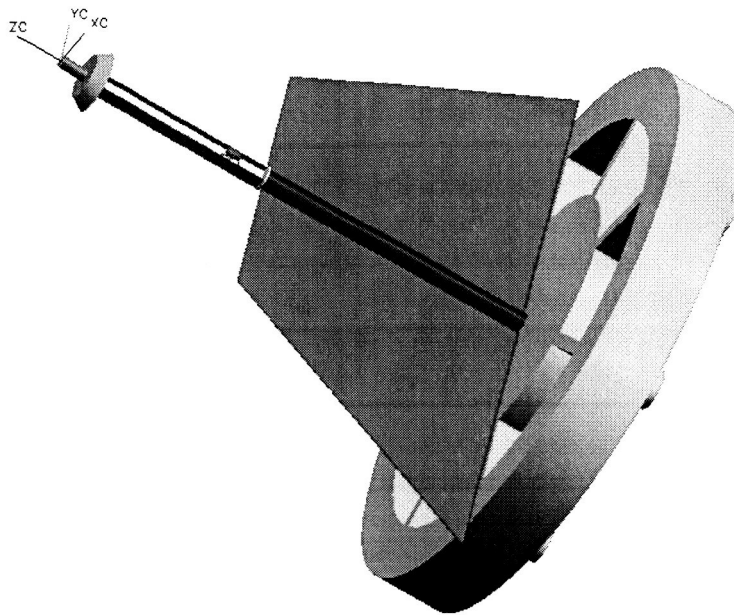
EP Module

Geometry

Trajectory

Much initial effort was focused on defining the interfaces between the modules and the algorithm to will allow seamless replacement of low-fidelity models with more detailed and sophisticated models as they are developed.

A fixed vehicle configuration, shown in Figure 1, was established to permit the development of the evaluation algorithm.



FRONT WORK

Figure 1: Example conceptual configuration of the NEP vehicle being optimized by NEVOT as developed by Marshall Space Flight Center. The reactor and shield are upper left and are extended from the habitat (green) by a truss system. The radiator panels (red), power conversion systems and PMAD systems fit between the shield and the habitat. This vehicle spins to produce an artificial gravity field at the outer radius of the habitat.

### **Fitness Evaluation in NEVOT**

The fitness assigned to an individual is used in the GA algorithm to determine its worth within the population of possible individuals and therefore its probability of survival. It is possible, and indeed more likely than not, that the vehicle subsystems created will not be well matched to one another. There is really no penalty for this except that the system as a whole will be given a low fitness and will be bred out of the population.

The evaluation program must have a method for evaluating how well the created vehicle meets the mission.

In the methodology, the vehicles are “created”. Each vehicle must be evaluated and assigned a fitness. The general flow of the evaluation is shown schematically in Figure 2. Fitness Determination

NEVOT takes inputs from a mission description file and a vehicle description file and generates an estimate of that vehicle’s fitness to perform the mission. The fitness of the vehicle could be constructed from a combination of information, including but not limited to the following:

Trip Time

Fuel Burnup compared to target safety margin

Propellant consumption compared to target safety margin

Fluence to radiation sensitive components compared to allowed values

AND

Minimizing or maximizing optimization parameters (mass, cost, etc.).

Constraints that may be imposed (limiting radiator area for example) and the definition of fitness can be changed to emphasize different sensibilities.

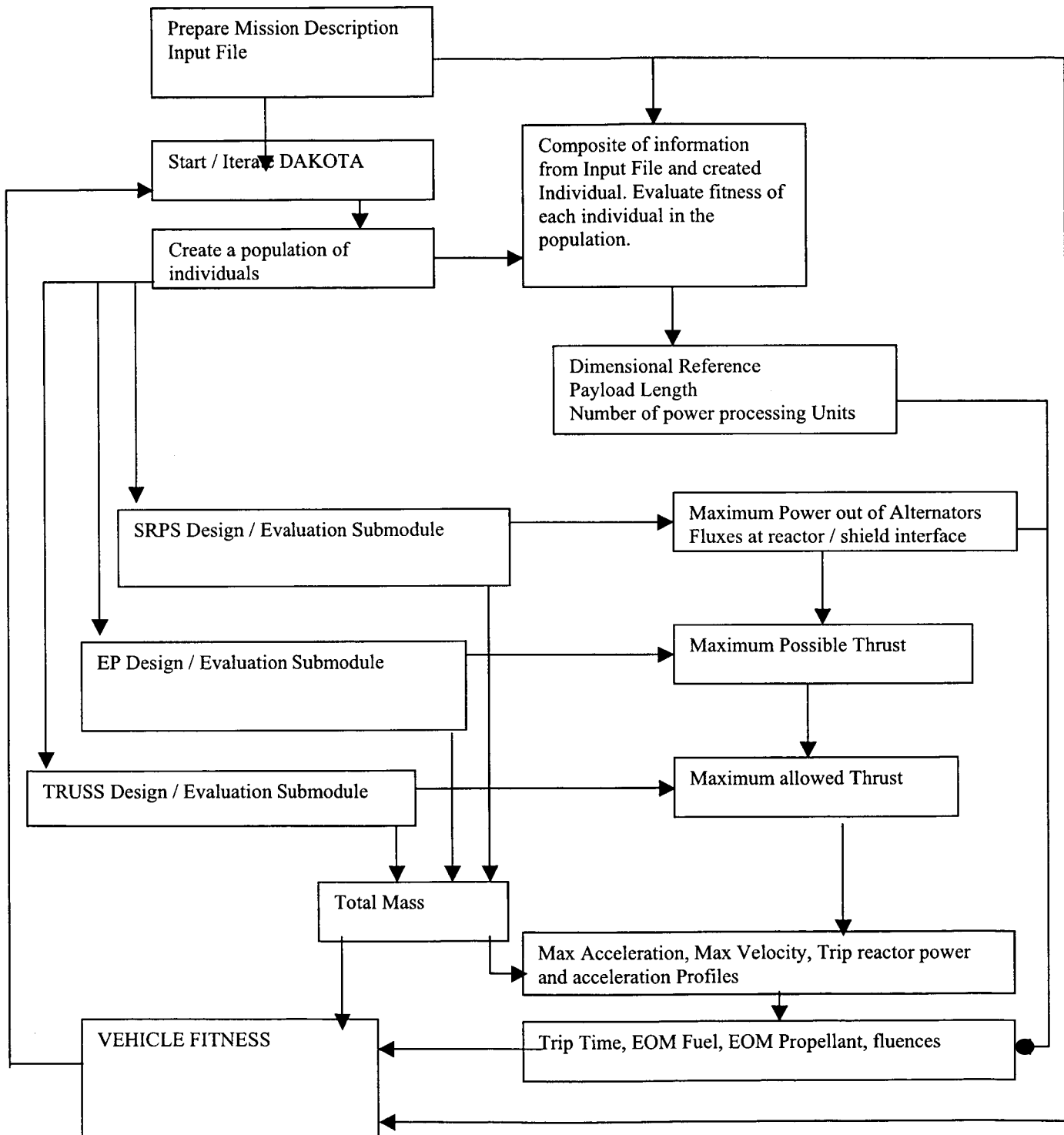
The power of the NEVOT methodology is that once the algorithm is developed it does not have to be modified to search for the optimal solution to different missions, to emphasize a different set of optimization parameters or to use a different definition of fitness. This makes NEVOT a flexible and powerful tool for performing subsystem trades studies.

### **Implementation**

The DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) Toolkit was selected as the optimization tool to apply the GA technique to the NEVOT programs. DAKOTA is a multilevel parallel object oriented framework for design optimization, parameter estimation, uncertainty quantification and sensitivity analysis. It contains an extensive set of gradient based and non-gradient based optimization techniques, which makes it possible to perform direct comparisons between two techniques.

The relationship among DAKOTA, the evaluation programs and the fitness evaluation program are shown schematically in Figure 3. The DAKOTA GA algorithm randomly generates an initial population of vehicles and manipulates the vehicle description input file so that NEVOT can assess the fitness of each "created" vehicle. The fitness assigned to an individual is used in the GA algorithm to determine its worth within the population and therefore its probability of survival. Mutations from fit vehicles are randomly created to see if more fit individuals might be accidentally created. It is possible, and indeed more likely than not, that a vehicle's subsystems will not be well matched to one another. There is no penalty for this except that the system as a whole receives a low fitness and is bred out of future populations. After many generations only the fittest vehicles remain.

Figure 2: Simplified flow diagram of the NEVOT operating under the DAKOTA GA optimization routine.



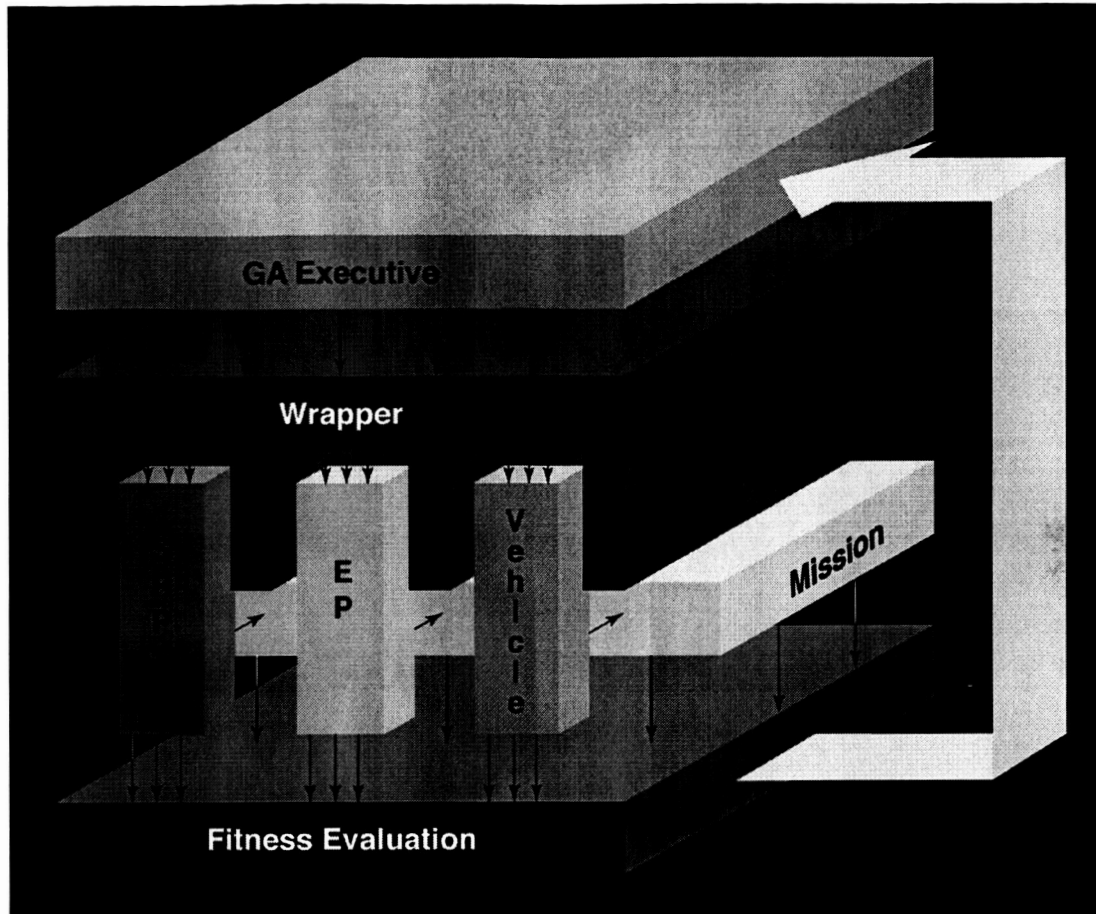


Figure 3: Schematic representing the relationships of the components of the NEVOT. The GA executive creates vehicles, which are evaluated for their ability to perform a mission. The fitness is used within the algorithm to determine whether the design will survive to successive generations.

### Initial Results

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### Proposed Future Work

The power of the NEVOT methodology is that combinations of subsystems are not logically coded together. The GA algorithm will experiment with truly unique vehicle combinations, which provides the power to find new and better solutions.

The second year of effort will focus on 1) extending the number of available subsystem modules for evaluation and increasing their fidelity, 2) improving the prototype NEVOT tool by making it modular and increasing the flexibility of the vehicle configuration, 3) coupling the higher level evaluation modules to the NEVOT and 4) developing user friendly interface tools.