IDENTIFICATION OF THE PHYSICALLY IDEAL HUMAN RATED REACTION BASED INTERPLANETARY TRANSPORTATION SYSTEM (PHRITS)

by

Ralph Ewig

A proposal submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy

University of Washington

Department of Aeronautics & Astronautics

INTRODUCTION

> “The choice, as Wells once said, is the Universe – or nothing…. The challenge of the great spaces between the worlds is a stupendous one; but if we fail to meet it, the story of our race will be drawing to its close. Humanity will have turned its back upon the still untrodden heights and will be descending again the long slope that stretches, across a thousand million years of time, down to the shores of the primeval sea.”
>
> *Arthur C. Clarke, in his book “Interplanetary Flight”, 1950*

The concept of rocket propulsion has to this day been the fundamental principle of the vast majority of space transportation devices developed and flown by humankind. In recent years NASA has been committing an increasing number of resources to the exploration of our planetary neighbors, and a crewed mission to other planets in our solar system has become a possibility under serious consideration. When trying to extrapolate the existing technology base of chemical rocket propulsion to serve such a mission, fundamental shortcomings become apparent.

Many alternative types of rocket propulsion have been proposed in the scientific and engineering communities, ranging from the evolutionary development of proven concepts, to radical approaches requiring spacecraft of massive size, utilizing exotic power sources. This highly diverse pool of ideas is largely technology driven, and new concepts inevitably inherit the limitations of the underlying technology which spawned their conception.

PHYSICALLY IDEAL REACTION BASED PROPULSION

This paper proposes to investigate the concept of reaction based propulsion in its most fundamental terms, and extrapolates from basic principles the design of the most capable, interplanetary transportation system (ITS) as it is possible with today's understanding of physics. No engineering restrictions are imposed, unless required to define the system. For example, physically ideal energy conversion methods are assumed, capable of converting all available fuel into energy at the maximum theoretical efficiency, regardless of whether or not technology can provide such a device. However, the system is required to provide transport while maintaining acceleration levels appropriate for a human crew.

Within the constraints necessary to define the problem, nature has already provided a single, most capable solution. It is the goal of this research to identify this ideal solution to the stated problem of human transport within the solar system. The resulting design of the physically ideal, human-capable, reaction based, interplanetary transportation system (PHRITS) is envisioned to serve as a guide for all other technology bases, pointing the way towards maximum utilization of their potential.

Historic Background

This study was motivated in part by the historical example of the Carnot cycle, and its impact on the development of the steam engine. The following brief overview of Sadi Carnot's contribution to the physical sciences in general, and the development of the steam engine in particular, is taken from a number of biographical sources.[1,2]

Sadi Carnot was the eldest son of Lazare Carnot and graduated from the École Polytechnique in Paris in 1814. He worked on the mathematical theory of heat and helped start the modern theory of thermodynamics. Carnot's major work was a paper which he wrote in 1822-23. This paper attempted to find a mathematical expression for the work produced by one kilogram of steam. The paper is similar in its aims and also in its methods to several other papers which appeared around this time by Hachette, Navier and

Petit. However, it is unique in its methodology of identifying the physical ideal of a steam engine, thus providing the indisputable direction for technological efforts to improve steam engine performance.

In 1824 he published his work describing the Carnot cycle titled “Reflections on the motive power of heat”.[3] It was his accomplishment, to give efforts of improving the steam engine technology a concise direction, separating the “black magic” of adding “bells and whistles” with a concrete metric to assess and improve design performance.

Figure 1: Sadi Carnot, 1796-1832.

It is the hope of the author that the work presented in this proposed research will be of similar help towards the development of a practical interplanetary transportation system, capable of serving human needs for all space-based activities inside the solar system.

Scope of Investigation

When considering space vehicles propelled by momentum exchange, one important distinction to keep in mind is the separation of propellant and fuel. The propellant is defined as the substance which is used to transfer vehicle momentum, thus allowing the vehicle to accelerate in a desired direction without violating Newton’s third law of motion. The fuel of the vehicle is defined as the substance (or substances) from which the energy is derived to accelerate the propellant, and thus the vehicle itself. The familiar technology of chemical rockets is a special case, in which fuel and propellant are the same substance.

This investigation is limited to those transportation systems based on momentum exchange with some form of ejected or deflected mass (reaction based propulsion). The two main categories within this parameter space are rocket propulsion devices, carrying their propellant on board, and sail type devices, where the propellant is provided by a source external to the vehicle. Propulsion devices in either category may derive their energy from a source (fuel) external to the vehicle (e.g. solar sails, solar electric ion-drives), or from an internal source (e.g. fusion electric propulsion).

Space-drives, interacting with the quantum level of the vacuum itself may be thought of as an example where the vessel carries its energy source (fuel) internally, but not its reaction mass (propellant). However, this investigation is limited to those devices based on the well understood physics of rocketry, and solar sail type concepts.

In addition, all concepts considered in this research are only assessed for their usefulness as an interplanetary transportation system. While it is not a priori assumed that none of the possible concepts within the thus defined parameter space could be capable of travel beyond the solar system, these capabilities (should they exist) do not enter into the research proposed in this paper.

However, all mission types share one common factor: the gravitational potential of the point of origin. While the question of the particular celestial body from which the mission is to originate is left open in the interest of keeping the applicability of the results as broad as possible, one question that does need answering is whether or not the mission is to originate from a planet’s surface or low orbit.

Many examples already exist in various transportation applications. Commercial airliners are optimized for cruise, and not for dropping each passenger at their individual destinations. Intercontinental naval vessels require special infrastructure to achieve land fall at the end of their journeys. Under the same reasoning it is evident that a vessel meant to carry humans through interplanetary space cannot from the onset be designed to achieve planetary landing as well. Should the resulting design be capable of landing and launching inside a gravity well (with or without an atmosphere), so much the better. However, the focus of the design effort must be concentrated on travel through interplanetary space. Until a clearer picture emerges and the ability to perform a planetary landing (possibly with supporting infrastructure) can be investigated, the postulated ITS is not intended to ever fly in an atmosphere or land on a planetary surface.

RESEARCH PROCESS OVERVIEW

In order to arrive at the goal of identifying the best physically possible solution for the challenge of transporting humans within the solar system, a multidisciplinary, mathematically rigorous approach is suggested.

Figure 2 illustrates the approach proposed in this research:

- A multidisciplinary analysis into the possible needs and uses of humans for transportation inside the solar system is performed. Together with the limitations of physical possibility, the identified needs establish the system objectives for an interplanetary transportation system.

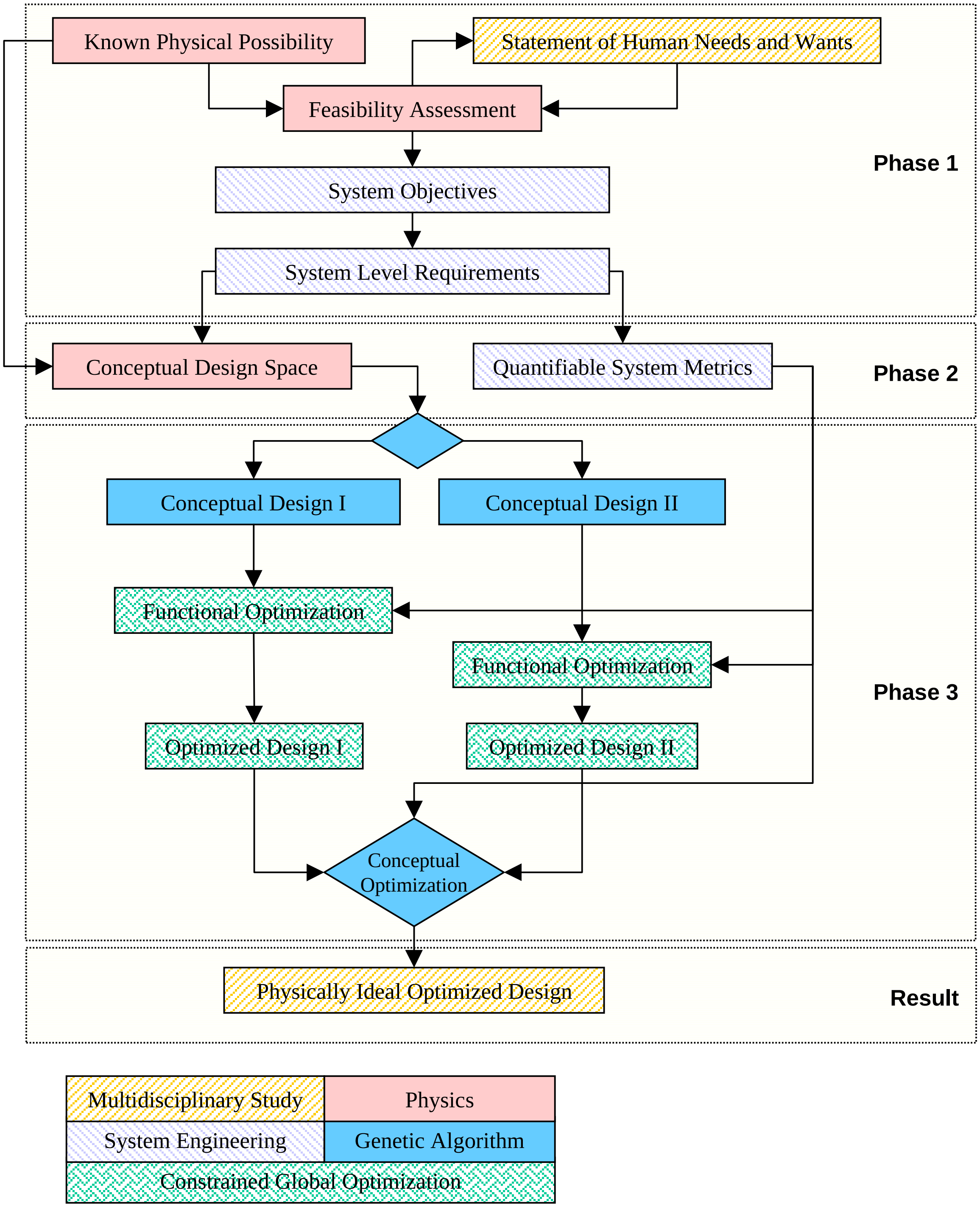

Figure 2: Research approach overview.

- From the system objectives, system level requirements are derived, following established systems engineering practice.

- From these requirements, quantifiable system metrics are derived to serve as a tool in assessing system performance.

- Physical possibility is used in conjunction with the previously derived system requirements to limit the design space to all physically possible configurations.

- A genetic algorithm is used to evolve the design to the sought ideal. The process begins with selecting a random seed population out of the design space.

- Each individual candidate concept is optimized in its functionality, using the previously defined system metrics and mathematical global optimization techniques.

- The optimized candidate concepts are evaluated against each other using the previously established system metrics. Continued iteration of the genetic algorithm and ‘survival of the fittest’ eventually yields the sought ideal solution.

Each of these steps is introduced in more detail in the following paragraphs.

System Objectives

Any sound design process should begin with a clear problem definition. A fundamental shortcoming in current development efforts for future ITS is that the development process usually begins with the inception of a new technological concept: a technological advance is made, the potential of this technology for space travel applications is identified, and a case is made to justify additional research to further develop this particular technology application. The majority of ITS concepts proposed in the literature is thus technology based. Preston White nicely summarized my misgivings towards this approach when he wrote[4]:

> "Defining the problem is as much a part of design as is defining the artifact itself. An elegant and efficient solution to the wrong problem is an inefficient use of resources."

Another difficulty with this approach is that, as soon as the technology becomes outdated, the proposed concept becomes outdated as well. A good example is the interplanetary transport propelled by nuclear explosions reacting against a pusher plate, named the Orion Project.[5] The concept was proposed in a time when the possibility of controlled nuclear energy, at the levels required for interplanetary travel, was still thought to be beyond the existing or near-term technological possibilities. With today's advances in controlling nuclear fission and fusion reactions, the design has lost any promise of usefulness, and has become obsolete.

The steering of development efforts in directions of soon to be outdated technology can be avoided, by using a mission-driven approach instead. Through clearly defining the system objectives of an ITS, a clear goal is set, that is independent of the technology being applied to achieve it. System objectives are technology independent; once identified, they remain unchanged.

In his publication "How To Do Systems Analysis" Gibson[6] defines the application of systems engineering towards establishing the objectives of a given system as follows:

> "In systems engineering the extant technologies are where we are now. The system objectives are our statement of where we want to be at some time in the future. And the systems engineering process is how we get from here to there."

However, since the research suggested in this proposal is to be based on physical possibility rather than technological feasibility, the term "extant technologies" should be replaced with "known physical possibility". Having made that adjustment, the process of identifying the mission objectives can than be visualized as shown in Figure 3.

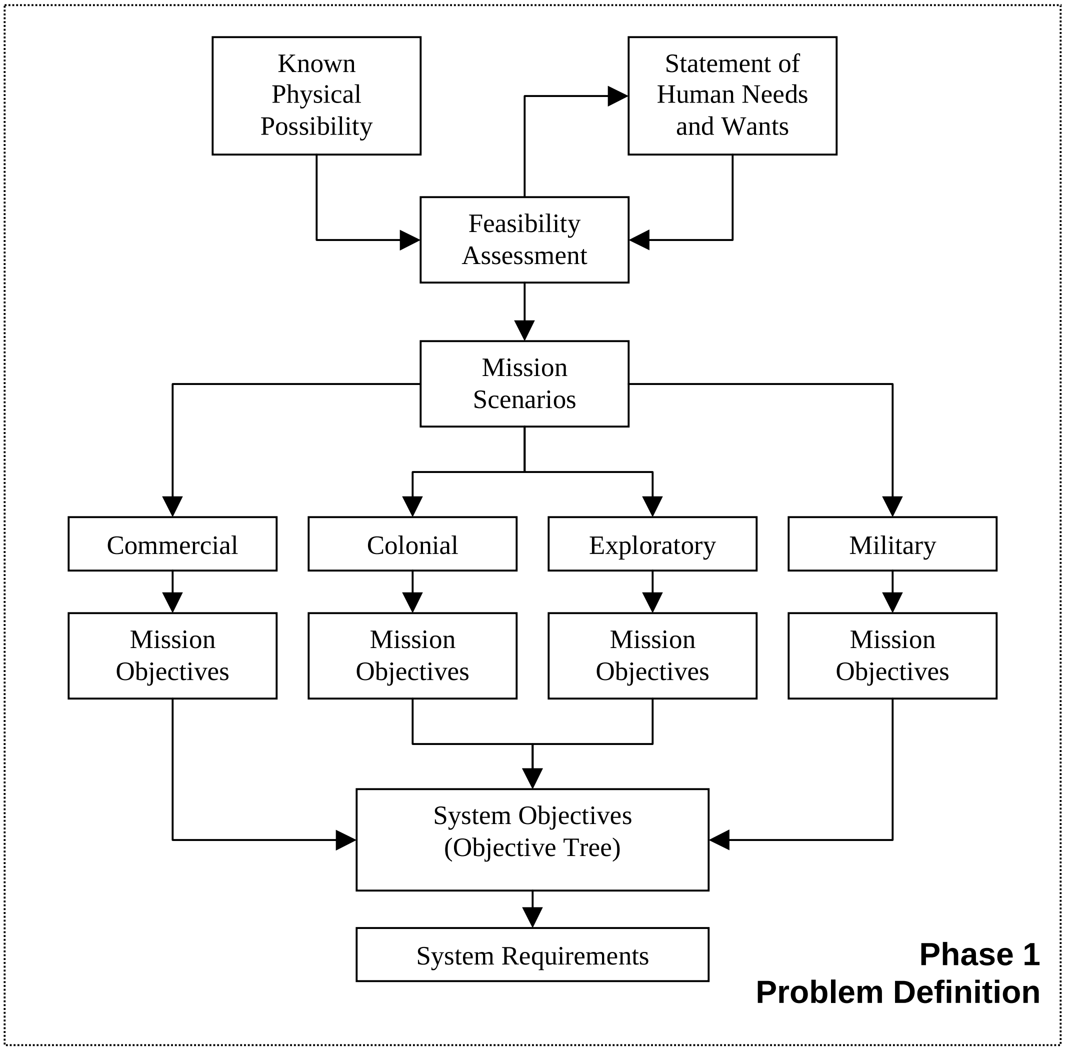

Figure 3: Phase 1 detailed process flow.

System Requirements

In order to continue the ‘top-down’ approach begun with the identification of the system objectives, system level requirements need to be derived from them. While most texts on space systems engineering agree that the derivation of system level requirements from mission or systems objectives is an important part of the design process, only a few attempts have been made to formalize this step. Tatnall et all[7] define mission requirements of any given system as follows:

> "The mission requirements are the top level requirements on the spacecraft. They are […] an assessment of the performance required to meet the mission objectives."

Wertz[8] suggests the following categorization when transforming mission objectives into requirements:

1. *Functional Requirements*, which define how well the system must perform to meet its objectives.
2. *Operational Requirements*, which determine how the system operates and how users interact with it to achieve the mission objectives.
3. *Constraints*, which limit cost, schedule, and implementation techniques available to the designer.

However, the suggested methodology is aimed towards the development of commercial satellites, and thus requires adjusting to adapt it to the problem under discussion. In particular, the implementation mentioned under item 3 can be focused onto a single constraint: physical possibility. The adapted version used in this research then reads as follows:

1. *Functional Requirements*, which define how well the system must perform to meet its objectives.
2. *Operational Requirements*, which determine how the system operates and how users interact with it to achieve the mission objectives.

3. *Physical Constraints*, which limit applicable concepts available to the designer.

In order to further clarify the distinction of these three categories, an example for each could read as follows:

1. The ITS shall be capable of reaching all the planets in the solar system.

2. The ITS shall never exceed acceleration limits beyond what can be endured by a human crew without causing permanent impairment.

3. The ITS must use chemical (combustion), nuclear (fission, fusion), environmental (solar illumination, solar wind magnetohydrodynamic), or nucleonic (anti-matter) energy sources for operation.

This rigorous approach endeavors to minimize the subjective component of the 'Art of Systems Engineering', and thus to yield a set of requirements as complete and objective as possible.

System Architecture

Since it is the goal of this study to be as general in nature as possible, the detail level of the architecture is kept at the minimum required to perform the study. The ITS is broken down into the following components (Figure 4).

- **Power Subsystem**: provides all power to other subsystems. Includes energy (fuel) storage, conditioning, and associated structure.

- **Propulsion Subsystem**: provides motive force to the ITS. Includes propellant storage, engine(s), and associated structure.

- **Command Subsystem**: provides all command and data handling activities for the ITS. Includes the crew (and life support for the crew), avionics, communication, and associated structure.

- **Payload Subsystem**: the item(s) intended for delivery (transportation), includes associated environmental conditioning (life support if people), payload specialists (scientist, flight attendants, etc.), and associated structure.

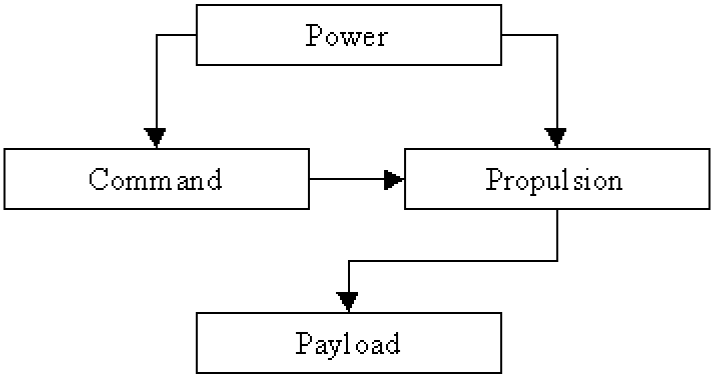

Figure 4: Subsystem breakdown for the ITS.

It is likely that there will be some overlap between the command and payload subsystems in the cases of crewed exploratory missions, where the crew (considered part of the Command subsystem), also serves as the payload operators and thus accounts for part of the Payload Subsystem as well.

System Metrics

Establishing the system objectives and requirements defines a limited design space for the sought idealized solution. However, in order to quantify the proximity of a particular concept to the physical ideal, a set of numerical metrics is required. In particular, the use of computational methods in the conceptual and functional optimization phases of the proposed research requires the definition of numerical parameters.

Metrics are derived from system requirements. Having stated what a system is required to accomplish, it is possible to identify a numerical expression to quantify the degree of success of the design under consideration in fulfilling the given requirement. In order to ensure appropriate ‘weighing’ of all metrics relative to each other, each parameter is normalized with its Range of Usefulness (ROU). For example, the ROU for the distance a candidate ITS can cover is 0.3 AU (straight line distance from Earth to Venus at conjunction) to 70 AU (distance from Neptune to Pluto at opposition). Below the lower bound the ITS becomes useless (since it will not be able to span the distance between any two planets in the solar system), and on the upper bound it gains capability which has no impact on its usefulness as an interplanetary transport design. Thus the actual distance parameter of each candidate concept is normalized to a value between 0 and 1. Values in excess of a normalized value of 1, are forced to a value of 1 to prevent an increase in the overall cost function (see “Functional Optimization”, page 18) that does not represent actual capability, and negative values are forced to zero, thus immediately identifying concepts which have no useful application. Any general metric M_i intended for maximization can thus be normalized with the same mathematical relationship:

$$\begin{aligned}
&\overline{M}_i = \frac{M_i - M_{ROU\_lower,i}}{M_{ROU\_upper,i} - M_{ROU\_lower,i}} \\
&\text{if} \quad \overline{M}_i < 0, \overline{M}_i = 0 \\
&\text{if} \quad \overline{M}_i > 1, \overline{M}_i = 1
\end{aligned} \qquad \text{(Eq.1)}$$

Figure 5 gives an example, showing the value of the normalized distance parameter versus the actual distance in Astronomical Units.

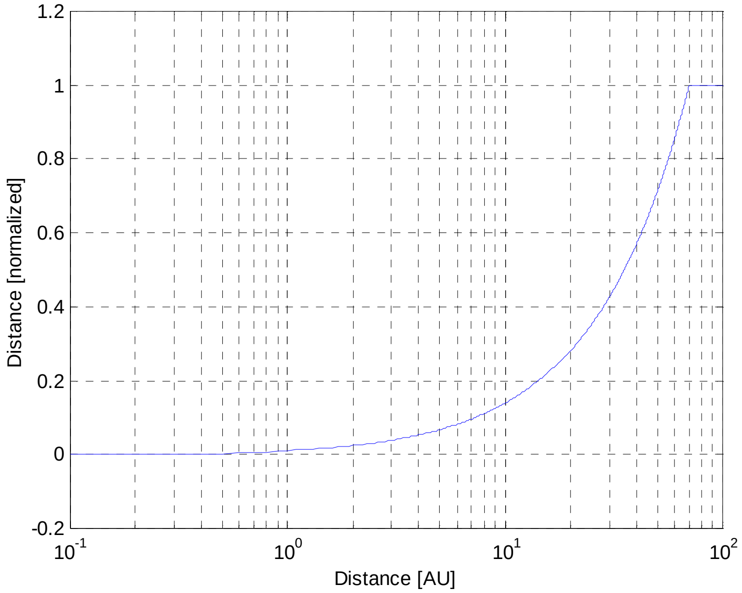

Figure 5: Normalized distance parameter vs. actual distance in AU

In the case of a metric which is desired to be as small as possible (minimized) within its associated ROU, the relational expression in Eq.1 needs to be modified, while the conditional expressions remain unchanged:

$$\begin{aligned}
&\overline{M}_i = \frac{M_i - M_{ROU\_upper,i}}{M_{ROU\_lower,i} - M_{ROU\_upper,i}} \\
&\text{if} \quad \overline{M}_i < 0, \overline{M}_i = 0 \qquad \text{(Eq.2)} \\
&\text{if} \quad \overline{M}_i > 1, \overline{M}_i = 1
\end{aligned}$$

Figure 6 shows an illustration for a hypothetical metric with an ROU of 3-10, which is to be minimized.

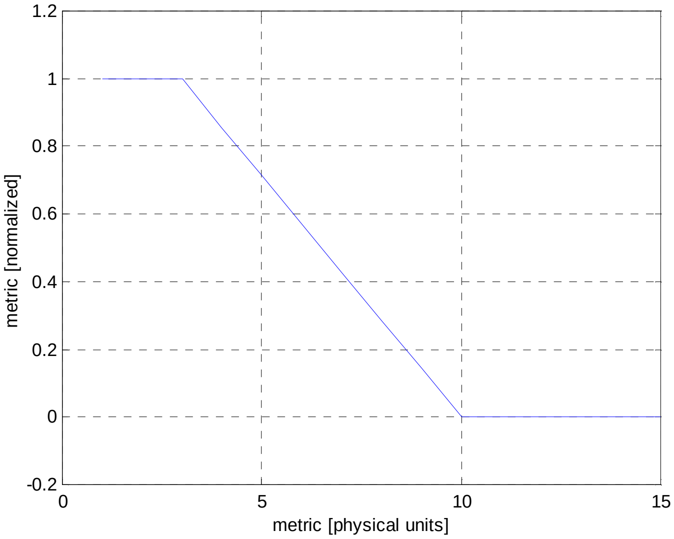

Figure 6: Metric to be minimized within a given ROU.

The use of clearly defined system metrics allows for objective comparison between concept alternatives.

Conceptual Optimization

Next to the a priori focus of new concepts on a given technology, another shortcoming of many designs is the necessarily subjective approach in their optimization. While many very advanced engineering tools exist to perform detailed subsystem optimization, tools for optimization at the conceptual level have come into being only very recently.[9] In addition, these tools have been applied only to concepts based on existing, or near term predictable technology, thus limiting the scope of the optimization.

In the traditional approach towards conceptual system design optimization, the previous experience of the engineer(s) involved with the process has a high impact. This inevitably leads to a final design that reflects the subjective likes and dislikes of the investigator. In addition, the number of options (trade studies) that can be investigated in the design phase is limited, due to the limited amount of personnel hours which can economically be invested into the design.

The research proposed in this paper makes use of the rigorous tools of applied mathematics to identify the truly optimal design solution within the established constraints of only physical possibility and identified user needs.

The various types of available optimization methods can be grouped into three broad categories:

1. Parameter methods based on experimental data and previous experience (the 'traditional' approach).
2. Gradient or calculus based methods, involving a complex function of continuous variables to be either maximized or minimized, under a variety of external constraints (functional optimization).
3. Stochastic methods such as genetic algorithms (start with a random seed and evolve to the best solution) or enumeration (evaluate all possible combinations), where parameter values are of a discrete nature.[10]

The research proposed in this document makes use of all three of these methods. The first is employed to establish the constraints of the problem: the definition of the system objectives draws on the body of knowledge documented in the professional literature. Functional optimization is used to identify the highest performing variation of a given candidate concept (see next section), and conceptual optimization is performed using a genetic algorithm to effectively probe the large design space.

The very large number of physically possible combinations of conceptual design choices is prohibitive to standard enumeration methods (testing every possible combination). One possible alternative would be the use of stochastic methods (e.g. Monte Carlo methods), but their probability based nature makes it inherently difficult to identify a non-disputable ideal solution.[11] Through use of a genetic algorithm instead, the solution can be evolved while dealing with only a smaller subset of all possible combinations, yet still produce the globally superior design solution with a high degree of certainty. [10]

Functional Optimization

Before a given candidate concept can be fairly evaluated, it needs to be optimized within the parametric space of its conceptual design. This process is referred to as functional optimization. As an example, it might be known that the design is to use magnetically confined fusion as a power source (a conceptual choice), but the specific impulse history over the mission duration is still a design parameter to be optimized within the constraints of that conceptual choice. In algebraic notation, the problem can be expressed as follows:

$$\begin{array}{lll} \text{Objective:} & \text{maximize,} & f(\bar{x}) \\ \text{Inequality constraints:} & \text{subject to} & g_j(\bar{x}) \leq 0, \quad j = 1,\dots,p \\ \text{Equality constraints:} & & h_k(\bar{x}) = 0, \quad k = 1,\dots,q \\ \text{Design variables:} & & \bar{x} = \{x_1, x_2, \dots, x_n\} \end{array}$$

The function f(x) is the overall cost function to be maximized. It is defined as the product of the various, normalized metrics defined previously, where the individual metrics (M_i) will be functions of many interrelated variables (x_i).

$$f(\bar{x}) = \prod_{i=1..n} \overline{M}_i(x_1, x_2, \dots) \qquad \text{(Eq.4)}$$

An ITS candidate design outside the ROU in any of the defined metrics is then immediately identified by a zero value for the overall cost function; and all remaining concepts can be compared with a single numerical value: $0 < f(\bar{x}) < 1$.

This type of optimization problem occurs in a large variety of disciplines, such as science, engineering, or economics. It is called a constraint global optimization problem. In this case, the constraints are imposed by the original system definition. The global attribute is added to denote that the overall ideal solution is sought, and not just a local minimum, which significantly increases the degree of difficulty.

Techniques of global optimization of non-linear functions are an area of intense research in the field of applied mathematics.[12] Over the years a large arsenal of tools has been developed to solve these type of problems. The research proposed in this paper makes use of these existing tools, rather than attempting to derive an original formulation.

Resulting Physically Ideal Optimized Design

Through continued iteration of the genetic algorithm, using the single value of the cost function for each optimized design concept as the criteria for ‘survival’, the sought after, overall ideal is identified.

SUMMARY

This paper proposes to investigate the concept of reaction-based propulsion in its most fundamental terms, and extrapolates from basic principles the design of the most capable, interplanetary transportation system (ITS) as it is possible with today’s understanding of physics. It is the hope of the author that the idealized design thus derived, will be of help in the development of a practical interplanetary transportation system; capable of serving human needs for all space-based activities inside the solar system.

In order to define the problem, a multidisciplinary analysis into the possible needs and uses of humans for transportation inside the solar system is performed. Together with the limitations of physical possibility, the identified needs establish the mission and system objectives for an interplanetary transportation system. From the objectives, system level requirements are derived, following established systems engineering practice. These requirements then serve to identify quantifiable system metrics as a tool in assessing system performance. A genetic algorithm is proposed to evolve the design to the sought ideal. Each individual candidate concept is optimized in its functionality, using the previously defined system metrics and mathematical global optimization techniques. The optimized candidate concepts are evaluated against each other using the previously established system metrics, and continued iteration of the genetic algorithm eventually yields the sought ideal solution.

BIBLIOGRAPHY

[1] Hills, R.L., Power from Steam: A history of the stationary Steam Engine, Cambridge University Press, 1989.

[2] Galloway, R.L., “ The Steam Engine and its Inventors: a Historical Sketch”, Landmarks of Science, New York , 1975.

[3] Carnot, Sadi, “Reflexions sur la puissance motrice du feu. (Reflections on the motive power of heat and on machines fitted to develop that power)”, from the original French of N.-L.-S. Carnot ; edited by R.H. Thurston, J. Wiley, New York, 1890.

[4] White, K.P., jr., “Systems Design Engineering”, Journal of the International Council on Systems Engineering, Vol. 1, No. 4, Wiley Publishing, 1998, pp. 285

[5] Metzger, J. D., Parlos, A. G., “A Review of Contained Pulsed Nuclear Propulsion System Analysis”, AIAA Paper 95-2902, 31st AIAA/ASME/SAE/ASEE, Joint Propulsion Conference and Exhibit, 31st, San Diego, CA, July 10-12, 1995.

[6] Gibson, J.E., “How To Do Systems Analysis”, University of Virginia, Charlottesville, VA, 1991

[7] Tatnall, R.L., Farrow, J.B., Francis, R., Stark, J.P.W., Spacecraft Systems Engineering, 2nd Edition, p.532, Wiley Publishing, 1995.

[8] Larson, W.J., Wertz, J.R. (ed.), Space Mission Analysis and Design, “The Space Mission Analysis and Design Process”, Wertz, J.R., 2nd Edition, Space Technology Series, Microcosm, Inc., 1992, p. 14-15.

[9] Lawrence, F. R., Braun, R. D., “Multidisciplinary Design Optimization of Space Transportation Systems”, Journal of Aircraft, Vol. 36, No. 1, January – February, 1999.

---

[10] Mosher, T., “Conceptual Spacecraft Design using a Genetic Algorithm Trade Selection Process”, Journal of Aircraft, Vol. 36, No. 1, January – February, 1999.

[11] Pardalos, P.M., Rosen, J.B., “Constrained Global Optimization: Algorithms and Applications”, Lecture Notes in Computer Science, Springer, 1987.

[12] Horst, R., Hoang, T., Global Optimization: Deterministic Approaches, 3rd Revision, Springer, 1996.