Conceptual Design of Single-Stage Launch Vehicle with Hybrid Rocket Engine for Scientific Observation Using Design Informatics

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Abstract

A single-stage launch vehicle with hybrid rocket engine has been conceptually designed by using design informatics, which has three points of view as problem definition, optimization, and data mining. The primary objective of the design in the present study is that the sufficient down range and duration time in the lower thermosphere are achieved for the aurora scientific observation whereas the initial gross weight is held down. The multidisciplinary design optimization and data mining were performed by using evolutionary hybrid computation under the conditions that polypropylene as solid fuel and liquid oxygen as liquid oxidizer were adopted and that single-time ignition is implemented in sequence. Consequently, the design information regarding tradeoffs and the behavior of the design variables was obtained.

Key words: Design Informatics, Single-Stage Launch Vehicle for Scientific Observation, Hybrid Rocket Engine Using Solid Fuel and Liquid Oxidizer

1. Introduction

Single-stage rockets have been being researched and developed for the scientific observations and the experiments of high-altitude zero-gravity condition, whereas multi-stage rockets have been being also studied for the orbit injection of payload. The Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA) has been managing K, L, and M series rockets as the representatives of solid rocket in order to contribute to the space scientific research. A next-generation single-stage rocket as well as multi-stage rocket is necessary due to the retirement of M-V in 2008 and in order to promote space scientific research. In fact, E rocket will begin to be operated from August 2013. On the other hand, the launch vehicle with hybrid rocket engine using solid fuel and liquid oxidizer has been being researched and developed as an innovative technology in mainly Europe and United States [1,2].

The present study will investigate the conceptual design in order to develop a next-generation single-stage launch vehicle with hybrid rocket engine. Since the technologies of hybrid rocket engine for single-stage and multi-stage are not independent, the solution of the fundamental physics regarding single-stage hybrid rocket is also the knowledge for multi-stage. Although three-stage hybrid rocket is parallel studied [3], design requirements are different because of the difference of the operation objectives. A hybrid rocket offers the several advantages as higher safety, lower cost, and pollution free flight. In fact, the SpaceShipOne successfully
uses a hybrid rocket engine for a private manned space flight. The multi-time ignition is the especial advantage of hybrid rocket engine [4]. On the other hand, the disadvantage of a hybrid rocket engine is in its combustion. As a hybrid rocket engine has low regression rate of solid fuel, the thrust of hybrid rocket engine is less than that of pure solid and pure liquid engines. Multidisciplinary design requirements should be considered in order to surmount the disadvantage of hybrid rocket engine. Moreover, design information will be obtained in order to exhaustively grasp the design space.

Design informatics is essential for practical design problems. Although solving design optimization problems is important under the consideration of many disciplines of engineering [5], the most significant part of the process is the extraction of useful knowledge of the design space from results of optimization runs. The results produced by multiobjective optimization (MOO) are not an individual optimal solution but rather an entire set of optimal solutions due to tradeoffs. That is, the result of a MOO is not sufficient from the practical point of view as designers need a conclusive shape and not the entire selection of possible optimal shapes. On the other hand, this set of optimal solutions produced by an evolutionary MOO algorithm can be considered a hypothetical design database for design space. Then, data mining techniques can be applied to this hypothetical database in order to acquire not only useful design knowledge but also the structurization and visualization of design space for the conception support of basic design. This approach was suggested as design informatics [6]. The goal of this approach is the conception support for designers in order to materialize innovation. This methodology is constructed by the three essences as 1) problem definition, 2) efficient optimization, and 3) structurization and visualization of design space by data mining. A design problem including objective function, design variable, and constraint, is strictly defined in view of the background physics, then optimization is implemented in order to acquire nondominated solutions (quasi-Pareto solutions) as hypothetical database. Data mining is performed for this database in order to obtain design information. Mining has the role of a postprocess for optimization. Mining result is the significant observations for next design phase and also becomes the material to redefine a design problem.

In the present study, a single-stage launch vehicle with hybrid rocket engine of solid fuel and liquid oxidizer for the scientific observation of aurora will be conceptually designed by using design informatics approach in order to quantitatively reveal the advantage and in order to discover the fundamental physics regarding hybrid rocket engine. As a first step, an optimization problem on single-time ignition, which is the identical condition of the current solid rocket, is defined under the present studying constructions, and then the design information, which is the correlation among objective functions (design requirements) and the influence of design variables, is obtained. As a second step, the implication of solid fuels in performance of hybrid rocket will be revealed because the regression rate is one of the key elements for the performance of hybrid rocket. The validity of the problem definition will be considered by using the design information from the two-step results. Finally, the sequence using multi-time ignition, which is the great advantage of a hybrid rocket, will be investigated in order to reveal the ascendancy of hybrid rocket and also practically contribute to space science. The standing point of the present research is on the first step as the milestone to observe the quantitative difference of performance between conventional solid rocket and the present hybrid rocket. Moreover, the present research investigates the role as the reference result to quantitatively show the ascendancy of multi-time ignition.

2. Design Informatics

Design informatics after the definition of detailed problem is constructed by two phases as optimization and data mining. Evolutionary computation is used for optimization. Although a surrogate model [7, 8] like as the Kriging model [9, 10], which is a response surface model developed in the field of spatial statistics and geostatistics, can be employed as optimization method, it will not be selected because it is difficult to deal with a large number
of design variables. In addition, since the designers require to present many exact optimum solutions for the decision of a compromise one, an evolutionary-based Pareto approach as an efficient multi-thread algorithm, which the plural individuals are parallel conducted, is employed instead of gradient-based methods. The optimizer used in the present study is the evolutionary hybrid method between the differential evolution (DE) and the genetic algorithm (GA) [11]. Moreover, global design information is primarily essential in order to determine a compromise solution. Therefore, a self-organizing map (SOM) [12, 13] is used as a data mining technique in the present study because SOM extracts the global information in design space [14].

2.1. Hybrid Optimizer

The view of hybridization is inspired by the evolutionary developmental biology [15]. When there is the evolution which the Darwinism cannot explain in the identical species, each individual might have a different evolutionary methodology. When the practical evolution is imitated for the evolutionary computation, the different evolutionary algorithms might ultimately be applied to each individual in population. The making performance of next generation for each methodology depends on not only their algorithms but also the quality of candidate of parent in the archive of nondominated solutions. The present hybridization is intended to improve the quality of candidate of parent by sharing the nondominated solutions in the archive among each methodology. In the present study, the evolutionary hybrid optimization methodology between DE and GA is employed. It was confirmed that this methodology had the high performance regarding the convergence and diversity, as well as the strength for noise [11]. Note that noise imitates the error on computational analyses and experiments and is described as the perturbation on objective functions. It is an important factor when the optimization for practical engineering problem is considered.

The flowchart of the present hybrid methodology is shown in Fig. 1. First, multiple individuals are generated randomly as an initial population. Then, objective functions are evaluated for each individual. The population size is equally divided into sub-populations between DE and GA (although sub-population size can be changed at every generations on the optimizer, the determined initial sub-populations are fixed at all generations in the present

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**Fig. 1** Conceptual flowchart of the present evolutionary hybrid methodology.
study). New individuals generated by each operation are combined in next generation. The nondominated solutions in the combined population are archived in common. It is notable that only the archive data is in common between DE and GA. The respective optimization methods are independently performed in the present hybrid methodology.

2.2. Configurations of Operators for Each Optimizer

The present optimization methodology is a real-coded optimizer [16]. Although GA is based on the real-coded NSGA-II (the elitist nondominated sorting genetic algorithm) [17], it is made several improvements in order to be progressed with the diversity of solutions. Fonseca’s Pareto ranking [18] and the crowding distance [17] are used for the fitness value of each individual. The stochastic universal sampling [19] is employed for parents selection. The crossover rate is 100%. The principal component analysis blended crossover-α(PCABlx) [20] and the confidence interval based crossover using $L_2$ norm(CIX) [21] are used because of the high performance for the convergence and the diversity as well as the strength for noise [11]. The subpopulation size served by GA is equally divided for these two crossovers. The mutation rate is set to be constant as the reciprocal of the number of design variables. For alternation of generations, the Best-N selection [17] is used. DE is used as the revised scheme [22] for multiobjective optimization from DE/rand/1/bin scheme. The scaling factor $F$ is set to be 0.5. The present optimizer has the function of range adaptation [23], which changes the search region according to the statistics of better solutions, for all design variables. In the present study, the range adaptation is implemented at every 20th generations.

2.3. Data-Mining Technique

In the present study, SOM is selected as a data-mining technique because the primary objective of data mining is the acquisition of global design information in order to implement the structuring of design space. The previous study [14] indicated that SOM extracted the global design information for whole design space. The distinguishing feature of SOM is the generation of a qualitative description. The advantage of this method includes the intuitive visualization of two-dimensional colored maps of design space using bird’s-eye-views. As a result, SOM reveals the tradeoffs among objective functions. Moreover, SOM addresses the effective design variables and also reveals how a specific design variable gives effects on objective functions and other design characteristics. One SOM is colored for one variable of objective function, design variable, and other characteristic value so that the coloring pattern is compared each other. Therefore, the data mining using SOM might have a disadvantage to overlook important correlation in the problem with a large number of objective functions and design variables. Since the present study has a total number of 10 at most among the objective functions and design variables, SOM is sufficient for the data mining manner. Figure 2 shows the comparison example on colored SOMs for objective functions. The relationship among

Fig. 2 Comparison example of colored SOMs for minimization problem with three objective functions as $f_1$, $f_2$, and $f_3$. Red describes high value and blue is low value.
objective functions and design variables can be observed at a glance by the colored grids with component values of the vector. When SOM has a large number of grids, the coloring pattern will be compared on SOM.

In the present study, SOMs are generated by using commercial software Viscovery® SOMine 4.0 plus produced by Eudaptics, GmbH. The uniqueness of the map generated by SOMine is assured due to Kohonen’s Batch SOM algorithm and search of the best-matching unit for all input data and adjustment of weight vector near the best-matching unit. This is much like epoch learning as an unsupervised learning model in neural networks. Batch-SOM is a more robust approach as it mediates over a large number of learning steps. SOMine creates a map in a two-dimensional hexagonal grid. Starting from numerical, multivariate data, the nodes on the grid gradually adapt to the intrinsic shape of the data distribution. As the position on the grid reflects the neighborhood within the data, the features of the data distribution can be read from the emerging map on the grid. The trained SOM is systematically converted into visual information. Once the high-dimensional data is projected onto the two-dimensional regular grid, the map can be used for visualization and data mining. It is efficient to group all neurons by similarity to facilitate SOM for qualitative analysis, because the number of neurons on the SOM is large. This process of grouping, called clustering, was performed using the hierarchical agglomerative algorithm [24]. First, each node itself forms a single cluster and two clusters adjacent on the map are merged in each step. The distance between two clusters is calculated using the SOM-ward distance. The number of clusters is determined by the hierarchical sequence of clustering. Relatively small numbers of clusters are used for visualization, while large numbers are used for generation of weight vectors for the respective design variables.

3. Problem Definition

The conceptual design for a single-stage hybrid rocket [25], simply composed of a payload chamber, an oxidizer tank, a combustion chamber, and a nozzle shown in Fig. 3, is considered in the present study. A single-stage hybrid rocket for aurora scientific observation will be focused because the rocket for more efficient scientific observation is desired for successfully obtaining new scientific knowledge on the aurora observation by ISAS in 2009. In addition, a single-stage hybrid rocket problem fits for the resolution of the fundamental physics regarding hybrid rocket engine and for the improvement of the present design problem due to its simplification.

3.1. Objective Functions

Three objective functions are defined in the present study. First objective is the maximization of the down range in the lower thermosphere (altitude of 90 to 150km) $R_d$ [km] (obj1). Second is the maximization of the duration time in the lower thermosphere $T_d$ [sec] (obj2). It recently turns out that atmosphere has furious and intricate motion in the lower thermosphere due to the energy injection, which leads aurora, from high altitude. The view of these objective functions are to secure the horizontal distance and time for the competent observation of atmospheric temperature and the wind for the elucidation of atmospheric dynamics and the balance of thermal energy. Third objective is the minimization of the initial
Table 1  Limitation of upper/lower values of each design variable.

<table>
<thead>
<tr>
<th>serial number</th>
<th>design variable</th>
<th>design space</th>
</tr>
</thead>
<tbody>
<tr>
<td>dv1</td>
<td>initial mass flow of oxidizer ( \dot{m}_\text{oxi}(0) ) [kg/sec]</td>
<td>( 1.0 \leq \dot{m}_\text{oxi}(0) \leq 30.0 )</td>
</tr>
<tr>
<td>dv2</td>
<td>fuel length ( L_{\text{fuel}} ) [m]</td>
<td>( 1.0 \leq L_{\text{fuel}} \leq 10.0 )</td>
</tr>
<tr>
<td>dv3</td>
<td>initial radius of port ( r_{\text{port}}(0) ) [m]</td>
<td>( 0.01 \leq r_{\text{port}}(0) \leq 0.30 )</td>
</tr>
<tr>
<td>dv4</td>
<td>combustion time ( t_u ) [sec]</td>
<td>( 10.0 \leq t_u \leq 40.0 )</td>
</tr>
<tr>
<td>dv5</td>
<td>initial pressure in combustion chamber ( P_{\text{cc}}(0) ) [MPa]</td>
<td>( 3.0 \leq P_{\text{cc}}(0) \leq 6.0 )</td>
</tr>
<tr>
<td>dv6</td>
<td>aperture ratio of nozzle ( \epsilon ) [-]</td>
<td>( 5.0 \leq \epsilon \leq 8.0 )</td>
</tr>
<tr>
<td>dv7</td>
<td>elevation at launch time ( \phi ) [deg]</td>
<td>( 50.0 \leq \phi \leq 90.0 )</td>
</tr>
</tbody>
</table>

The gross weight of launch vehicle \( M_{\text{tot}}(0) \) [kg] (obj3), which is generally the primary proposition for space transportation system.

3.2. Design Variables

Seven design variables are used as initial mass flow of oxidizer \( \dot{m}_\text{oxi}(0) \) [kg/sec] (dv1), fuel length \( L_{\text{fuel}} \) [m] (dv2), initial radius of port \( r_{\text{port}}(0) \) [m] (dv3), combustion time \( t_u \) [sec] (dv4), initial pressure in combustion chamber \( P_{\text{cc}}(0) \) [MPa] (dv5), aperture ratio of nozzle \( \epsilon \) [-] (dv6), and elevation at launch time \( \phi \) [deg] (dv7). Note that there is no constraint except the limitations of upper/lower values of each design variable summarized in Table 1. These upper/lower values are exhaustively covering the region of design space which is physically admitted. When there is a sweet spot (the region that all objective functions proceed optimum directions) in the objective-function space, the exploration space would intentionally become narrow due to the operation of range adaptation on the evolutionary computation.

3.3. Evaluation Method

First of all, the mixture ratio between liquid oxidizer and solid fuel \( O/F(t) \) is computed by the following equation.

\[
\frac{O}{F}(t) = \frac{\dot{m}_\text{oxi}(t)}{\dot{m}_{\text{fuel}}(t)}
\]

\[
\dot{m}_{\text{fuel}}(t) = 2\pi r_{\text{port}}(t) L_{\text{fuel}} \rho_{\text{fuel}} \bar{P}_{\text{port}}(t)
\]

\[
r_{\text{port}}(t) = r_{\text{port}}(0) + \int r_{\text{port}}(t) dt
\]

\( \dot{m}_{\text{oxi}}(t) \) and \( \dot{m}_{\text{fuel}}(t) \) are the mass flow of oxidizer [kg/sec] and the mass flow of fuel [kg/sec] at time \( t \), respectively. \( r_{\text{port}}(t) \) is the radius of port [m] at \( t \), \( L_{\text{fuel}} \) describes fuel length, and \( \rho_{\text{fuel}} \) is the density of fuel [kg/m³]. \( r_{\text{port}}(t) \) describes the regression rate of fuel. After that, an analysis of chemical equilibrium is performed by using NASA-CEA (chemical equilibrium with applications) [26, 27], then trajectory, thrust, aerodynamic, and structural analyses are respectively implemented. The present rocket is assumed as a point mass. As the time step is set to be 0.5[sec] in the present study, it takes roughly 10[sec] for the evaluation of an individual using a general desktop computer. The contents of each analysis are briefly summarized as follows.

3.3.1. Trajectory/Thrust Analysis

The following equation of motion, which ignores the influence of atmosphere, described by using \( T(t) \) [N] and drag \( D(t) \) [N] is computed for rocket motion.

\[
M_{\text{tot}}(t)(a(t) - g) = T(t) - D(t)
\]

\( M_{\text{tot}}(t) \) is the gross weight [kg] at \( t \), \( a(t) \) describes acceleration [m/sec²] at \( t \), and \( g \) is gravity [m/sec²]. \( T(t) \) is evaluated by using the following equation.

\[
T(t) = \eta_T \left\{ \lambda \dot{m}_{\text{prop}}(t) \cdot u_e + (P_e - P_a) \cdot A_e \right\}
\]

where, \( \eta_T \) is total thrust loss coefficient, \( \lambda \) is momentum loss coefficient at nozzle exit by friction, \( \dot{m}_{\text{prop}}(t) \) is the mass flow of propellant, \( u_e \) is the velocity at nozzle exit, \( P_e \) is the pressure at nozzle exit, \( P_a \) is the pressure of atmosphere at flight altitude, and \( A_e \) describes the area of nozzle exit.

\[
\dot{m}_{\text{prop}}(t) = -(\dot{m}_{\text{oxi}}(t) + \dot{m}_{\text{fuel}}(t))
\]
A combustion chamber is filled with solid fuel with a single port at the center to supply oxidizer. As the regression rate to the radial direction of the fuel \( r_{\text{port}}(t) \) [m/sec] generally governs the thrust power of hybrid rocket engine, it is a significant parameter. The following empirical model [28, 29] is used in the present study.

\[
\dot{r}_{\text{port}}(t) = a_{\text{fuel}} \times G_{\text{oxi}}(t)^{n_{\text{fuel}}}
\]

where, \( G_{\text{oxi}}(t) \) is oxidizer mass flux [kg/(m²·sec)] and it has upper limitation of 1,000 in the present study. \( a_{\text{fuel}} \) [m/sec] and \( n_{\text{fuel}} \) [-] are the constant values empirically determined by fuels. In the present study, liquid oxygen as liquid oxidizer and polypropylene as thermoplastic resin for solid fuel in order to adopt swirling flow for the supply mode of oxidizer. Therefore, \( a_{\text{fuel}} \) and \( n_{\text{fuel}} \) are respectively set to be 8.26 × 10⁻⁵ [m/sec] and 0.5500. The locus of the regression rate of fuel for polypropylene described in eq. (5) is shown in Fig. 4. The horizontal axis represents the oxidizer mass flux per unit area.

### 3.3.2. Structural Analysis

Body is divided into the components as combustion chamber, oxidizer tank, and nozzle in order to decide weight and shape. First, total length \( L_{\text{tot}} \) is defined by using the length of combustion chamber \( L_{\text{cc}} \), the length of oxidizer tank \( L_{\text{oxi}} \), and the length of nozzle \( L_{\text{noz}} \) as follows;

\[
L_{\text{tot}} = 1.5 \times (L_{\text{cc}} + L_{\text{oxi}} + L_{\text{noz}})
\]

It is assumed that the outside radius of fuel \( r_{\text{fuel}} \) is equal to the inside radius of combustion chamber. The outside radius of rocket \( R_{\text{tot}} \) is also defined as the outside radius of oxidizer tank by using the radius of fuel \( r_{\text{fuel}} \) and the thickness of oxidizer tank \( t_{\text{oxi}} \).

\[
R_{\text{tot}} = r_{\text{fuel}} + t_{\text{oxi}}
\]

where, oxidizer tank and combustion chamber are assumed as thin cylindrical/spherical structure. The thickness of oxidizer tank \( t_{\text{oxi}} \) is defined as the following equation.

\[
t_{\text{oxi}} = f_{s} \cdot \frac{P_{\text{oxi}} \cdot r_{\text{fuel}}}{\sigma_{\text{oxi}}}
\]

\( f_{s} \) is the safety factor (in the present study, the constant value of 1.25 is set), \( P_{\text{oxi}} \) is the internal pressure of oxidizer tank, \( \sigma_{\text{oxi}} \) is the allowable stress for oxidizer tank. The internal pressure of combustion chamber \( P_{\text{cc}}(t) \) is described as the following equation.

\[
P_{\text{cc}}(t) = \frac{(m_{\text{oxi}}(t) + m_{\text{fuel}}(t)) \cdot c'(t)}{A_{\text{throat}}}
\]
where, \( c^* \) and \( A_{\text{throat}} \) respectively represents characteristic exhaust velocity and the area at nozzle throat. \( c^* \) is estimated by NASA-CEA. Note that there is no constraint regarding the structural requirements for strength and vibration due to the simplification of the present problem. Initial gross weight \( M_{\text{tot}}(0) \) is evaluated by the following equation.

\[
M_{\text{tot}}(0) = M_{\text{prop}}(0) + M_{\text{pay}} + M_{\text{fuel}}(0)
\]

\[
M_{\text{tot}}(0) = \frac{0.65}{V_{\text{ass}}} \int_{t_0}^{t_{\text{burn}}} m_{\text{fuel}}(t) \, dt
\]

\[
M_{\text{fuel}}(0) = \int_{t_0}^{t_{\text{prop}}} m_{\text{fuel}}(t) \, dt
\]

\( M_{\text{prop}}(0), M_{\text{tot}}(0), \) and \( M_{\text{fuel}}(0) \) are the mass of propellant, the mass of oxidizer, and the mass of fuel, respectively. \( M_{\text{pay}} \) describes the mass of payload. The present \( M_{\text{pay}} \) is the constant value of 40 [kg]. The constant value of 0.65 in eq. (9) represents that the mass of propellant assumes 65\% of the initial gross weight \( M_{\text{tot}}(0) \). Total weight is defined as the summation of all components. The weight of each component is calculated by the product of volume and density.

3.3.3. Aerodynamic Analysis

\( D(t) \) is described by using pressure drag \( D_p(t) \) and friction drag \( D_f(t) \), which are respectively estimated by using the flight data of S-520 as the solid rocket in ISAS.

\[
D(t) = D_p(t) + D_f(t)
\]

\[
D_p(t) = \frac{1}{2} \rho V^2 S_{\text{ref}} C_{D_p}^{(S-520)}
\]

\[
D_f(t) = \frac{1}{2} \rho V^2 S_{\text{tot}} C_{D_f}
\]

where, \( S_{\text{ref}} \) is reference area and \( S_{\text{tot}} \) is total surface area. Pressure drag coefficient \( C_{D_p} \) and friction drag coefficient \( C_{D_f} \) are calculated as follows;

\[
C_{D_p}^{(S-520)} = C_{D_p}^{(S-520)} = C_{D_p}^{(S-520)} \cdot \frac{S_{\text{tot}}^{(S-520)}}{S_{\text{ref}}^{(S-520)}}
\]

\[
C_{D_f} = \frac{\log_{10} Re^{2.58}}{V_L^{(S-520)}} \cdot \frac{1}{1 + 0.144 M^2^{0.65}}
\]

\[
Re = \frac{V L_{\text{tot}}}{\sqrt{\gamma RT}}
\]

\[
M = \frac{V}{\sqrt{\gamma RT}}
\]

\( Re, M, \) and \( V \) respectively describe Reynolds number, Mach number, and velocity. Total length \( L_{\text{tot}}^{(S-520)} \) = 8.715 [m], specific heat ratio \( \gamma = 1.4 \), and gas constant \( R = 287 [J/(kg \cdot K)] \).

\[
C_{D_f} = \frac{0.455}{\log_{10} Re^{2.58}} \cdot \frac{1}{1 + 0.144 M^2^{0.65}}
\]

\[
Re = \frac{V L_{\text{tot}}}{\sqrt{\gamma RT}}
\]

Kinematic viscosity coefficient \( \nu \) [m²/sec] and atmospheric temperature \( T \) [K] are variables for altitude, referring International Standard Atmosphere.

4. Results

4.1. Optimization Result

The population size is set to be 18 and evolutionary computation is performed until 3,000 generations when the evolution is roughly converged. The plots of acquired nondominated solutions is shown in Fig. 5, which reveals that there generates no multimodal and clean convex curved surface.

There is no tradeoff between the down range \( R_d \) and the duration time \( T_d \) in the lower thermosphere shown in Fig. 5(b). This figure also shows that there are upper limitations...
of roughly 250[km] for the down range $R_d$ and of roughly 220[sec] for the duration time $T_d$. Therefore, the projection plots onto two dimension between the down range $R_d$ and the duration time $T_d$ do not converge in one point. In the present study, the initial mass flow of oxidizer $\dot{m}_{\text{oxi}}(0)$ (dv1) has the limitation of upper/lower values. Since the regression rate of fuel $r_{\text{fuel}}(t)$ as an empirical model uses the mass flow of oxidizer $\dot{m}_{\text{oxi}}(t)$, $r_{\text{fuel}}(t)$ has constraints. As a result, the limitations are generated for the down range $R_d$ and the duration time $T_d$.

There is an incomplete tradeoff between the duration time $T_d$ and the initial gross weight $M_{\text{init}}(0)$ shown in Fig. 5(c). The convex nondominated surface to optimum direction with incompleteness is generated due to the limitation of the duration time $T_d$. As the inclination $\Delta M_{\text{init}}(0)/\Delta T_d$ is small on the convex curve, the duration time $T_d$ can be substantially improved when trifling initial gross weight $M_{\text{init}}(0)$ would be sacrificed. In addition, Fig. 5(c) shows that the minimum initial gross weight to reach the limitation of the duration time (roughly 220[sec]) is approximately 700[kg]. And also, the minimum initial gross weight to attain to the lower thermosphere (altitude of 90[km]) is approximately 350[kg]. As these values are better than those of the solid rockets which are operated at present for scientific observation, it suggests that hybrid rocket has an advantage even when hybrid rocket does not have a sequence of multi-time ignition.

There is a severe tradeoff between the down range $R_d$ and the initial gross weight $M_{\text{init}}(0)$ shown in Fig. 5(d) (although the down range strictly has the upper limitation, it seems that the clean convex curve is generated because the limitation is on the edge of the nondominated surface). This figure shows that the maximum down range is roughly 130[km] when the minimum initial gross weight to reach the limitation of the duration time $T_d$(roughly 700[kg]) is

![Fig. 5 Plots of nondominated solutions derived by optimization.](image-url)
adopted. The initial gross weight $M_{\text{tot}}(0)$ should be absolutely increased in order to have more down range $R_d$ (greater than 130[km]) despite no increase of the duration time $T_d$ (remaining roughly 220[sec]). This fact suggests that the design strategies for the maximizations of the down range $R_d$ and the duration time $T_d$ are different.

4.2. Data-Mining Result

Figure 6 shows SOMs colored by the objective functions and the design variables. As this SOM learning is implicated based on the values of the objective functions as the indicator for the similarity on the neural network, SOMs colored by the objective functions have absolutely gradation shown in Fig. 6(a). SOMs colored by the design variables are shown in Fig. 6(b). The upper/lower values of coloring range are set to be the upper/lower values defined in the problem summarized in Table 1.

4.2.1. Acquired Information regarding Relationship among Objective Functions

The comparison of the coloring pattern in Fig. 6(a) reveals the tradeoffs among the objective functions. When obj1 is high value (red region), obj2 absolutely becomes high. However, as obj1 does not always become high whenever obj2 is high, this relationship is irreversible. This is because not only the down range $R_d$ (obj1) but also the attained maximum altitude gives the effect on the duration time $T_d$ (obj2). In contrast, when obj2 is low value (blue region), obj1 absolutely becomes low. However, as obj2 does not always become low whenever obj1 is low, this relationship is similarly irreversible. Although there is no tradeoff in the global space of the objective functions, there is locally tradeoff at the right bottom of Fig. 6. This local tradeoff is caused by the limitation of the duration time $T_d$(obj2), that is, reaching the maximum value of the duration time $T_d$(obj2) is easier than achieving the maximum value of the down range $R_d$(obj1).

Since the initial gross weight $M_{\text{tot}}(0)$(obj3) is the minimization function, there are severe tradeoffs among obj3 and the others. It especially reveals the severe problem that the optimum direction of the down range $R_d$(obj1) and the pessimum direction of the initial gross weight $M_{\text{tot}}(0)$(obj3) accord(observing the upper left on SOM regarding obj1 and obj2 reveals that
the better obj1 and the worse obj3 accord). The structural constraints and the combustion mode should be reconsidered in order to avoid this problem. On the other hand, the optimum region of the duration time $T_d(\text{obj2})$ and the pessimum direction of the initial gross weight $M_{\text{tot}}(0)(\text{obj3})$ overlap only in part. Therefore, the initial gross weight $M_{\text{tot}}(0)$ can become low when the duration time $T_d$ is the primary objective. On the other hand, the minimum initial gross weight is decided by the expected down range when the down range $R_d$ is the primary objective, that is, the minimum initial gross weight depends on the mission requirement as the necessary down range.

4.2.2. Acquired Information regarding Behavior of Design Variables

Figure 6(b) reveals the behavior of each design variable in the design space with the defined wide range which is physically available in order to become the nondominated solution. All nondominated solutions have higher $dv1$ than the lower bound of $dv1$ defined in Table 1. This fact suggests that the minimum initial mass flow of oxidizer is necessary in order to attain to the lower thermosphere (altitude of 90[km]). The mass flow of oxidizer $m_{\text{oxi}}(t)$ affects the structural weight because of the increase of the filling pressure of oxidizer tank and the pressure of the combustion chamber $P_{cc}(t)$. Therefore, the initial mass flow of oxidizer $m_{\text{oxi}}(0)(dv1)$ is essential in order to improve the initial gross weight $M_{\text{tot}}(0)(\text{obj3})$.

The value of $dv2$ does not have both high and low. As the minimum fuel length is necessary in order to attain to the lower thermosphere (altitude of 90[km]), $dv2$ does not have low. On the other hand, as it is considerable that the fuel length $L_{\text{fuel}}(dv2)$ does not affect strongly on the maximization of the down range $R_d$ and the duration time $T_d$ rather than the initial mass flow of oxidizer $m_{\text{oxi}}(0)(dv1)$, the fuel length $L_{\text{fuel}}(dv2)$ does not have high value.

The value of $dv3$ is roughly constant. This fact indicates that there is the optimum initial radius of port $r_{\text{port}}(0)(dv3)$, which might be determined by the combustion mode and the swirl intensity. The other combustion mode should be investigated in order to confirm it.

The value of $dv4$ is in the narrow region of the design space. But, the combustion time $t_{\text{burn}}(dv4)$ becomes high when the initial gross weight $M_{\text{tot}}(0)(\text{obj3})$ is high. That is, the combustion time $t_{\text{burn}}(dv4)$ has identical behavior of the initial radius of port $r_{\text{port}}(0)(dv3)$ in the design space except the direct affection on the initial gross weight $M_{\text{tot}}(0)(\text{obj3})$. Therefore, the implication of other fuels should be investigated.

The value of $dv5$ has low value. The high value of the initial pressure in combustion chamber $P_{cc}(0)(dv5)$ fundamentally gives high thrust. As it is expected that the structural requirement is not fulfilled due to high pressure, the structural fulfillment should be confirmed by the parametric study regarding the structural safety factor. In addition, the time fluctuation regarding the pressure in combustion chamber $P_{cc}(t)$ should be observed in the next-step design problem.

The value of $dv6$ has the coloring pattern in a muddle which is similar to that of $dv5$, although there is the difference of color. Since the aperture ratio of nozzle $\epsilon(dv6)$ becomes high in order to keep the high thrust, $\epsilon(dv6)$ indirectly give the effect on the objective functions. In fact, the high value of $dv6$ is on the upper left of SOM, which is the region to become high objective functions.

The coloring pattern of SOM by $dv7$ is similar to that by obj1. As the vertical launch would be implemented when the elevation at launch time $\phi(dv7)$ becomes high, it is easily understandable that the down range $R_d(\text{obj1})$ is low. The definition of the next-step design problem will be discussed by all designers using the above design information.

5. Conclusions

The next-generation single-stage launch vehicle with the hybrid rocket engine of solid fuel and liquid oxidizer in place of the present pure solid-fuel rockets has been conceptually designed by using design informatics in order to contribute to the low cost launch vehicle system and efficient space scientific observation. The objective functions as the design requirements in the design problem is the maximization of the down range and the duration
time in the lower thermosphere as well as the minimization of initial gross weight. The evolutionary hybrid computation between the differential evolution and the genetic algorithm is employed for the efficient exploration in the design space. A self-organizing map is used in order to structurize and visualize the design space. As a result, the design information has been revealed regarding the tradeoffs among the objective functions and the behavior of the design variables in the design space. Consequently, the design strategy for the maximizations of down range and duration time is different because the duration time can easily attain to the limitation rather than the down range. The characteristics as the regression rate of fuel and structure coefficients should be investigated as a next design phase in order to reveal the performance limitation of single-time ignition on hybrid rocket engine. And also, these results indicates that the ascendancy of multi-time ignition as the advantage of hybrid rocket will be quantitatively shown. The results show the quantitative data to compare the performances of solid-fuel rocket in present and hybrid rocket with multi-time ignition.

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References


