2015 IEEE Symposium Series on Computational Intelligence

Visualization of Design-Space Constitution for Single-Stage Hybrid Rocket with Rigid Body in View of Extinction-Reignition

Kazuhisa Chiba
Graduate School of Informatics and Engineering
The University of Electro-Communications, Tokyo 182-8585, Japan
Email: kazchiba@uec.ac.jp

Hideyuki Yoda, Shoma Ito, and Masahiro Kanazaki
Graduate School of System Design
Tokyo Metropolitan University, Tokyo 191-0065, Japan

***Abstract*—Visualization of design space has been performed for researching and developing a single-stage launch vehicle with hybrid rocket engine by using design informatics, which has three points of view such as problem definition, optimization, and data mining. The primary objective of the present design is that the ascendancy of extinction-reignition, which is one of the beneficial point of hybrid rocket, for improving the downrange and the duration time in the lower thermosphere. Polypropylene and liquid oxygen with swirling flow are adopted as solid fuel and liquid oxidizer, respectively. The multidisciplinary design optimization was performed by using a hybrid evolutionary computation; data mining was implemented by using a scatterplot matrix in order to efficiently perceive design space. As a result, it is revealed that extinction-reignition extends the duration time though it does not give an effect on improving the downrange. Data-mining results also show the physical mechanism of the design variables to improve the duration time on the visualization of design-space constitution.**

I. Introduction

Design informatics is essential for practical design problems. Although solving design optimization problems is important under the consideration of many disciplines of engineering[1], the most significant part of the process is the extraction of useful knowledge of the design space from results of optimization runs[2], [3]. 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 an 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[4]. 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 functions, design variables, and constraints, is strictly defined in view of the background physics for several months (problem definition is the most important process for all designers because it directly gives effect on the quality of design space. If the garrulous objective functions and design variables are considered, unnecessary evolutionary exploration should be performed; needless mining will be also carried out because it is conceived to be low-quality design space). 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 as a postprocess for optimization. Mining result is the significant observations for next design phase and also becomes the material to redefine a design problem.

Intelligent and evolutionary systems including design informatics mentioned above have the significance for not only the systems themselves but also their applications to practical problems in order that science contributes toward the real world. Results themselves do not possess versatility in application problems due to their particularity. The versatility of a system is indeed critical in application problems because it is revealed that application range is expanded. Furthermore, the application results indicate the guidance for the improvement of systems. In the present study, a single-stage launch vehicle with hybrid rocket engine using solid fuel and liquid oxidizer for the scientific observation of aurora will be conceptually designed by using design informatics approach. The final objective is that the advantage of extinction-reignition in the science mission for aurora observation on hybrid rocket will be quantitatively revealed. As a first step, an optimization problem on single-time ignition, which is the identical condition of the current solid rocket, was defined so as to obtain the design information[5]. As a second step, the implication of solid fuels in the performance of hybrid rocket was revealed because the regression rate is one of the key elements for the performance of hybrid rocket[6]. Finally, the sequence using multi-time ignition, which is the advantage of hybrid rocket,

978-1-4799-7560-0/15 $31.00 © 2015 IEEE
DOI 10.1109/SSCI.2015.137

IEEE computer society

will be investigated in order to reveal the ascendancy of hybrid rocket for aurora observation. This study corresponds to the above third step so that the ascendancy of one-time extinction-reignition is revealed.

The constitution of this treatise is as follows. The optimization and data-mining algorithms used in design informatics approach are explained in Chapter II. The problem definition for designing single stage hybrid rocket are shown in Chapter III. The results regarding the optimization and data-mining are revealed; the knowledge is also discussed in Chapter IV.

II. Design Informatics

A. Optimization Method

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] like as the Kriging model[8], 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 hybrid evolutionary method between the differential evolution (DE) and the genetic algorithm (GA)[9]. Moreover, global design information is primarily essential in order to determine a compromise solution. The view of hybridization is inspired by the evolutionary developmental biology[10]. 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[9]. 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.

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 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.

The present optimization methodology is a real-coded optimizer[11]. Although GA is based on the real-coded NSGA-II (the elitist nondominated sorting genetic algorithm)[12], it is made several improvements on in order to be progressed with the diversity of solutions. Fonseca's Pareto ranking[13] and the crowding distance[12] are used for the fitness value of each individual. The stochastic universal sampling[14] is employed for parents selection. The crossover rate is 100%. The principal component analysis blended crossover-α (PCABLX)[15] and the confidence interval based crossover using L_2 norm (CIX)[16] are used because of the high performance for the convergence and the diversity as well as the strength for noise[9]. 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, a cross-generational elitist selection model is used. This model utilizes the crowding distance for clustering; it selects N solutions from all parents and offspring. Thereupon, candidates of the next generation are $2N$. The fitness of the region that individuals congregate because of falling into local optimum and s on is estimated to be low for diversity maintaining. DE is used as the revised scheme[17] 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[18], 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.

B. Data Mining

Scatterplot matrix (or simply scatterplots)[19] remains one of the general visual descriptions for multidimensional data due to its simplicity. Scatterplots is available to simultaneously visualize multidimensional data constructed by all of the objective functions and the design variables. Other data-mining techniques which have flexibility and effective visual expressiveness exist. Since first-step design information through observing overview of the design space will be obtained in this study, scatterplots is merely selected.

III. Problem Definition

Single-stage rockets have been researched and developed for the scientific observations and the experiments of high-altitude zero-gravity condition, whereas multi-stage rockets have been also studied for the orbit injection of payload. The Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA) has been operating K (Kappa), L (Lambda), and M (Mu) series rockets as the representatives

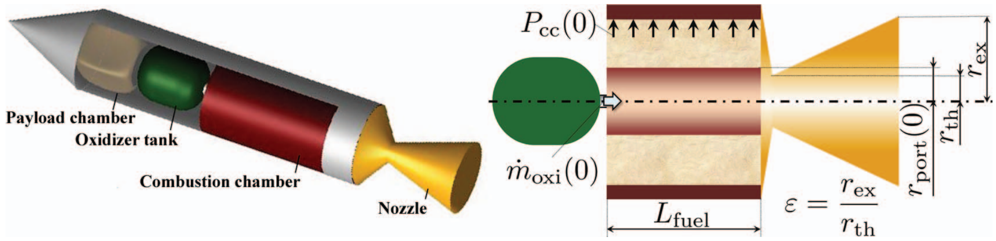

Fig. 1. Conceptual illustrations of hybrid rocket and its design variables regarding the geometry. Aperture ratio of nozzle ϵ is described by using the radius at nozzle exit r_{ex} and the radius at nozzle throat r_{th}.

TABLE I
LIMITATION OF UPPER/LOWER VALUES OF EACH DESIGN VARIABLE.

serial number	*design variable*		*design space*	
dv1	initial mass flow of oxidizer	$1.0 \leq$	$\dot{m}_{ox}(0)$ [kg/sec]	≤ 30.0
dv2	fuel length	$1.0 \leq$	L_{fuel} [m]	≤ 10.0
dv3	initial radius of port	$0.01 \leq$	$r_{port}(0)$ [m]	≤ 0.30
dv4	total combustion time	$20.0 \leq$	t_{burn} [sec]	≤ 60.0
dv5	1st combustion time	$10.0 \leq$	t_{burn_1st} [sec]	≤ 40.0
dv6	extinction time	$1.0 \leq$	t_{ext} [sec]	≤ 300.0
dv7	initial pressure in combustion chamber	$3.0 \leq$	$P_{cc}(0)$ [MPa]	≤ 6.0
dv8	aperture ratio of nozzle	$5.0 \leq$	ϵ [-]	≤ 8.0
dv9	elevation at launch time	$60.0 \leq$	$\phi(0)$ [deg]	≤ 90.0

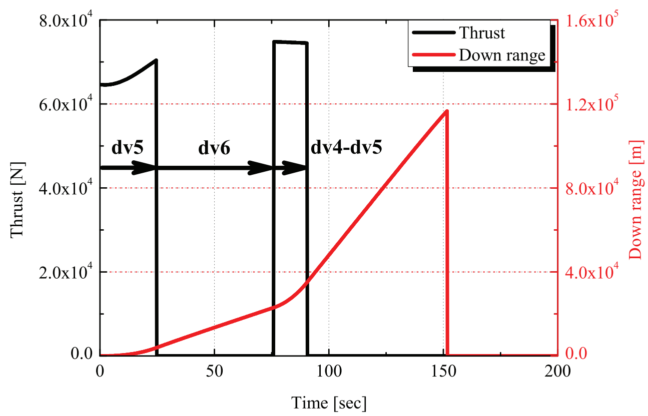

Fig. 2. Conceptual graph of extinction-reignition. Two-times combustion generates two pulses of thrust. The second pulse of thrust yields the increase of inclination of $\mathrm{d}R_d/\mathrm{d}t$.

of solid rocket in order to contribute to the space scientific research. A lower-cost and more efficient rocket is necessary due to the retirement of M-V in 2008 and in order to promote space scientific research. In fact, E (Epsilon) rocket began to be operated from September 2013. On the other hand, the launch vehicle with hybrid rocket engine using solid fuel and liquid oxidizer has been researched and developed as an innovative technology in mainly Europe and United States[20], [21]. 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 diverted to multi-stage one. A hybrid rocket offers the several advantages as higher safety, lower cost, and pollution free flight. The multi-time ignition is the especial ascendancy of hybrid rocket engine[22]. 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 due to turbulent boundary layer combustion, the thrust of hybrid rocket engine is less than that of pure solid and pure liquid engines which can obtain premixed combustion[23]. In addition, as the mixture ratio between solid fuel and liquid oxidizer is temporally fluctuated, thrust changes with time. Multidisciplinary design requirements should be considered in order to surmount the disadvantage of hybrid rocket engine. Moreover, exhaustive design information will be obtained in order to additionally consider productive and market factors for practical problems (it is difficult that optimization deals with them due to the difficulty of the definition).

The conceptual design for a single-stage hybrid rocket, simply composed of a payload chamber, an oxidizer tank, a combustion chamber, and a nozzle[24] shown in Fig. 1, 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.

A. Objective Functions

Three objective functions are defined in the present study. First objective is the maximization of the downrange in the lower thermosphere (altitude of 90 to 150 [km]) R_d [km]

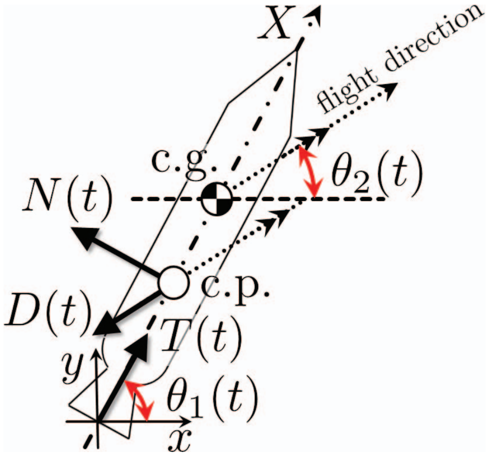

Fig. 3. Illustration of a kinematic model of single-stage launch vehicle for 3DoF flight simulation. Note that c.g. and c.p. respectively denote the center of gravity and the center of pressure.

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

B. Design Variables

Nine design variables are utilized for problem definition: initial mass flow of oxidizer $\dot{m}_{\rm ox}(0)$ [kg/sec] (dv1), fuel length $L_{\rm fuel}$ [m] (dv2), initial radius of port $r_{\rm port}(0)$ [m] (dv3), total combustion time $t_{\rm burn}$ [sec] (dv4), first combustion time $t_{\rm burn\_1st}$ [sec] (dv5), extinction time between the end of first combustion and the beginning of second combustion $t_{\rm ext}$ [sec] (dv6), initial pressure in combustion chamber $P_{\rm cc}(0)$ [MPa] (dv7), aperture ratio of nozzle ϵ [-] (dv8), and elevation at launch time ϕ [deg] (dv9). The design variables regarding the geometry of launch vehicle are visualized in Fig. 1. The relationship among dv4, dv5, and dv6 regarding combustion time is conceptually shown in Fig. 2. Under the condition of $t_{\rm burn} \leq t_{\rm burn\_1st}$, it is defined that total combustion time is set to be $t_{\rm burn}$ and second-time combustion is not performed. Note that there is no constraint except the limitations of upper/lower values of each design variable summarized in Table I. These upper/lower values are exhaustively covering the region of the 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.

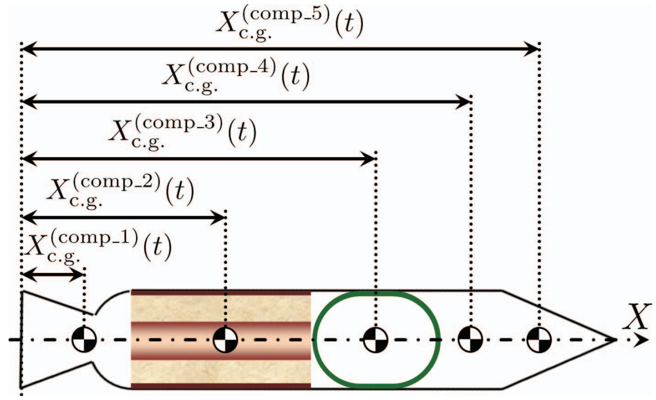

Fig. 4. Definition of positions for the five-components' center of gravity.

C. Evaluation Method of Hybrid Rocket

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

$$O/F(t) = \frac{\dot{m}_{\rm ox}(t)}{\dot{m}_{\rm fuel}(t)}, \tag{1}$$

where,

$$\begin{aligned} \dot{m}_{\rm fuel}(t) &= 2\pi r_{\rm port}(t) L_{\rm fuel} \rho_{\rm fuel} \bar{\dot{r}}_{\rm port}(t), \\ r_{\rm port}(t) &= r_{\rm port}(0) + \int \dot{r}_{\rm port}(t) {\rm d}t. \end{aligned} \tag{2}$$

$\dot{m}_{\rm ox}(t)$ and $\dot{m}_{\rm fuel}(t)$ are the mass flow of oxidizer [kg/sec] and the mass flow of fuel [kg/sec] at time t, respectively. $r_{\rm port}(t)$ is the radius of port [m] at t, $L_{\rm fuel}$ describes fuel length, and $\rho_{\rm fuel}$ is the density of fuel [kg/m^3]. $\dot{r}_{\rm port}(t)$ describes the regression rate. Note that since hybrid rocket engine performs no premixed combustion which conventional rocket engine implements but turbulent boundary layer combustion, $O/F(t)$ is not constant but timely fluctuated. After that, an analysis of chemical equilibrium is performed by using NASA-CEA (chemical equilibrium with applications) [25], 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.

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 $\dot{r}_{\rm port}(t)$ [m/sec] generally governs the thrust power of hybrid rocket engine, it is a significant parameter. The following experimental model[26], [27] is used in the present study.

$$\begin{aligned} \dot{r}_{\rm port}(t) &= a_{\rm fuel} \times G_{\rm ox}^{n_{\rm fuel}}(t) \\ &= a_{\rm fuel} \times \left(\frac{\dot{m}_{\rm ox}(t)}{\pi r_{\rm port}^2(t)} \right)^{n_{\rm fuel}}, \end{aligned} \tag{3}$$

where, $G_{\rm ox}(t)$ is oxidizer mass flux [kg/m^2/sec]. $a_{\rm fuel}$ [m/sec] and $n_{\rm fuel}$ [-] are the constant values experimentally 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, $a_{\rm fuel}$ and $n_{\rm fuel}$ are respectively set to be 8.26×10^{-5} [m/sec] and 0.5500.

Evaluation system is enhanced in order that the vehicle is treated as rigid body[28]. Figure 3 shows the kinematic model for three-degree-of-freedom (3DoF) flight simulation. Since $T(t)$ is estimated, a flight pass is computed by using the following 3DoF equations of motion.

$$\begin{cases} \ddot{x} = \dfrac{T(t)\cos\theta_1 - D(t)\cos\theta_2}{M_{\rm tot}(t)}, \\ \ddot{y} = \dfrac{T(t)\sin\theta_1 - D(t)\sin\theta_2}{M_{\rm tot}(t)} - g, \\ \ddot{\theta_1} = \dfrac{N(t)|X_{\rm c.p.} - X_{\rm c.g.}|}{I(t)}, \end{cases} \tag{4}$$

where, $N(t)$ is the normal component of the aerodynamic force. $N(t)$ is approximately evaluated by using the following equation.

$$N(t) = \frac{1}{2}\rho(t)V^2(t)S_{\rm ref}\sin(|\theta_1 - \theta_2|). \tag{5}$$

$\rho(t)$ and $V(t)$ respectively denote the air density and velocity of launch vehicle at elapsed time t. θ_1 and θ_2 respectively describe the attitude angle of launch vehicle and flight path angle. Equations 4 assume that thrust vector corresponds to attitude direction (i.e. body axis). Therefore, thrust angle is not generally identical compared with flight pass due to the revolution of launch vehicle. $I(t)$ denotes the moment of inertia, which is estimated by using the coordinate of the center of gravity for entire body $X_{\rm c.g.}(t)$ and that for the components of body $X_{\rm c.g.}^{(n\_{\rm comp})}(t)$ shown in Fig. 4 according to the following equation.

$$I(t) = \sum_{n\_{\rm comp}=1}^{5} m_{n\_{\rm comp}}(t) \times (X_{\rm c.g.}^{(n\_{\rm comp})}(t) - X_{\rm c.g.}(t))^2. \tag{6}$$

$X_{\rm c.g.}$ is computed by the following equation, which considers the variance of the fuel and the oxidizer masses.

$$X_{\rm c.g.}(t) = \sum_{n\_{\rm comp}=1}^{5} \frac{m_{n\_{\rm comp}}(t) \times X_{\rm c.g.}^{(n\_{\rm comp})}(t)}{m_{\rm tot}(t)}. \tag{7}$$

$X_{\rm c.g.}^{(n\_{\rm comp})}(t)$ describes the distance between nozzle exit and the center of gravity of each component. $n_$comp denotes the serial number of the components. Five components are considered in the present study. $n_$comp of 1, 2, 3, 4, and 5 respectively correspond to nozzle, combustion chamber, oxidizer tank, payload bay, and nose cone. Note that $m_{n\_{\rm comp}}(t)$ for nozzle, payload bay, and nose cone merely depends on the structures of these components and are also assumed to be constant. On the other hand, $m_{n\_{\rm comp}}(t)$ for combustion chamber and oxidizer tank depends on not only the structure but also the change in the amount of fuel and oxidizer over time. That is, $X_{\rm c.g.}^{(2)}(t)$ and $X_{\rm c.g.}^{(3)}(t)$ are time-dependent functions. $m_{\rm tot}(t)$ denotes the total mass for the whole body of launch vehicle.

IV. Results

A. Optimization Results

The population size is set to be 18 in one generation; evolutionary computation is performed until 4,000 generations. The population size of 18 is determined as a small number of the order of 10^1 because generation number will be earned as much in evolution. The generation number is decided by the convergence of evolution. The plots of acquired nondominated solutions are shown in Fig. 5, which reveals that the connecting and convex nondominated surface except several isolated individuals is generated.

The tradeoffs are identical to the previous study[6]; the difference whether extinction-reignition is considered or not will be explained here. The essential difference between the previous and the present results is to break the upper limit of duration time T_d and to expand it approximately 14%. This result indicates that extinction-reignition fulfills the hovering in the lower thermosphere. Extension of T_d accompanies the increase of initial gross weight $M_{\rm tot}(0)$. Downrange R_d is not, however, improved due to extinction-reignition. This fact suggests that the significant design variable is not 2nd combustion time (dv4−dv5) but extinction time. When 2nd combustion time will serve functions, vehicles move away from lower thermosphere; both of R_d and T_d are not increased. If the direction of thrust can be horizontally controlled, 2nd combustion time is expected to give an effect on raising R_d and T_d simultaneously. Since thrust direction corresponds to body axis shown in Fig. 3 due to considering 3DoF equations of motion , 2nd combustion time is not performed functions; only extinction time gives an effect on T_d.

B. Data-Mining Results

Figure 6 shows the scatterplots. Since Fig. 5 addresses T_d expansion on the present problem, the physical mechanism of it will be investigated by using scatterplots. Total combustion time, 1st combustion time, and extinction time as respectively dv4, dv5, and dv6 are exhaustively indicated to give an effect on extending T_d. 1st combustion time keeps high value so that the summit altitude reaches the lower thermosphere. In addition, appropriate extinction time (100 to 200 [sec]) is needed for efficient hovering. Furthermore, total combustion time should be restrained in order not to implement long 2nd combustion time (which causes the summit altitude beyond the lower thermosphere). These are the necessary conditions to improve T_d. Reaching the upper limit of the initial mass flow of oxidizer $\dot{m}_{\rm ox}$ (dv1) of 30 [kg/sec] shown in Table I is also the reason to saturate $t_{\rm burn\_1st}$ of roughly 40 [sec]. The upper limit of $\dot{m}_{\rm ox}$ of 30 [kg/sec] is the present technological limitation; increasing it is infeasible.

On the other hand, the present optimization results show that downrange R_d is not improved. It is considerable that there are two strategies for the expansion of R_d. First strategy is to launch horizontally; second strategy is thrust vectoring within the lower thermosphere. Figure 6 reveals that elevation angle at launch time $\phi(0)$ (dv9) is the strongly effective design

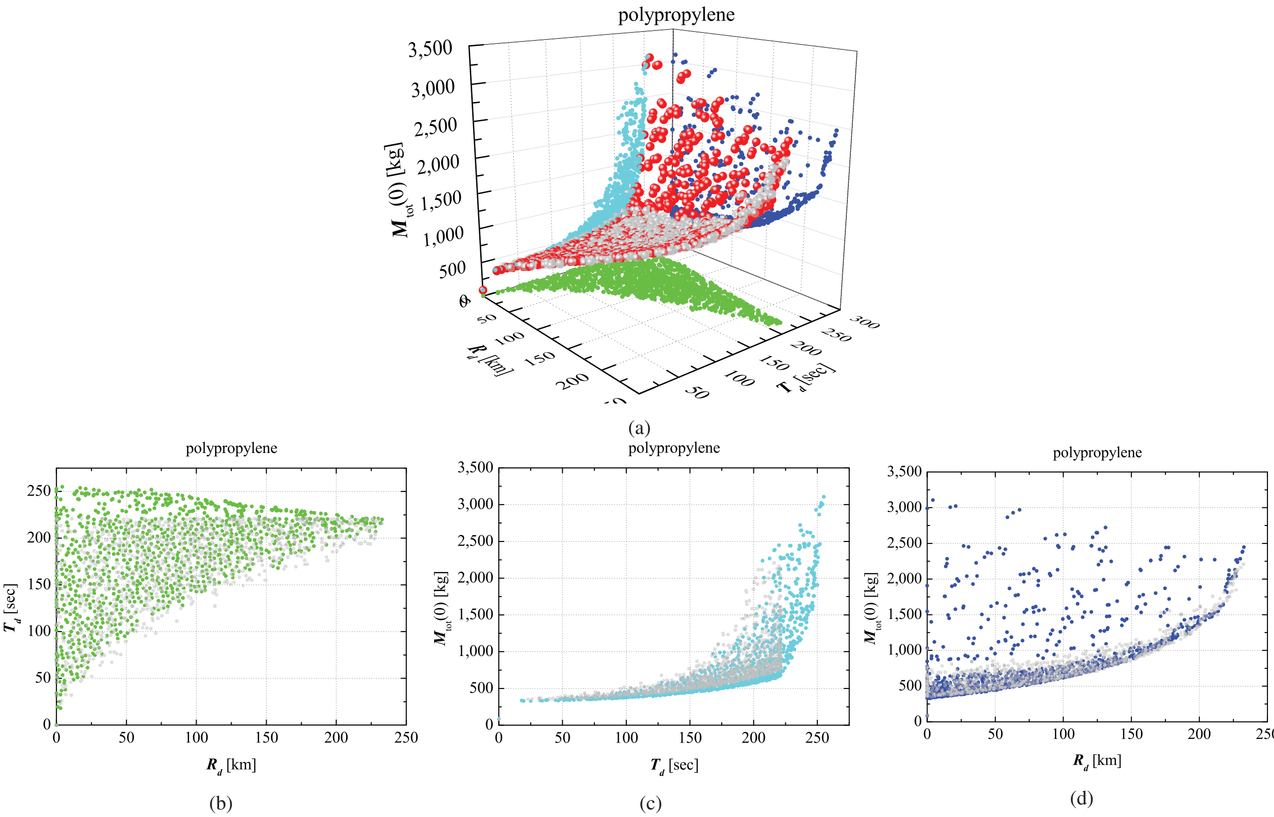

Fig. 5. Plots of nondominated solutions derived by optimization, (a) plotted in the three-dimensional objective-function space (red) and their plots projected onto two dimensions, (b) plots projected onto two dimension between downrange R_d (obj1) and duration time T_d (obj2) (light green), (c) plots projected onto two dimension between duration time T_d (obj2) and initial gross weight $M_{\text{tot}}(0)$ (obj3) (light blue), and (d) plots projected onto two dimension between downrange R_d (obj1) and initial gross weight $M_{\text{tot}}(0)$ (obj3) (blue). Note that gray-colored plots represent the results of previous work[6] in view of point mass without extinction-reignition.

variable. In addition, there is negative correlation between R_d and $\phi(0)$. That is, if R_d will be increased, $\phi(0)$ is set to be low value; vehicle has no choice but to be launched as horizontally as possible. The value of dv9 does not, however, attain lower limit as 60 [deg] shown in Fig. 6 because the summit altitude is unable to reach the lower thermosphere due to insufficient thrust. Thereupon, initial mass flow of oxidizer $\dot{m}_{\text{ox}}(0)$ (dv1) is the bottleneck for first strategy. Extinction-reignition is essential for second strategy. But extinction-reignition does not effectively function because thrust direction corresponds to body axis and thrust vectoring is not artificially implemented due to difficult control. Since vehicle with extinction-reignition might be over the lower thermosphere under the above situation, R_d is not extended.

Figure 6 also indicates the behaviors of the design variables. What is especially notable that there is a strong positive correlation between initial mass flow of oxidizer $\dot{m}_{\text{ox}}(0)$ (dv1) and fuel length L_{fuel} (dv2). This result suggests that since $\dot{m}_{\text{ox}}(0)$ arrives the upper limit 30 [kg/sec] defined in Table I, L_{fuel} cannot reach the upper limit 10 [m] due to the strong correlation; accordingly this is one of the reason not to increase total combustion time. The shortcoming of hybrid rocket engine is the low regression rate $\dot{r}_{\text{port}}(t)$. $\dot{r}_{\text{port}}(t)$ is the function described by $\dot{m}_{\text{ox}}(t)$. The improvement of initial mass flow of oxidizer (dv1) is essential work to effectively utilize extinction-reignition and to develop impressive hybrid rocket system.

V. Conclusions

Visualizing design space has been implemented for research and development of single-stage hybrid rocket by using design informatics in order to efficiently recognize design space. Especial objective of this study is to reveal the ascendancy of extinction-reignition on hybrid rocket engine. Launch vehicle was assumed as rigid body so that the practical flight dynamics of launch vehicle is considered in the evaluation. Design informatics manages a hybrid evolutionary computation for the multidisciplinary design optimization and a scatter plot matrix for data mining. The optimization result consequently indicates that extinction-reignition expands the duration time despite no improvement of the downrange. Moreover, data-mining result shows the physical mechanism how the design variables definitely improve the duration time on the visualization of the design space.

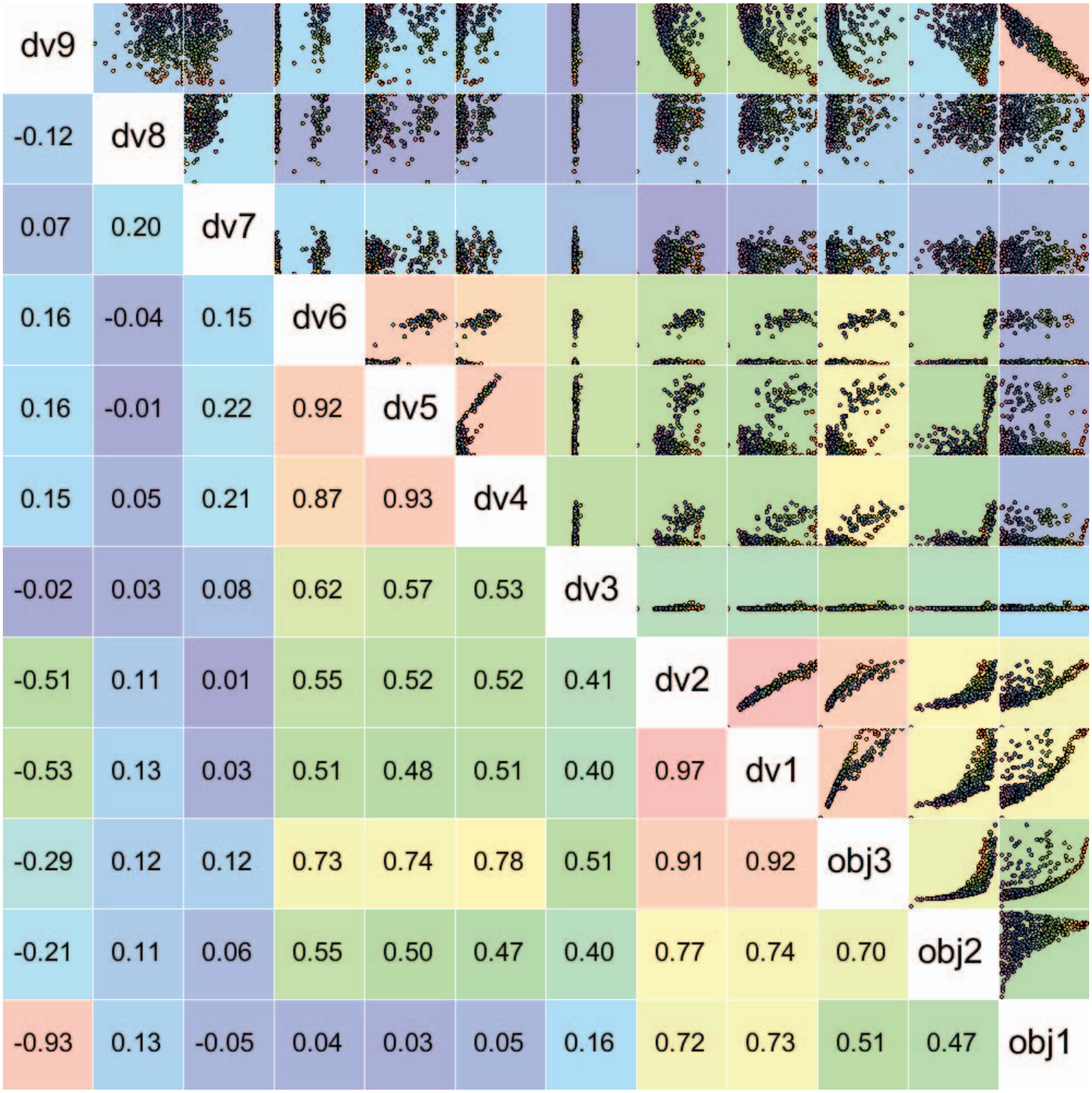

Fig. 6. Scatterplots of the optimization results and their correlation coefficients. The upper/lower values of the axes of the design variables on graphs are set to be the upper/lower limits of each design variables shown in Table I. Plots are colored by R_d as obj1; each block is colored by the absolute value of their correlation coefficients.

ACKNOWLEDGMENTS

The present study was partially supported by the Hybrid Rocket research Working Group of ISAS, JAXA. The interactive Scatter Plot Matrix, which was developed by ISAS, JAXA under Industrial Innovation R&D Topic 4 on High Performance Computing Initiative Field 4, was utilized for generating the scatterplots in this treatise.

REFERENCES

[1] A. Arias-Montano, C. A. C. Coello, and E. Mezura-Montes, “Multiobjective evolutionary algorithms in aeronautical and aerospace engineering,” *IEEE Transactions on Evolutionary Computation*, vol. 16, no. 5, pp. 662–694, 2012.

[2] K. Chiba, S. Obayashi, and K. Nakahashi, “Design exploration of aerodynamic wing shape for reusable launch vehicle flyback booster,” *Journal of Aircraft*, vol. 43, no. 3, pp. 832–836, 2006.

[3] K. Chiba and S. Obayashi, “Knowledge discovery in aerodynamic design space for flyback-booster wing using data mining,” *Journal of Spacecraft and Rockets*, vol. 45, no. 5, pp. 975–987, 2008.

[4] K. Chiba, Y. Makino, and T. Takatoya, "Design-informatics approach for intimate configuration of silent supersonic technology demonstrator," *Journal of Aircraft*, vol. 49, no. 5, pp. 1200–1211, 2012.

[5] K. Chiba, M. Kanazaki, M. Nakamiya, K. Kitagawa, and T. Shimada, "Conceptual design of single-stage launch vehicle with hybrid rocket engine for scientific observation using design informatics," *Journal of Space Engineering*, vol. 6, no. 1, pp. 15–27, 2013.

[6] ——, "Diversity of design knowledge for launch vehicle in view of fuels on hybrid rocket engine," *Journal of Advanced Mechanical Design, Systems, and Manufacturing*, vol. 8, no. 3, pp. JAMDSM0023, 1–14, 2014.

[7] A. J. Keane, "Statistical improvement criteria for use in multiobjective design optimization," *AIAA Journal*, vol. 44, no. 4, pp. 879–891, 2006.

[8] S. Jeong, M. Murayama, and K. Yamamoto, "Efficient optimization design method using kriging model," *Journal of Aircraft*, vol. 42, no. 2, pp. 413–420, 2005.

[9] K. Chiba, "Evolutionary hybrid computation in view of design information by data mining," in *Proceedings on IEEE Congress on Evolutionary Computation*. IEEE, 2013, pp. 3387–3394.

[10] W. Arthur, "The emerging conceptual framework of evolutionary developmental biology," *Nature*, vol. 415, no. 6873, pp. 757–764, 2002.

[11] A. Oyama, S. Obayashi, and T. Nakamura, "Real-coded adaptive range genetic algorithm applied to transonic wing optimization," *Applied Soft Computing*, vol. 1, no. 3, pp. 179–187, 2001.

[12] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Transactions on Evolutionary Computation*, vol. 6, no. 2, pp. 182–197, 2002.

[13] C. M. Fonseca and P. J. Fleming, "Genetic algorithms for multiobjective optimization: Formulation, discussion and generalization," in *Proceedings of the Fifth International Conference on Genetic Algorithms*. Morgan Kaufmann, 1993, pp. 416–423.

[14] J. E. Baker, "Adaptive selection methods for genetic algorithms," in *Proceedings of the International Conference on Genetic Algorithms and their Applications*. Lawrence Erlbaum Associates, 1985, pp. 101–111.

[15] M. Takahashi and H. Kita, "A crossover operator using independent component analysis for real-coded genetic algorithms," in *Proceedings of IEEE Congress on Evolutionary Computation 2001*. IEEE, 2001, pp. 643–649.

[16] C. Hervas-Martinez, D. Ortiz-Bayer, and N. Garcia-Pedrajas, "Theoretical analysis of the confidence interval based crossover for real-coded genetic algorithms," in *The 7th International Conference on Parallel Problem Solving from Nature, LNCS 2439*. Berlin Heidelberg: Springer-Verlag, 2002, pp. 153–161.

[17] T. Robic and B. Filipic, "DEMO: Differential evolution for multiobjective optimization," in *The 3rd International Conference on Evolutionary Multi-Criterion Optimization, LNCS 3410*. Guanajuato, Mexico: Splinger-Verlag, 2005, pp. 520–533.

[18] D. Sasaki and S. Obayashi, "Efficient search for trade-offs by adaptive range multi-objective genetic algorithms," *Journal of Aerospace Computing, Information, and Communication*, vol. 2, no. 1, pp. 44–64, 2005.

[19] N. Elmqvist, P. Dragicevic, and J. Fekete, "Rolling the dice: Multidimensional visual exploration using scatterplot matrix navigation," *IEEE Transactions on Visualization and Computer Graphics*, vol. 14, no. 6, pp. 1539–1548, 2008.

[20] M. A. Karabeyoglu, "Advanced hybrid rockets for future space launch," in *Proceedings on 5th European Conference for Aeronautics and Space Sciences*. EUCASS, 2013.

[21] L. Simurda, G. Zilliac, and C. Zaseck, "High performance hybrid propulsion system for small satellites," in *AIAA Paper 2013-3635*. AIAA, 2013.

[22] M. A. Saraniero, L. H. Caveny, and M. Summerfield, "Restart transients of hybrid rocket engines," *Journal of Spacecraft and Rockets*, vol. 10, no. 3, pp. 215–217, 1973.

[23] M. A. Karabeyoglu, D. Altman, and B. J. Cantwell, "Combustion of liquefying hybrid propellants: Part 1, general theory," *Journal of Propulsion and Power*, vol. 18, no. 3, pp. 610–620, 2002.

[24] Y. Kosugi, A. Oyama, K. Fujii, and M. Kanazaki, "Multidisciplinary and multi-objective design exploration methodology for conceptual design of a hybrid rocket," in *AIAA Paper 2011-1634*. AIAA, 2011.

[25] S. Gordon and B. J. McBride, "Computer program for calculation of complex chemical equilibrium compositions and applications I. analysis," in *NASA Reference Publication RP-1311*. NASA, 1994.

[26] K. Hirata, C. Sezaki, S. Yuasa, N. Shiraishi, and T. Sakurai, "Fuel regression rate behavior for various fuels in swirling-oxidizer-flow-type hybrid rocket engines," in *AIAA Paper 2011-5677*. AIAA, 2011.

[27] S. Yuasa, N. Shiraishi, and K. Hirata, "Controlling parameters for fuel regression rate of swirling-oxidizer-flow-type hybrid rocket engine," in *AIAA Paper 2012-4106*. AIAA, 2012.

[28] K. Chiba, M. Kanazaki, A. Ariyarit, H. Yoda, S. Ito, K. Kitagawa, and T. Shimada, "Multidisciplinary design exploration of sounding launch vehicle using hybrid rocket engine in view of ballistic performance," *International Journal of Turbo and Jet Engines*, vol. 32, no. 3, pp. 299–304, 2015.