SIMULATION-BASED DESIGN WITH UQ FOR CREATING NEW COMBINATION OF FUNCTIONS CONSIDERING UNCERTAINTY

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ABSTRACT
The situation of product development takes a high cost, because designers have to remake the design plan for the design specification uncertainty of the upstream design. 75% of product development costs is the most serious problem for the product development. In this study, SBD with UQ (Simulation-Based Design with UQ) as a new design process is proposed to improve the problem of product development. SBD with UQ creates design plans with an optimized combination of functions and parameters by classifying uncertain specifications created in basic design and quantifying the uncertainties. In this paper, we consider the proposed method using CanSat which is a simple artificial satellite, and show the effectiveness of SBD with UQ.

Keywords: Simulation, Taguchi Method, Uncertainty Quantification,

1. INTRODUCTION

Since the 1990s, the globalization of world markets has progressed rapidly, and many companies have been faced with heating up product competition. Along with this, difficulties to develop products are an important issue in the industry because of trade-offs, like between improving product qualities and reducing production costs. When a designer plans a design process in a complex and rapidly changing design environment, it is difficult for the designer to grasp mutual relationships among tasks and to manage quality of design and product comprehensively throughout the design process if the complexity of the product increases (Karl and Steven 1995). Furthermore, there are a lot of uncertain information about a design object in upstream designs. As a result, it is difficult for the designer to make a decision because detailed specifications are not decided due to uncertainties. According to Bruno Lotter, 75% of product development costs are caused by mistakes of the making decision at the design stage (Bruno 2013). Figure 1 shows the breakdown of responsible stage of product development costs. The design stage consists of concept design, basic design and detail design. If a fault is discovered after the design phase like a manufacturing and a shipping, redesigns take much cost to deal with the fault. In other words, it can be said that the responsibility of the designer is heavy.

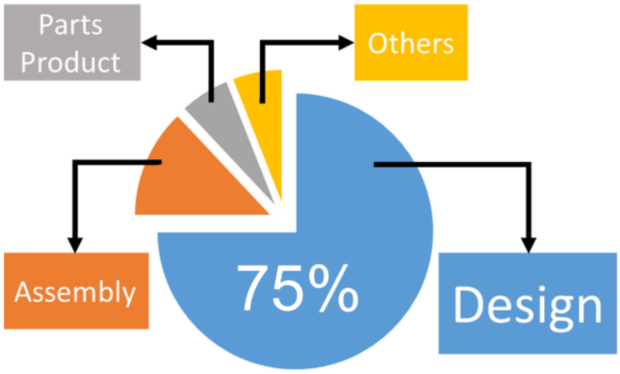

Figure 1: Responsible stage of product development costs

On the other hand, Ohtomi described the importance of the design stage in product development. According to Ohtomi, 80% of the total life cycle cost of the product is decided by the design stage (Ohtomi 2005). Focusing on the relationship between easiness of design change and cost of occurrence, it can be seen that the upstream design, which has not determined the details, has much choice for the design plan. These relationships are shown in Figure 2.

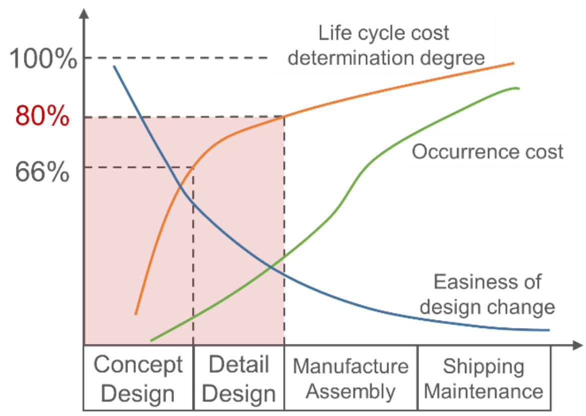

Figure 2: Importance of design in product developments

Therefore, it is important to quantify uncertainties to help making decisions and to simulate product development with trials and errors using by CAD, CAE, etc. In addition, it is the key to improve the quality of design whether or not it is possible to obtain a design plan that maximizes the function while satisfying many constraints.

The purpose of this research is to propose a new design process which introduces simulation which combines various functions and parameters in concept design and creates many design plans taken into consideration of uncertainties of specification. This design process eliminates the difficulty of decision making due to uncertainties in upstream design and maximizes functions while satisfying various tradeoffs and constraints such as design quality improvement and cost reduction.

2. SIMULATION-BASED DESIGN WITH UQ

In this chapter, in order to solve the problem of the current design process, firstly we analyze the current design process and reliability of simulation and identify problems. From the result, we describe what elements are missed and needed to solve, and model new design method.

2.1. Present state and problems of design process

2.1.1. Current design process and 1DCAE

According to Ohtomi, it is pointed out that redesigns have a big influence on the development cost as the design process progresses if the upstream decision making contents are mistaken (Ohtomi 2005). With the current design process, the widespread adoption of Computer Aided Designing (CAD) and Computer Aided Engineering (CAE) to detailed design greatly changed the way of development. Meanwhile, in improved designs, developments based on structural design by CAD and CAE is suitable, but in new designs, developments based on the values and functions required for products. A system that reflects them in the structure is necessary. However, it is difficult to develop the system because of a gap between the upstream design and the downstream design. This gap is shown in Figure 3.

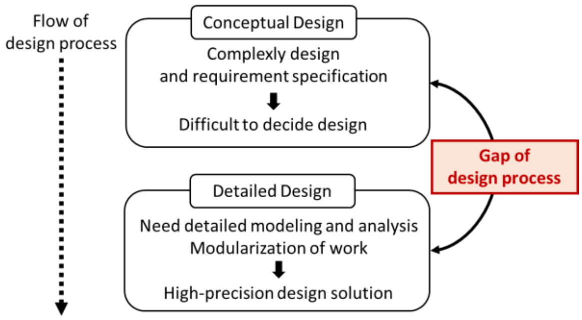

Figure 3: Gap between the upstream design and the downstream design

In the design based on value or function, the current CAD/CAE cannot be applied. In upstream design, decision making for product requirements and constraints is ambiguous. Also, the designer needs to consider all uncertainties of the design object. As a result, the designer needs to divide the design problem into partial problems that can be solved, however it is necessary to have a deep understanding and knowledge about the design object, the design process, the use environment, the market, the life cycle, etc. Therefore, there is a gap that the downstream design requires detailed design solution while there is a lot of uncertain information in the upstream design. Because of this reason, it is difficult to manage comprehensive design quality and work flow with the conventional design method.

In order to solve these problems, Ohtomi and colleagues have proposed One Dimension Computer Aided Engineering (1DCAE) which introduces and supports concept design simulation of new products (Ohtomi and Hato 2012). 1DCAE is a design method that supports various computer aided tools and models for decision making in conceptual design while constantly overlooking the entire design problem by expressing the essence of the design problem in a simple form. However,

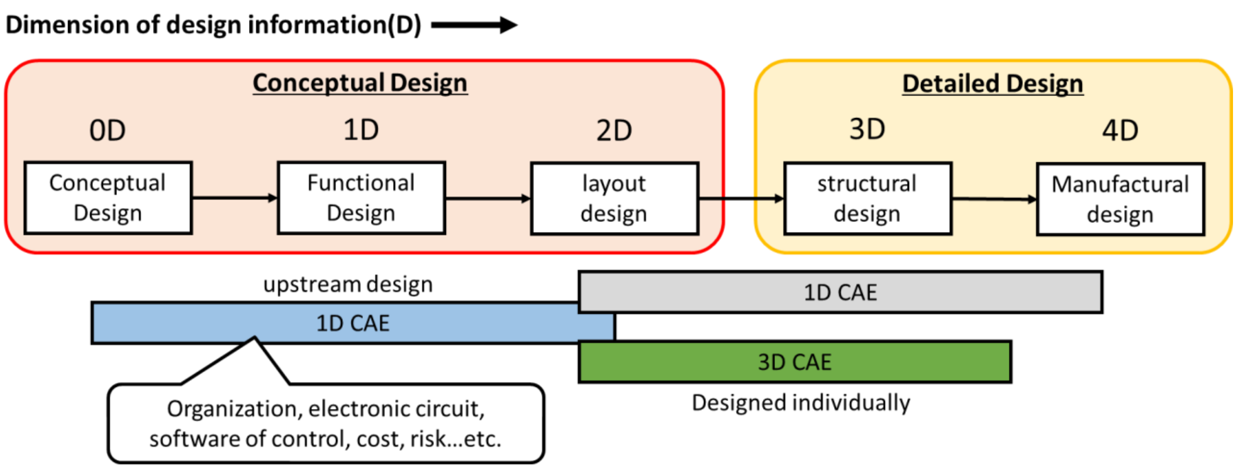

Figure 4: Position of 1DCAE in the design process

it is stated that "1D" means not expressing one dimension in particular, but expressing functions simply. 1DCAE makes it possible to evaluate from the upstream to the downstream stage of design by CAE. The position of 1DCAE in the design process is shown in Figure 4.

Before designing the structure, 1DCAE expresses the entire system to be designed by function, so that it can be evaluated and analyzed. Then, it is possible to create an optimum design plan in consideration of various functions of the entire design object in the upstream design. Further, using the result as an input, the divided design task is solved. Finally, return the result of the individual design to the whole design, and perform system verification.
By using 1DCAE, designers can gain two benefits. One is the creation of an optimal design solution in the upstream design and the other is the visualization of the entire system. By creating an optimal design solution in the upstream design, it is possible to obtain a robust design solution overlooking the downstream design. This is because it is applicable from the upstream design, so it can cover a wide design area and lead to the creation of new value. In addition, design problems can be found at an early stage of design, and design quality and development efficiency can be improved. Although the CAE method to the conventional structure made partial optimization possible, it was difficult to optimize the whole system by overlooking the entire system. However, 1DCAE can maximize value, minimize cost, and minimize risk by overall optimization. In addition, visualization of the whole system makes it possible to formulate specifications crossing fields such as machines, electrical machinery fields, and software that were designed separately. This makes partial optimization of field alone possible, enables overall optimization across fields, eliminating unreasonable and wasteful. Also, it is possible to prevent missing in the whole system, leading to quality improvement and safety and security. In addition to the visualization of the results, it is possible to visualize information such as parameters constituting each function, function, mechanisms, mechanisms, electric fields, and which fields are targeted. Based on these benefits, 1DCAE can be said to be a method of searching for global design solutions based on constraint conditions and design areas.

2.1.2. Reliability of simulation and uncertainty

Simulations such as CAD and CAE are the key to improving product quality in current product development. In other words, design quality can be complemented by improving the accuracy of simulation. However, from the 1990s to the present, the diffusion of CAD and CAE contributed greatly to the field of engineering, but simulation tools packed with advanced knowledge such as dynamics and computational science became black boxes. CAD and CAE can be designed very efficiently if the designer properly uses them. However, if the designer makes an incorrect usage, the safety of the design object developed based on that mistake can not be guaranteed. Securing safety is the most important in product development, and this is the same in the simulation for product development. In other words, it is extremely important to create a system to guarantee the quality of simulation. The importance of this problem was pointed out in the National Agency for Finite Element Methods and Standards (NAFEMS) and The American Society of Mechanical Engineers (ASME), strategic efforts to international standardization are being developed. ASME recommends Verification and Validation (V&V) (ASME Standard V&V 10-2006 2006). Figure 5 shows the V-model process.
The purpose of V&V is to ensure the reliability of numerical simulation. "Verification" is a confirmation as to whether the object meets the specifications, design, planning, and other requirements. Also, "Validation" is an evaluation on whether the target function or performance meets the purpose or purpose and whether it has practical effectiveness.
The precision of the simulation also depends on the amount and quality of the information to be designed. The variation of these information is expressed as uncertainty. Uncertainty Quantification (UQ) is proposed in ASME V&V 10-2006 so that uncertainty is not reflected largely in the simulation model. The lower the quality of simulation, the lower the design quality. That is, consideration of uncertainty greatly affects design quality.

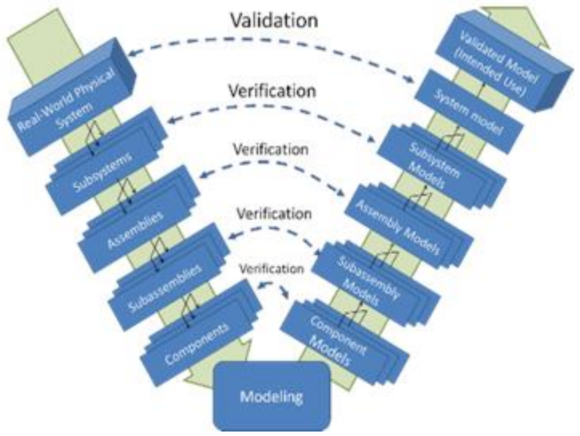

Figure 5: V-model process

2.2. Proposal of Simulation-Based Design with UQ

Based on the contents of chapter 2.1, in this research, we propose a new design process introduced a new uncertainty classification systematically considering uncertainties and a new quantification that enables design of various functions like 1DCAE for the basic design. The authors named this design process Simulation-Based Design with Uncertainty Quantification (SBD with UQ). Figure 6 shows the flow of SBD with UQ.
SBD with UQ creates a design plan with an optimized combination of functions and parameters by classifying uncertain specifications created in concept design and quantifying the uncertainties based on the classification in basic design. There are four advantages of SBD with

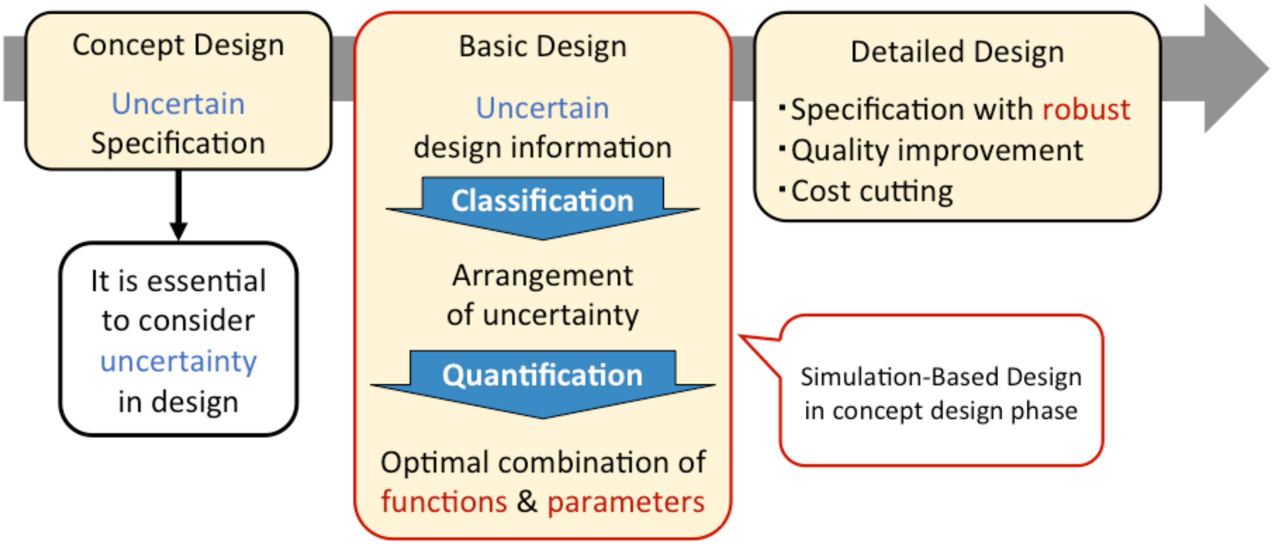

Figure 6: Flow of SBD with UQ

UQ. The first is to be able to obtain a combination of optimum functions and parameters from a large number of design plans. And the design plan takes the trade-off into account. Furthermore, in the upstream design, it is possible to optimize the whole function by the characteristics of 1DCAE, and it is possible to perform model creation using CAD in detailed design and verification simulation using CAE as robust design. As a result of these advantages, it is possible to secure reliability by early functional verification and to obtain a design solution considering V&V. In addition, detailed modeling of SBD with UQ is shown below.

2.2.1. Uncertainty classification and UQ

There are various uncertainties such as those due to factors that can not be modeled in simulation when designing and manufacturing products. In the preceding research various classifications are done. Among them, Kuroda classifies the uncertainty of the building field into six categories (Kuroda 1983). Since this classification by Kuroda covered the uncertainty in the building field, the authors applied this classification to the design field. The new classification of uncertainty in this study is shown in Figure 7.

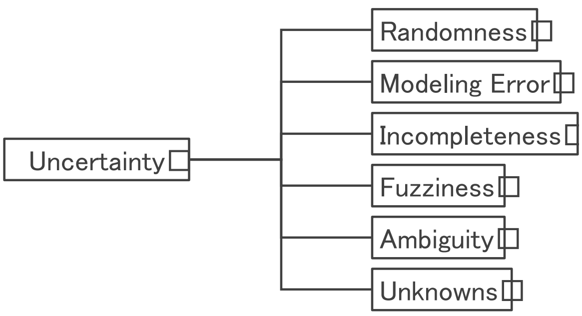

Figure 7: New classification of uncertainty

In this classification, variations in natural phenomena and physical properties are classified as "Randomness". Randomness is relatively quantifiable from experiments and observations. On the other hand, there are gaps between calculation results given by simplified mathematical models and analytical models via various assumptions and real phenomena. Such uncertainty is called "Modeling Error". Although it is difficult to quantify the uncertainty of the Modeling Error, it can be reduced by giving a parameter range to the error. Furthermore, in Figure 6, "Incompleteness" is caused by lack of information at the time of design plan creation. In addition, there is "Ambiguity" which is difficult to determine in one analysis field by parameters belonging to a plurality of analysis areas. And there is "Unknown" which makes it difficult to predict after product shipment, such as change of social values .

The quality of design depends on how the uncertainty can be quantified in the upstream design. Current researches have developed various methods and support tools as Uncertainty Quantification (UQ). A design that considers uncertainty is called a robust design, and it is a robust design that is not easily affected by variations in product manufacturing and the use environment. In the current research, there are many researches on the method used for UQ and its robustness evaluation (ASME Standard V&V 10-2006 2006, Madsen, Krenk and Lind 1986, Hoshiya and Ishii 1993). In this research, we classified UQ into four levels according to the parameters used for UQ and its robustness evaluation. Level 1 is a definite value for which the parameter to be used is determined to be one. Examples include criteria such as upper limit and safety factor. In level 2, although the parameter to be used can not be decided as one value, its formation range is determined. Examples include physical property values such as temperature and humidity. Level 3 is a probabilistically confirmed parameter because even the established range of the parameter to be used is not fixed yet. It is often used for safety assessment of design objects, and there are many applications to space satellites and nuclear facilities. Examples include random numbers and genetic algorithms. Finally, in addition to the uncertain parameters related to the

robustness of the product, the concept of cost and benefit is introduced. Considering the cost of manufacturing, maintenance and repair, interest rate etc. for evaluation, design in total sense. "Design" which vaguely considered everything is considered to belong to level 4.
As the level increases from 1 to 4, the difficulty of quantification increases. There are many parameters with high difficulty of quantification in the specifications of the upstream design, and the reliability is low. As a result, the accuracy and stability of the design solution are lowered. Figure 8 shows the classification of UQ based on the used parameters and its robustness.

Lv.	Type	Examples	Volume of information	Reliability
1	Fixed value	size, weight etc.	Low	High
2	Values for which the range is fixed	physical property value etc.		
3	Confirmed value probabilistically	random number etc.		
4	Unknown	Fluctuations in Social values etc.	High	Low

Figure 8: Classification of UQ based on the used parameters and its robustness

In this research, we introduce the Taguchi method to stabilize the design quality. Application of the Taguchi method evaluates the uncertainty of Level 1 to 3 with the technical characteristics of each element by early functional verification and makes design development more efficient. In addition, early functional verification prevents level 4 market complaint and achieves cost reduction.

2.2.2. New UQ applying Taguchi method

Taguchi method is a concept created by Taguchi to efficiently realize product development and process management (Inoue 2008, Tatebayashi 2005). The quality in the Taguchi method is the reproducibility of the function. Reproducibility is how much precision you can make a thing in the same way and stabilizes quality by improving reproducibility. Characteristics of the Taguchi method are the evaluation of functionality and its improvement method. Taguchi method is to perform functional evaluation, and the big feature is use of orthogonal array, Signal Noise Ratio (SN Ratio) and sensitivity. By applying two parameters of control factor and error factor to an orthogonal array that can reduce the number of trials by performing statistical processing later, it is possible to know the trend of the overall functionality of the phenomenon. These trends can be known from indices of SN ratio and sensitivity. The SN ratio shows how stable the result can be obtained, and the sensitivity can be known to what extent each factor influences the output. However, since the Taguchi method is a method for quality checking and it is used in detailed design, it is rarely used in upstream design. This is because the parameters of the control factor and the error factor need to be determined. However, the stabilization of quality, which is a characteristic of the Taguchi method, may solve the problem of the current upstream design. Therefore, this research proposes UQ using Taguchi method.
Kado proposes Product & Operation Sensitivity Analysis Method (P&O method) as new UQ (Kado 2014). The P&O method creates experiments and simulations using the orthogonal array by the Design of Experiments (DoE), and the calculation method of SN ratio and sensitivity is the same algorithm as Taguchi method. The difference from the Taguchi method is the following two points.

A) Utilizing the data of experimental capsules of “product information” and “operation information” created by DoE at the PLAN (experiment creation) stage of the P&O design method.
B) Definition of “noise factor” required for calculation of sensitivity and SN ratio, “operation information” is noise factor as seen from “product information” and “Product Information” is treated as error factor as seen from “operation information”.

First, in the Taguchi method, the definition of "control factor" "noise factor" is common. This applies to Item A, control factor is what can be controlled by the designer, noise factor is what cannot be controlled by the designer. Using the orthogonal array applying a noise factor, its SN ratio and sensitivity are obtained. In other words, the intersection of the orthogonal array is synonymous with considering the error of the design object itself and the error in use as the design object. Therefore, by assigning the information product information about the design object itself and the usage situation operation information of the design object to the two axes of the orthogonal array, it can be regarded as experimenting the design object in the actually assumed environment. Furthermore, in Item B, it can be considered that it can be established as a DoE by considering the product information assigned to the two axes of the orthogonal array and the uncertainty which is a noise factor in the operation information.
Therefore, Taguchi method became applicable in the upstream design, and it was able to prepare to play the role like 1DCAE. This makes it possible to obtain the robust design solution in upstream designs. Moreover, in the P&O sensitivity analysis method, it is possible to have multiple levels for one factor. This makes it possible to obtain a noise-resistant design, although it is a discrete parameter, using the orthogonal array in DoE.
First, in this method, the design object is hierarchized as shown in Figure 9. By performing this hierarchy, it is possible to clarify the system hierarchy of the system, function, and parameter to be designed, so it is possible to relatively easily set the parameters considering the uncertainty to the level of the orthogonal array. The SN ratio and the sensitivity of the design object are calculated for each hierarchy based on the set lowest layer parameters, and the overall SN ratio and sensitivity are calculated by the bottom up scheme.

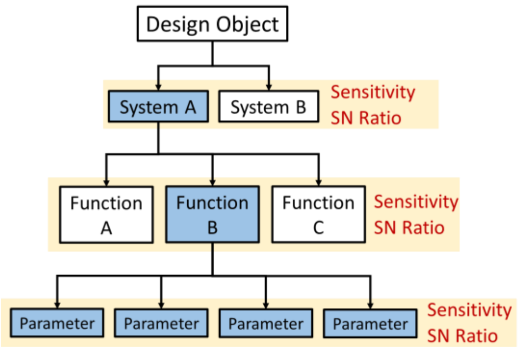

Figure 9: Hierarchized design targets

Based on the six types of uncertainty classification in design, SBD with UQ reclassifies the information into two types of uncertainty information to be assigned to the P&O method. In order to take account of uncertainty, these information are assigned to the orthogonal array as an established range. For example, it is assumed that the "Parameter A" exists and the established range is 0 to 100. Also, when an orthogonal array with three levels is used in this time, it is assigned to 0, 50, 100 and so on. This assignment is performed as same for other parameters. The example is shown in Figure 10.

Example : 【Parameter A】 Range 0 to 100

Parameter	Level 1	Level 2	Level 3
A	0	50	100

Figure 10: Setting "Parameter A"

2.2.3. Selecting the optimum combination

The parameters of the function selected as shown in Figure 11 are similarly calculated for other functions. Parameters efficiently selected by the DoE belong to the each function because of the hierarchicalization. Therefore, selecting various parameters according to the DoE is synonymous with deriving many design plans combining various functions. Moreover, it is possible to contribute to decision making in the upstream design because it is possible to set whether or not to use the function in these obtained design plans. For deriving the optimum design solution from among them, we choose the one with the highest average of sensitivity and SN ratio of each calculated factor. In this way, it is possible to select an optimum design solution in consideration of sensitivity and SN ratio.

The validation of this optimum design solution is confirmed by comparison with the requirements specification.

3. METHOD VALIDATION WITH CANSAT

We used Can Satellite (CanSat) for the validation of the proposed method in this research. CanSat is a simple artificial satellite that is as large as a hole can size.

3.1 Outline of verification

This validation is a comparison between CanSat which was designed using SBD with UQ and CanSat which the author made in the past. Figure 12 shows the overall view of CanSat.

Figure 12: The overall view of CanSat.

The feature of CanSat which we made in the past is that this CanSat was made by amateur designers with little consideration of uncertainty and was made by many trials and errors, but the mission was successful. These features are consistent with the problem which should be solved by SBD with UQ, so it is considered to be suitable for verification. Therefore, we compare and verify by using

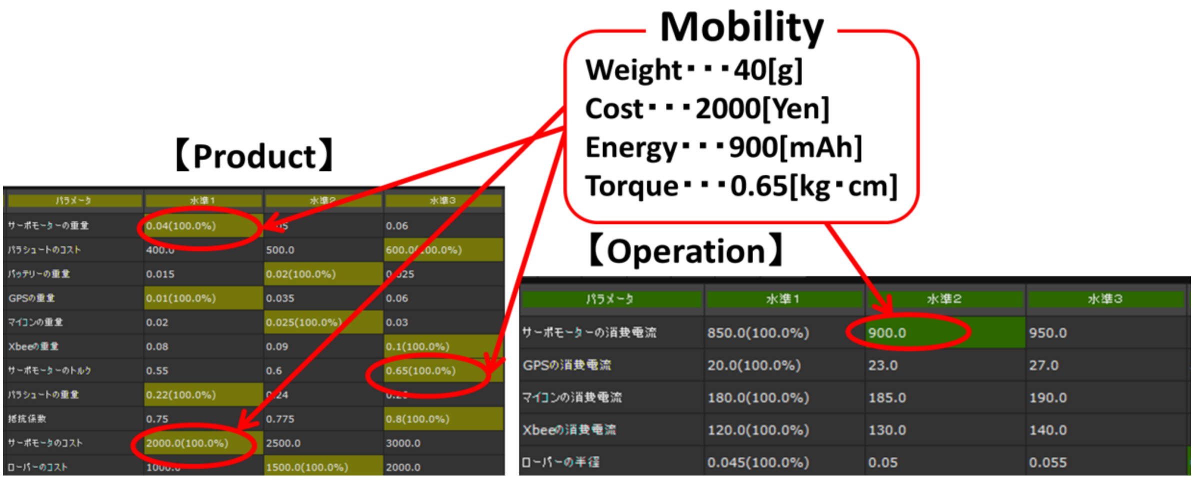

Figure 11: Example of parameter selection

SBD with UQ in the same mission as CanSat which we made in the past.
The outline of the mission is shown in Figure 13. CanSat is raised from the ground to about 50 meter with the aircraft, and CanSat is released from there. And CanSat unfolds the parachute and is landed. After that, it is guided by a sensor such as GPS and moved to the destination using Rovers.

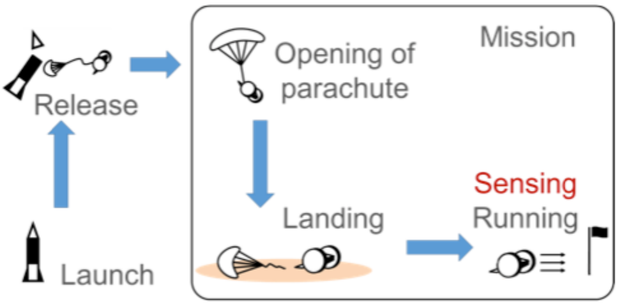

Figure 13: Outline of the mission

Moreover, the comparison verification items are two points. The first is the entire functionality of CanSat. And the other is the optimum combination of sub functions for position identification. However, it is assumed that they are selected from many candidates of sub function, and the more measurement items are selected, the higher the measurement accuracy will be.

3.2. Simulation setting

In accordance with the flow of SBD with UQ, we first create CanSat specifications and success criteria (Kawamo and Suga 2003). Based on these specifications, parameters of each function to be considered in this trial are allocated to product information and operation information. Parameters of each function are weight, power consumption, cost, driving force and so on. Moreover, in this trial, L54 orthogonal array is used for product information, and L121 is used for operation information.

3.3. Result and discussion

As a result of trial based on the simulation setting in Section 3.2, 6534 design plans were obtained. Table 1 shows the comparison between trial results of the simulation and the past CanSat and improvement values. It can be seen that SBD with UQ realized about 7% to 10% weight reduction, energy saving, cost reduction and performance improvement overall. Furthermore, in selecting the sub function for position identification, while realizing weight saving, energy saving, and cost reduction, it was possible to increase the number of selections and improve the system. Also, a part of the obtained sensitivity and SN ratio is shown in Figure 14.
The design direction can be obtained from the indicators of the influence on the design plan such as the sensitivity and the SN ratio shown in Figure 14. In particular, it is understood from this trial that the presence or absence of

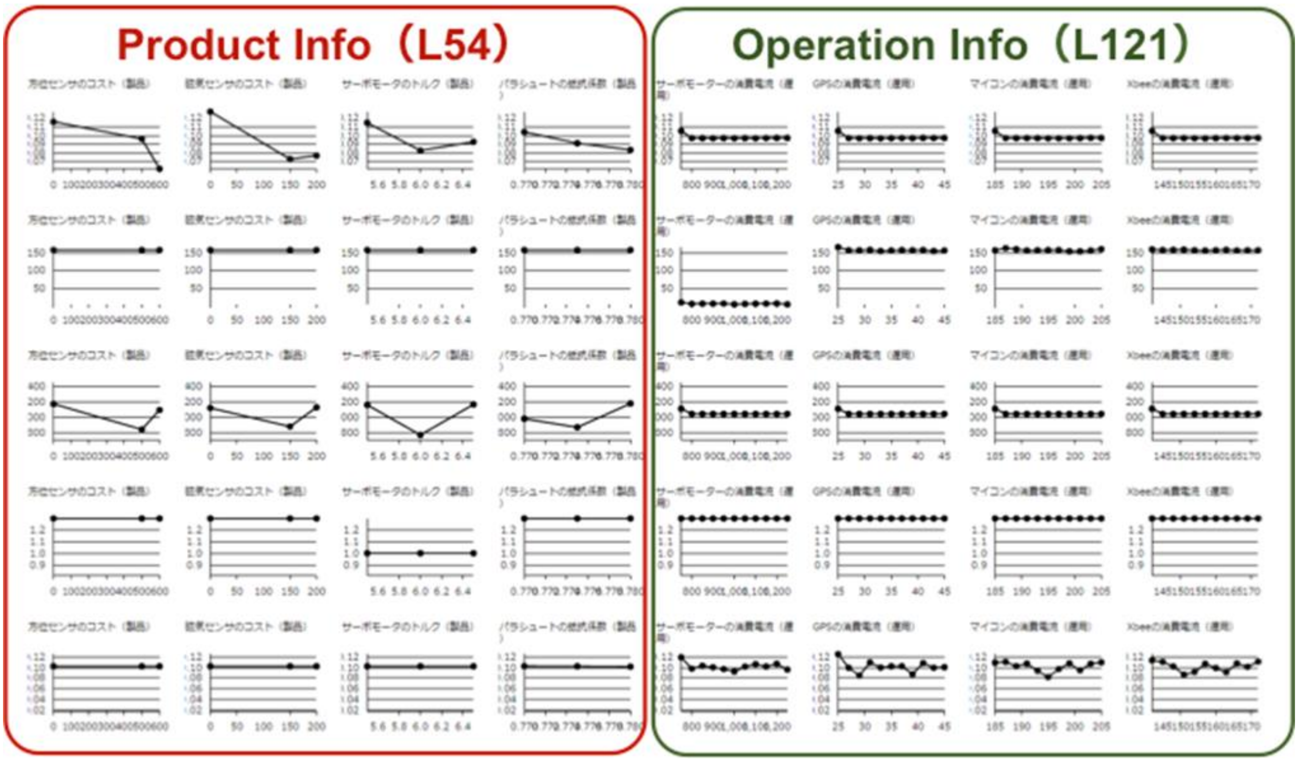

Figure 14: Part of the obtained sensitivity and SN ratio

selection of function is important. Figure 15 shows changes in SN ratio and sensitivity depending on whether or not the function is selected.
As can be seen from the change in the SN ratio and the sensitivity, the selection of the function has a large influence on the design plan, and it is possible to lead to the cost reduction by performing the early function verification in the upstream design and selecting the correct function.

Table 1: Comparison and Improvement Values

	Past	Optimal	Improvement[%]
Weight of structure [g]	380	350	7.89
Power consumption [mAh]	1240	1100	11.29
Cost [yen]	19000	17150	9.74
Thrust[kg・cm]	9.2	10.42	11.71
Parachute area[㎡]	0.62	0.67	7.46
Support function for position identification	1	2	1[個]

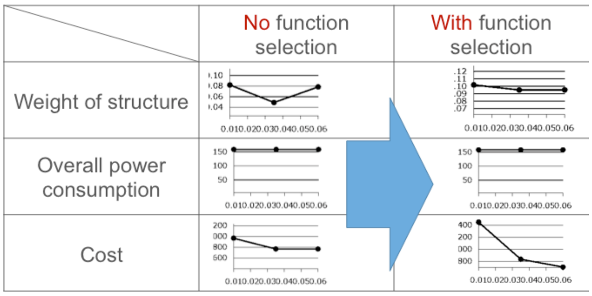

Figure 15: Changes in sensitivity and SN ratio depending on presence or absence of function selection

4. CONCLUSION

In this research, we proposed Simulation-Based design with Uncertainty Quantification, introduced the new UQ applied Taguchi method in upstream design
There are three points which we checked
Firstly, SBD with UQ is able to obtain a design solution with the optimal combination of functions and parameters. Second, we can choose and change easily design plan by early functional verification using sensitivity and SN ratio. Finally, function selection give a big impact on the pecification, therefore early functional verification at the upstream improves reliability of the design as V&V.
However, the level of uncertainty was low only in this trial. More design plans can be obtained when considering the parameter of Level 3 or higher, hence it is expected that a more complete design solution can be obtained.

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