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# SEDT (System Engineering Design Tool) development and its application to small satellite conceptual design

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**Abstract**

Although satellites are getting smaller and the development duration is getting shorter, it still takes a long time to conduct a satellite conceptual design. The System Engineering Design Tool (SEDT) has been developed to effectively and efficiently design small satellites (ranging from 10 kg-class nanosatellites to 200 kg-class microsatellite) in order to minimize the amount of labor involved in the conceptual design phase. The present SEDT consists of five design blocks and has some characteristics different from system engineering tools previously developed. First of all, it adopts a top-down design methodology which induces a distributed design architecture. SEDT has also implemented the subsystem design process connected in series. It enables the design order of a satellite system to be formed, based on design parameters given by satellite database constructed from over 200 small satellites launched between 1990 and 2004. Utilization of this database can improve the data reliability by acting as a design reference. SEDT incorporates system budgets, mass, and power as verification parameters, along with characteristic trend equations (CTEs). SEDT can do the conceptual system/subsystem design, analyze the design output, and predict the rough order of magnitude (ROM) development cost in accordance with user's requirements. Especially, SEDT implements graphic user interface (GUI) to provide convenience to the users.


*Keywords:* Satellite; Conceptual design; System; Engineering; Tool; CTEs

## 1. Introduction

The System Engineering Design Tool (SEDT) is a software tool that provides a convenient means to perform conceptual design of a satellite system. The ultimate purpose of the tool is to cut down the program time and cost of small satellites at the beginning phase. An added value is the database, which the tool is based on, such that the result reflects the current trend in satellite designs and helps to achieve more valid designs. The function of SEDT software is to compute mass and power, and estimate cost so that the shape of the satellite system can be estimated. This is done through numerous equations and algorithms according to the system engineer's requests. Also, trade-offs can be easily carried out by system engineers, through inputting mission critical factors, such as mission requirements and system requirements, and analyzing the effects of these factors on the satellite design [1]. The key function of the design tool is to determine the range of the design during the initial concept design.

SEDT developed here is fundamentally different in concept from other generic system engineering design

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software. A generic system design software, in general, refers to more than just an interconnection software, and includes tools and facilities for satellite design involving many people [2]. However, SEDT explained here refers to a piece of software. In using this software, one systems engineer can alone do the initial concept design of small satellites. SEDT is a program that can estimate the mass, size, and power consumption of a satellite based on the database of more than 200 satellites and design elements. The amount of analysis data included in the database is large enough such that the software can be considered as a statistical analyzer.

## 2. Development of SEDT

### 2.1. SEDT architecture

SEDT is divided into five major parts as shown in Fig. 1: mission and orbit design block (MDB), system design block (SDB) including payload, performance verification block (PVB), cost estimation block (CB), and visualization block (VB).

Also, SDB, which is used for bus design, includes subsystems such as payload, electrical power (EP), structure, attitude determination & control (ADC), propulsion, telemetry, tracking & communication (TT&C), thermal control (TC), and command & data handling (C&DH). In PVB, the mass and power estimates are compared to the allocated budget, and the power design verification is done using a simple energy balance analysis (EBA). CB can predict the satellite payload and the bus cost down to the subsystem level. VB displays the predicted satellite structure and component shape in 3D, when the above phases of the design are completed.

### 2.2. Satellite system design procedure

In general, requirements for initial satellite design are dictated by the mission and the development cost. The initial satellite conceptual design is achieved by first analyzing the required satellite system through mission analysis, then creating the cost model that can be used for tuning and modifying the design parameters according to the satellite customer (user)'s needs. Much effort was put into making SEDT so that more realistic satellite design process can be achieved.

MDB processes include a trade-off to satisfy the requirements derived from the orbital elements, that are

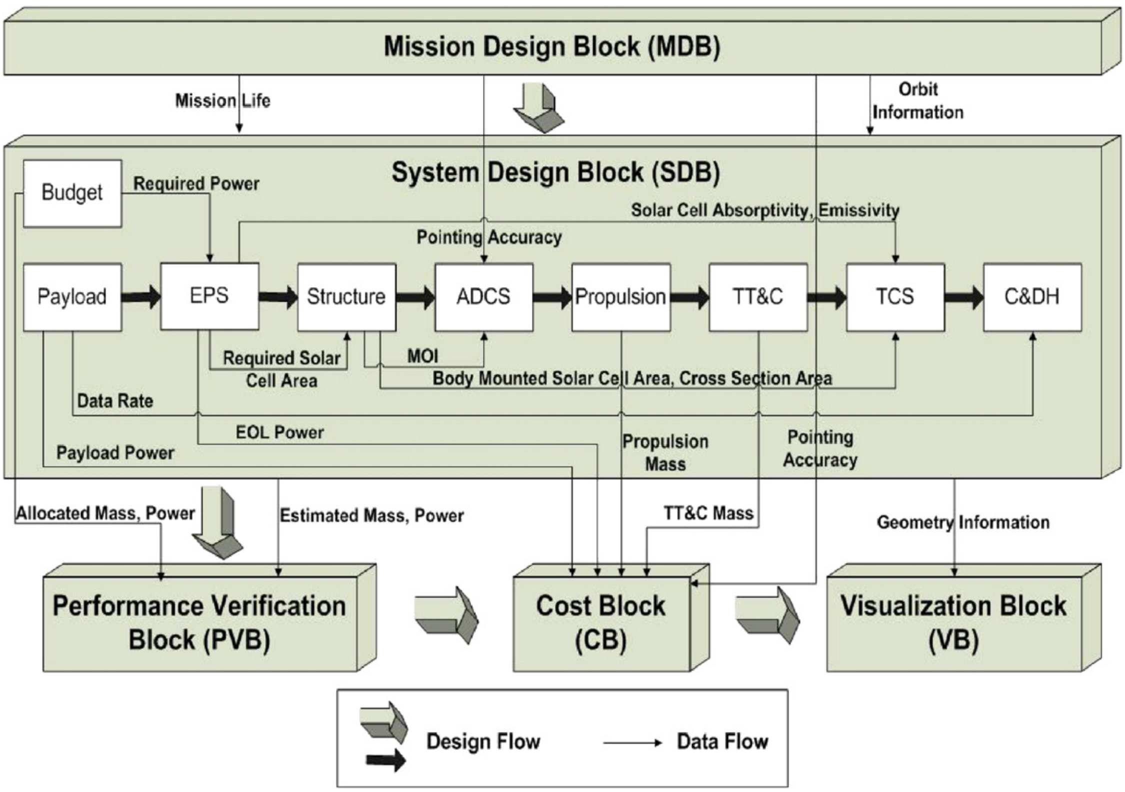


Fig. 1. SEDT architecture.

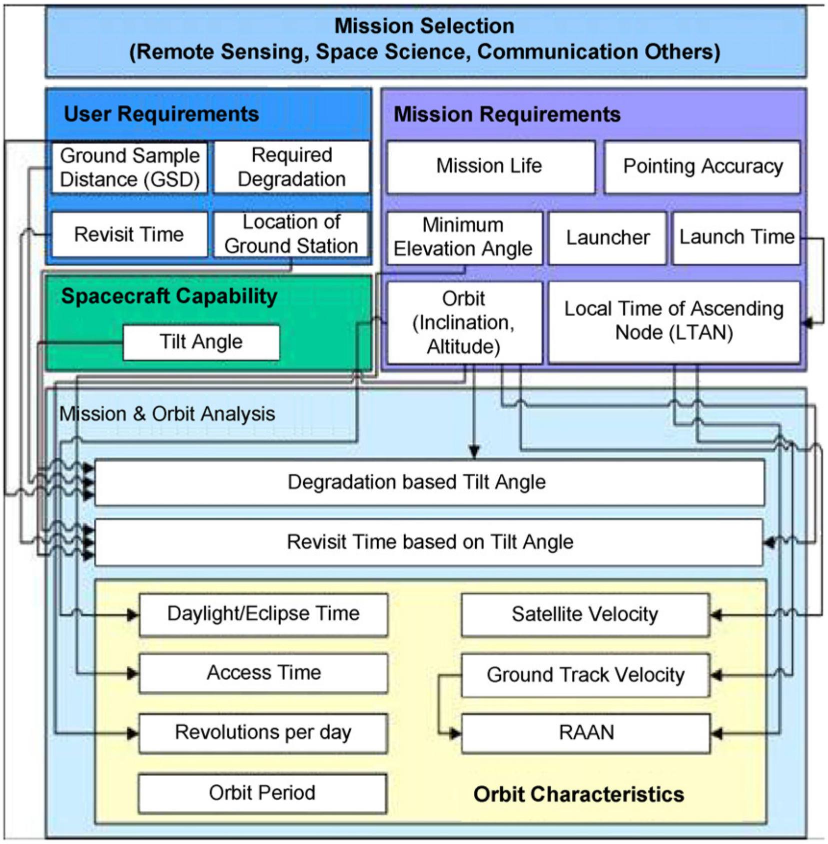


Fig. 2. MDB design flow.

deduced from user and mission requirements, as shown in Fig. 2. The current version only contains special requirements for missions that use optical sensors such as remote sensing and space science missions. The user requirements include ground sample distance (GSD) and revisit time, and the design parameters are altitude, orbit, and satellite tilt angle. The trade-off is accomplished by analyzing the GSD degradation and revisit time according to the tilt angle, checking to see if the requirements are satisfied, and then making appropriate changes to the design variables as illustrated in Fig. 3.

For communication or other missions, only the basic orbital elements are taken into consideration due to the vast range of missions that result in unique satellite designs, which cannot all be reflected in the software. Therefore, VB will predict the size of the payload using only the mass and power consumption data, on the system level, for mission designs other than optics related missions.

Payload design flow based on optical sensor is shown in Fig. 4.

A top-down methodology has been adopted for the subsystem design. Therefore, SEDT user should follow the subsystem design order suggested in this program. This method has the advantage of providing the user with a well-defined design process. The software is also flexible so that the user can perform trade-offs on the design changes by iterating on the design process already performed. It also provides the user a more clear idea of the system design and where it lies in respect to the given budget (mass, power).

SEDT designs electrical power subsystem (EPS) first, prior to other subsystems. In order for the user to determine the solar cell and battery specs, average power consumption and orbit information are received from MDB. The next process is to perform trade-offs using the end of life (EOL) power, required solar panel surface area and mass. Fig. 5 shows the flow of design elements for EPS.

Next, the user determines whether the structure can accommodate the solar panel area dictated by EPS, and whether the calculated mass is within the budget

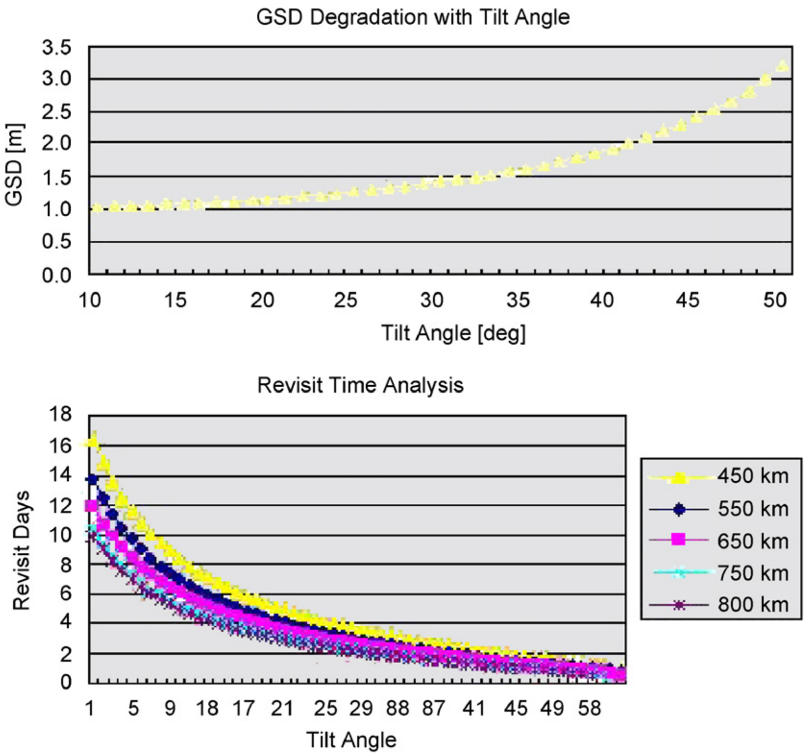


Fig. 3. Analysis of user requirements.

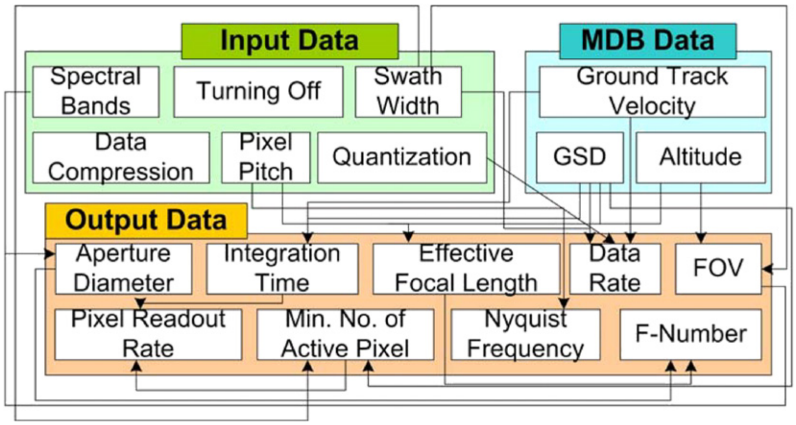


Fig. 4. Design flow of payload based on optical sensor.

through satellite size and material trade-offs. The most crucial design step is to compare the satellite surface area and the required EPS solar panel area, and determining whether solar panel deployment is required. If the 'generic' satellite size determined by the system level mass does not provide enough surface area for the required solar panel area, SEDT runs through a correction process where the user is required to change the satellite mass or the power requirements as shown in Fig. 6. Furthermore, the external structure mass is determined by applying the concept that the basic satellite configuration is formed by panels, and the internal structure mass is determined using the user-defined ratio.

In ADCS (Attitude Determination & Control Subsystem), the attitude control method required for

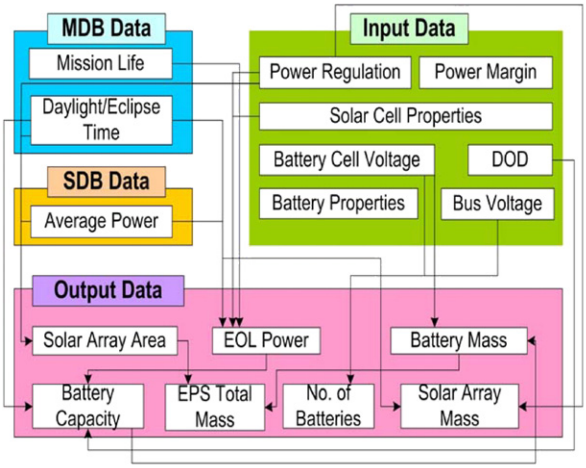


Fig. 5. EPS design flow.

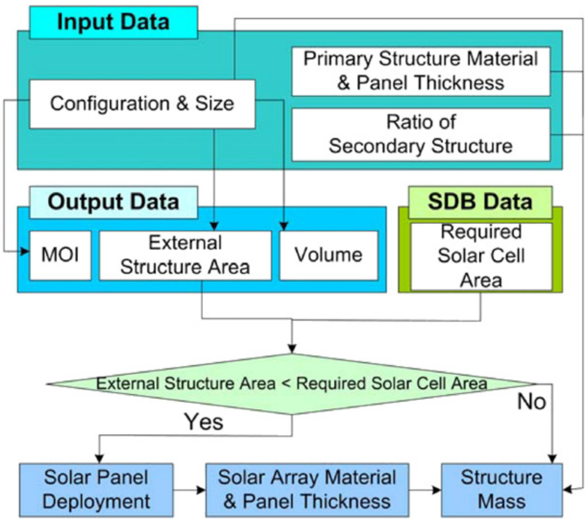


Fig. 6. Structure design flow.

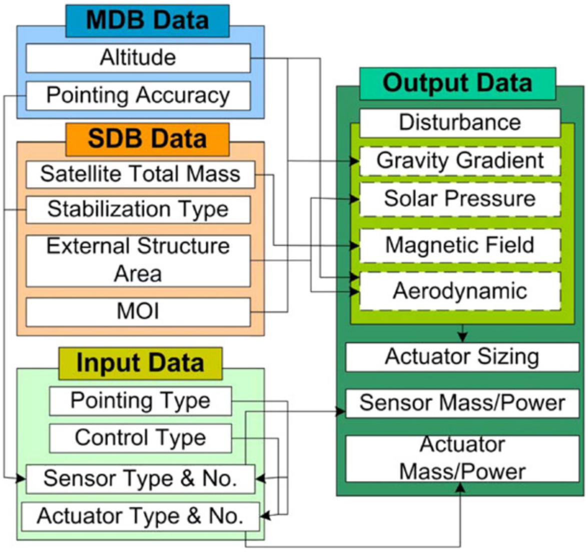


Fig. 7. ADCS design flow.

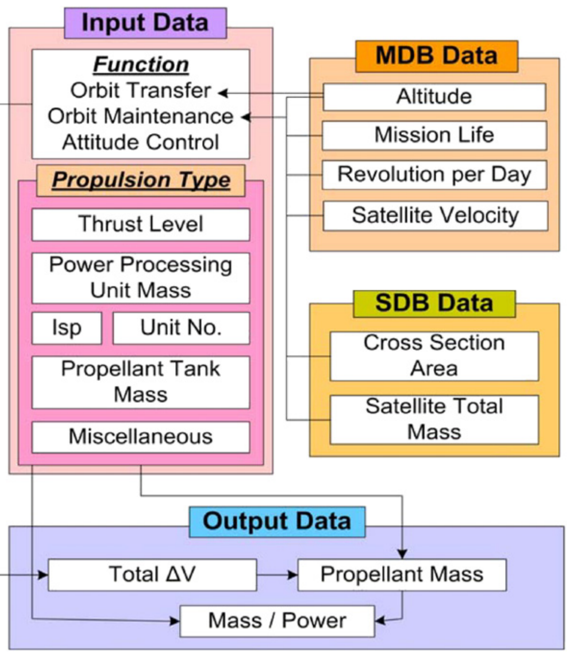


Fig. 8. Propulsion design flow.

accomplishing the mission is selected, and appropriate selection of actuators is done through trade-offs. SEDT recommends to the user suitable attitude control methods according to the nature of the mission, and also recommends possible sensor–actuator combinations that will satisfy the pointing accuracy requirement, using the small satellite ADCS database. This process has the advantage of automatically running feasibility checks. Fig. 7 represents the flow of the design parameters, as well as providing performance criteria for the actuators, taking into consideration the space environment disturbances.

Whether the satellite will implement a propulsion subsystem is determined in advance by the budget at the design stage. Most of small satellites have not incorporated the propulsion subsystem due to mass limitation in the past. However, as the electric propulsion technology matures, the current trend shows that the usage of electric propulsion system on small satellites increasing. Electric propulsion systems usually have the advantage of having a low mass and high

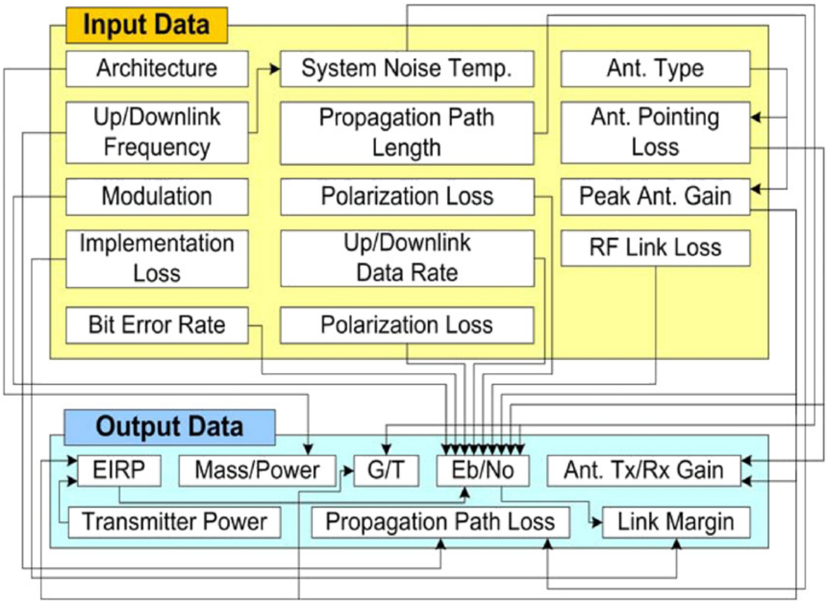


Fig. 9. TT&C design flow.

specific impulse (Isp), but require high power. SEDT is able to flexibly accommodate electric propulsion systems where the user can design the system by selecting parameters from a given design range provided by the software. The user runs trade-offs from the results obtained by first deciding on the role of the propulsion system, then selecting an appropriate propulsion system. SEDT allows designs of the following propulsion systems: hydrazine (micro-monopropellant), hydroxylammonium nitrate (micro-monopropellant), field emission electric propulsion (FEEP), colloid thruster, pulsed plasma transfer (PPT), ion engine, Hall thruster, (Micro) cold gas, free molecule micro-resistojet (FMMR), and Arcjet. Fig. 8 shows the design flow of a propulsion system.

For conceptual design in SEDT, it is assumed that the satellite has two antennas, one for downlink and the other for uplink. The purpose of TT&C design in SEDT is to presuppose possibility of communication through link budget analysis, and estimating mass and power of TT&C subsystem. Link budget analysis is performed by general parameters such as total loss, effective isotropic radiated power (EIRP), G/T, Eb/N0, and link margin as shown in Fig. 9.

Small satellites mainly use passive systems for thermal control in order to save mass and power. SEDT performs trade-offs under the assumption that only a basic passive thermal control system has been utilized. The user defines the type of surface treatment. And the corresponding worst case temperature is determined for the predicted emissivity and absorptivity. SEDT can also be used to determine whether an active thermal control system is required and also to determine the corresponding mass and power requirements. The worst case temperature can be calculated by considering max/min power dissipation. All processes are performed, not by simulation analysis, but by numerical formulas generalized as illustrated in Fig. 10.

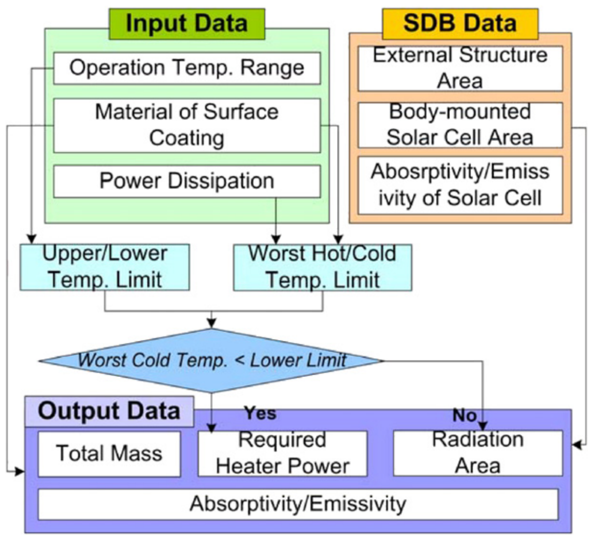


Fig. 10. TCS design flow.

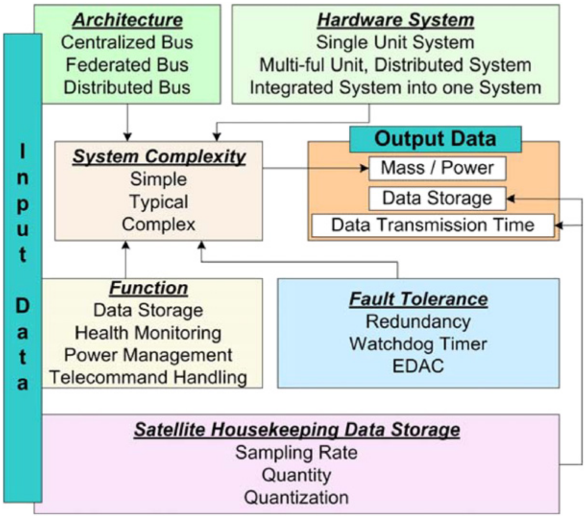


Fig. 11. C&DH design flow.

C&DH subsystem performs the function of determining the amount of each subsystem telemetry data and the amount of required data transmission during one orbit. The data transmission time is determined by predicting mass and power consumption of the previously designed subsystems, depending on the system complexity. The complexity of the system in turn depends on the architecture, system hardware, and function. If a redundancy has been employed for fault tolerance, then the increased mass is reflected on the mass prediction as shown in Fig. 11.

In PVB, the user performs trade-offs and partial subsystem redesign according to comparisons between the given budget and the calculated mass and power for each subsystem, after the design is completed in SDB. While comparing it with allocated budget at the PVB design window, the system engineer can adjust the design factors of all subsystems and recognize the changes in design results immediately. The total satellite mass as well as subsystem mass should be maintained in the following ratio:

$$\text{Available range:}\ 0.9 < \frac{M_{\text{Estimation}}}{M_{\text{Allocation}}} < 1.0. \qquad (1)$$

Then SEDT performs an EBA from the user-input values for the mission mode and standby mode power consumptions, and the mission duration. EBA checks to see if there will be any problems with supply of power.

In CB, the development year is considered for determining the overall satellite development cost. Each bus subsystem and the payload are assigned a certain fraction of the overall development cost. Realistically, gathering data for satellite development cost is a very difficult task. SEDT utilizes the Small Satellite Cost Model (SSCM) information from Aerospace Corporation, that has done the most research in this field [3]. Finally, the user can perform trade-offs of component placements in VB by using the estimated satellite component sizes, and placing these visual volumes around the satellite.

## 3. Construction of satellite database and application to system design

The other part of the crucial element of the satellite design scenario using SEDT, besides the algorithm, is the derivation of characteristic trend equations (CTE). CTE estimates the trend, and is based on the database of information gathered by analyzing over 200 small satellites. The currently derived CTE nicely describes the design characteristics of small satellites (less than 200 kg), except for a few special cases. In reality, estimating each subsystem mass, power, size, and cost is a difficult task. CTEs were made by appropriate simplifications and assumptions while focusing on the concept design phase in order to give a good estimate for each subsystem mass according to the associated factors. The estimation method is performed by two parts: CTEs and estimation using satellite design equations (basic design theory). SEDT makes an appropriate use of both methods in estimating each subsystem parameters.

### *3.1. Satellite mass and power*

Considering mass and power consumption during satellite system design at the system level is an important step. In addition, it also serves as an interface step in the conceptual design phase. First, the budget allocation uses the user-input total mass and average power consumption of the satellite as variables, as shown in Table 1. SEDT allocates budget using the database of small satellites data, instead of taking the generic budget information of large satellites, so that the allocation is appropriate for the satellite ADCS control method and electric propulsion power consumption.

Predicting the payload mass and power consumption is quite difficult. As a special case, the trend relationship between optical-based payload mass and the resolution, or the total satellite mass have been studied. The result showed that the payload mass is more sensitive to the resolution. A prediction coefficient that can estimate mass within an appropriate range of values has been chosen. Fig. 12 shows relationship between total satellite mass and the optical sensor-based payload mass based on the mission and group, respectively.

Table 1
Budget in SDB

| Subsystem | Free input (except optical sensor) | |
|---|---|---|
| Payload | Mass (%) | Power (%) |
| ADCS | | |
| Passive | $0.0217 \times M + 5.8198$ | $-0.0152 \times P + 8.858$ |
| Active | $-0.0142 \times M + 13.748$ | $0.0036 \times P + 18.304$ |
| C&DH | $-0.0079 \times M + 5.5627$ | $-0.03 \times P + 15.39$ |
| TT&C | $-0.0103 \times M + 6.5935$ | $0.0456 \times P + 25.583$ |
| TCS | $-0.0002 \times M^2 + 0.0498 \times M + 0.4785$ | $0.0067 \times P + 0.7862$ |
| EPS | $-0.0084 \times M + 18.237$ | – |
| Propulsion | $-0.012 \times M + 9.415$ | $0.0014 \times P + 8.5$ |
| Structure | $-0.01 \times M + 31.079$ | – |

$M$ (kg): total mass of satellite, $P$ (W): average power of satellite.

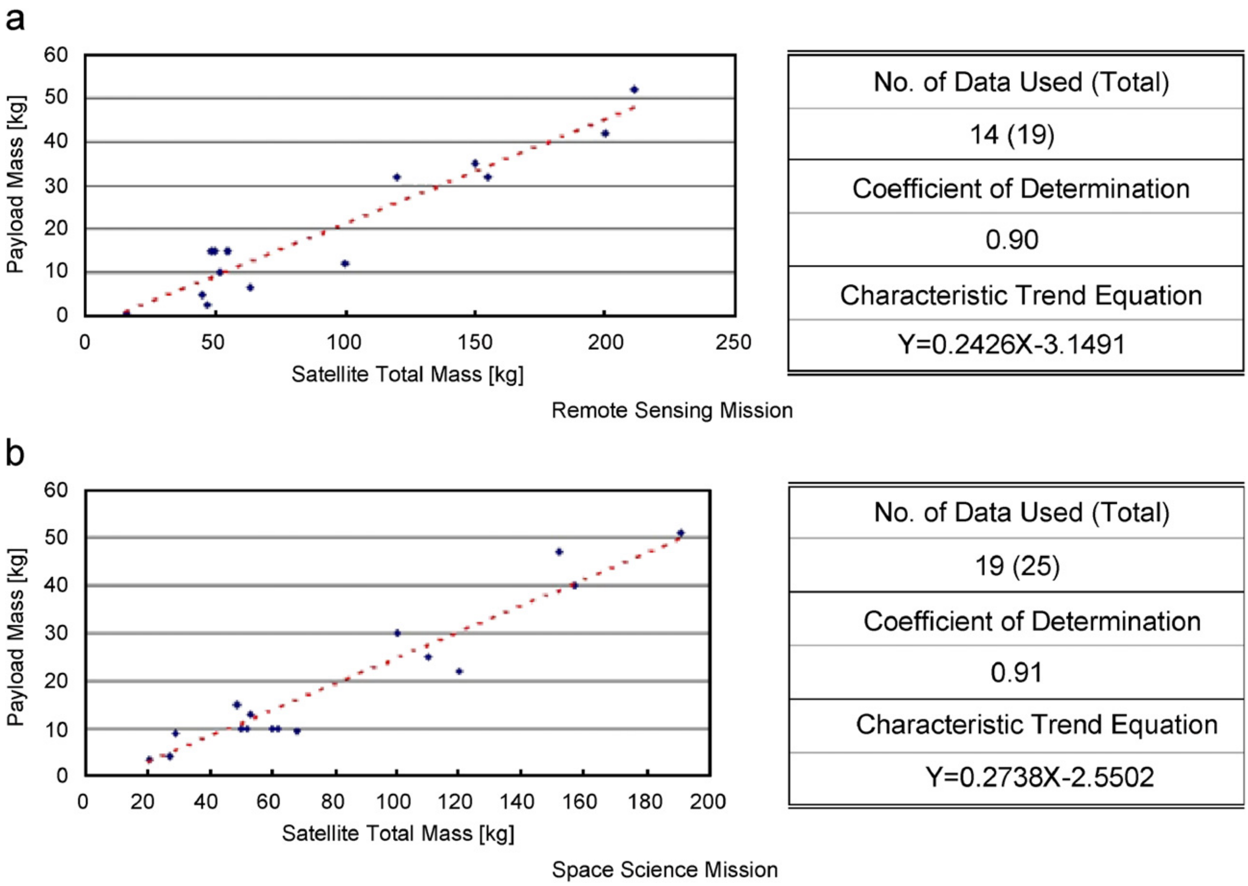


Fig. 12. The relationships between payload mass and satellite total mass. (a) Remote sensing mission, and (b) space science mission.

In regression analysis, 'coefficient of determination' presents a high 'power of explanation' as shown in Fig. 12 and is defined by Eq. (2). The satellite data from the low altitude and special missions, such as Ofeq satellite series, which have much higher ratio in the payload mass vs. total satellite mass, were removed from the database to get general characteristic

$$r^2 = \frac{\text{Sum of squares regression}}{\text{Sum of squares total}}. \qquad (2)$$

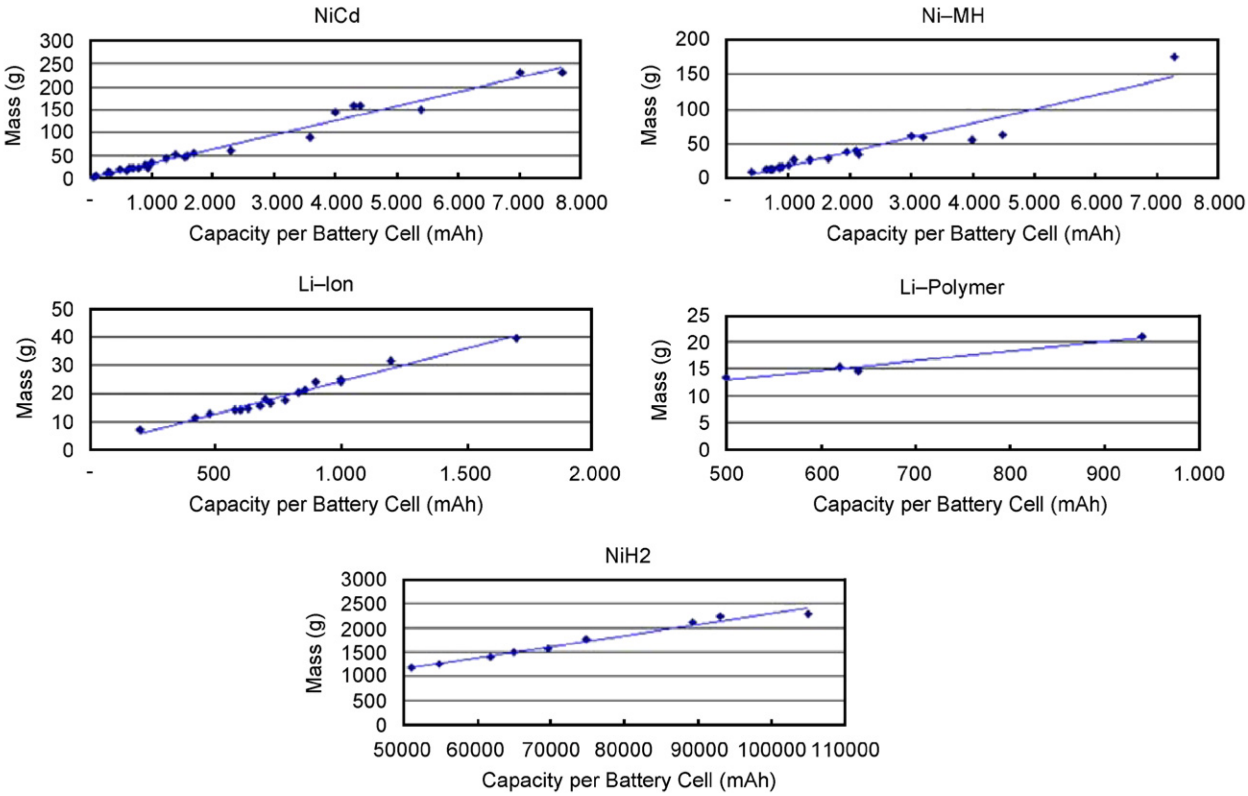


Fig. 13. Relationships between capacity and mass per battery cell.

Table 2
Characteristic trend equations of battery mass

| Battery | No. of data used | Coefficient of determination | Characteristic trend equation (kg) |
|---|---|---|---|
| Ni-Cd | 26 | | $0.0313 \times (J_B/V_{Cell}) + 1.6946$ |
| Ni-$H_2$ | 9 | | $0.0227 \times (J_B/V_{Cell}) + 29.252$ |
| Ni-MH | 21 | More than 0.9 | $0.0205 \times (J_B/V_{Cell}) - 3.0818$ |
| Li-Ion | 17 | | $0.0231 \times (J_B/V_{Cell}) + 1.1599$ |
| Li-Polymer | 4 | | $0.0179 \times (J_B/V_{Cell}) + 3.9565$ |

$J_B$ (W h): battery capacity, $V_{Cell}$ (V): battery cell voltage.

EPS total mass mainly consists of solar array mass, battery mass, and related power modules. Here, the solar array mass is estimated by a design theory (equations) in Ref. [4], and a special CTE that incorporates battery capacity and real-life product data is used for estimating the battery mass. The battery mass is derived from cell voltage ratio depending on the battery material and capacity as shown in Fig. 13 and Table 2. In case of Ni-$H_2$ and Li-Polymer, the number of data sets used may not be sufficient but the characteristic trend of data shows a good representation. The mass of related power modules is not considered in predicting EPS total mass because it is generally quite small compared to the solar array and battery mass.

The structure mass is estimated by determining the panel thickness based on the satellite configuration in addition to the internal mass fraction and margins. The validity of small satellite structure design has been increased by enabling the selection of aluminum honeycomb which has lately become widely used. Eq. (3) represents aluminum honeycomb density developed by SEDT development team, using basic physical theory

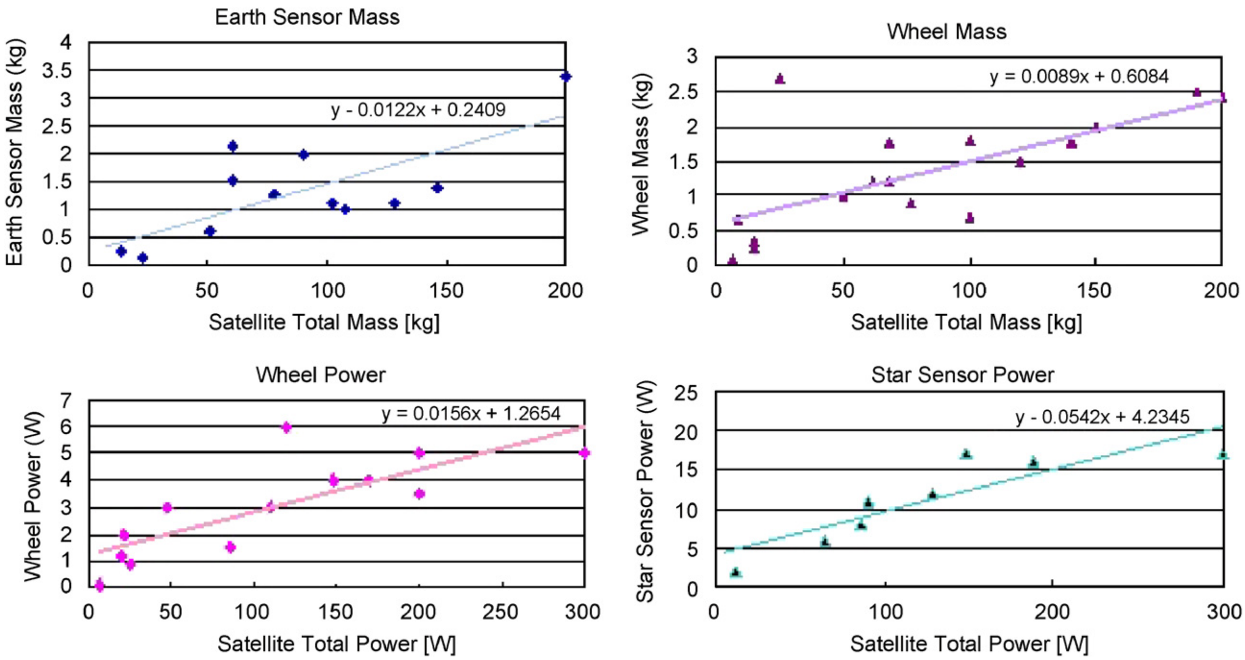


Fig. 14. Examples of relationships between component mass and satellite total mass (above) and component power and satellite total power (below).

within SEDT calculation algorithms.

$$\rho_{\mathrm{mean}} = \frac{2t_{\mathrm{f/s}}\rho_{\mathrm{f/s}} + t_{\mathrm{core}}\rho_{\mathrm{core}}}{2t_{\mathrm{f/s}} + t_{\mathrm{core}}}, \tag{3}$$

where $\rho_{\mathrm{mean}}$ is the mean panel density, $t_{\mathrm{f/s}}$ the face sheet thickness, $t_{\mathrm{core}}$ the honeycomb core thickness, $\rho_{\mathrm{f/s}}$ the face sheet material density, and $\rho_{\mathrm{core}}$ the honeycomb core density.

The ADCS total mass and power are mainly determined by the sensor and actuator mass and power consumption, thus the values are found by adding these two factors. Most of the sensors and actuators show a good trend against the total mass and power of the satellite as shown in Fig. 14. In particular, permanent magnet and damper masses show a good association (proportionality) to the total disturbances as shown in Table 3.

Since various electric propulsion systems are still at the development stage, it is difficult to collect data that can estimate the proper mass and power consumption trend. Therefore, the flexibility was given to SEDT for the user to select the mass and power consumption values within a given range determined from a propulsion system database of small satellites. The propulsion system part of the software especially needs continued update to follow technology developments.

Table 3
Characteristic trend equations of ADCS components

| Item | Characteristic equation | |
|---|---|---|
| | Mass (kg) | Power (W) |
| Sun sensor | $0.0006M + 0.122$ | $0.00003P + 0.1051$ |
| Magnetometer | $0.001M + 0.1166$ | $0.0006P + 0.3214$ |
| Earth/horizon sensor | $0.0122M + 0.2409$ | $0.0173P + 1.4271$ |
| Gyroscope | $0.0011M + 0.1663$ | $0.0007P + 2.3821$ |
| Star sensor | $0.0037M + 0.5493$ | $0.0542P + 4.2345$ |
| Permanent magnet | $951.8 \times T_{\mathrm{D}}$ | – |
| Damper | $5.4 \times 10^{3} \times T_{\mathrm{D}}$ | – |
| Reaction/momentum wheel | $0.0089M + 0.6084$ | $0.0156P + 1.2684$ |
| Magnetic torquer | $0.001M + 0.434$ | $0.0117P + 1.4017$ |
| Gravity gradient boom | $0.0289M + 1.3049$ | – |

$M$: satellite total mass, $P$: average power, $T_{\mathrm{D}}$: total disturbances.

TT&C selects and predicts subsystem architecture, and mass and power of the common components in small satellites such as Global Positioning System Receiver (GPSR), Terminal Node Controller (TNC), and Beacon. TT&C is required to output an estimate within the budget allocated by SDB, because the design usually follows the budget given by the database analysis.

Thermal control subsystem (TCS) of small satellites generally uses a passive method which results in a very small portion of the total system mass. On the other hand, TCS has a bigger impact on the design due to required power generation when an active method is implemented. SEDT calculates the power, taking into consideration the passive methods such as surface treatment and radiator such as multi-layer insulation (MLI), and the active methods such as heaters, as required. CTEs of TCS mass are different depending on the control scheme as shown in Table 4.

The C&DH mass and power consumption estimation depends on the system complexity. The system complexity is automatically categorized as one of the settings (simple, typical, or complex) according to the user-defined C&DH structure and hardware. The system mass and power consumption are then estimated from these factors. The CTE of 'typical' complexity is defined in Fig. 15. Ones of 'simple' and 'complex' are defined by estimating the error which can be generated between each data and criterion of 'typical' line as shown in Table 5.

Table 4
Characteristic trend equations of total mass in TCS

| Passive thermal control | Active thermal control |
|---|---|
| $M_{pt} = 0.0208M + 0.1826$ | $M_{at} = 0.0195M + 1.486$ |

$M$: satellite total mass.

### 3.2. Visualization of satellite configuration and component sizing

VB's key function is to transfer component mass to volume that fits within the satellite configuration. Component size is determined by CTEs, except for the satellite dimension. The size is provided by the user through a trade-off. The components that have been simplified

Table 5
Characteristic trend equations of C&DH system

| Characteristic equation of mass (kg) | |
|---|---|
| Simple | $(0.055 \times M_{Total} - 0.2266) \times (1 - 0.63)$ |
| Complex | $(0.055 \times M_{Total} - 0.2266) \times (1 + 0.48)$ |
| Power characteristic equation of power consumption (W) | |
| Simple | $(0.0817 \times P_{avg} + 1.584) \times (1 - 0.7)$ |
| Complex | $(0.0817 \times P_{avg} + 1.584) \times (1 + 0.63)$ |

$M_{Total}$: satellite total mass, $P_{avg}$: average power.

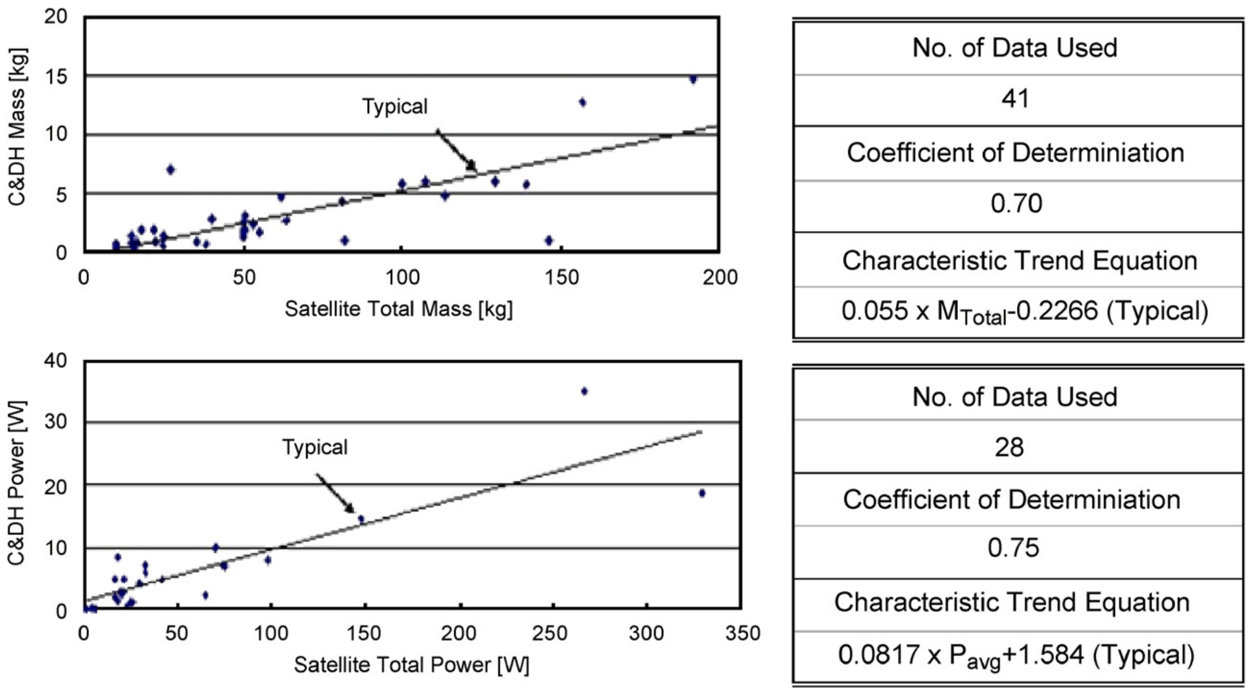


Fig. 15. Relationships between C&DH mass and satellite total mass (above) and C&DH power and satellite total power (below).

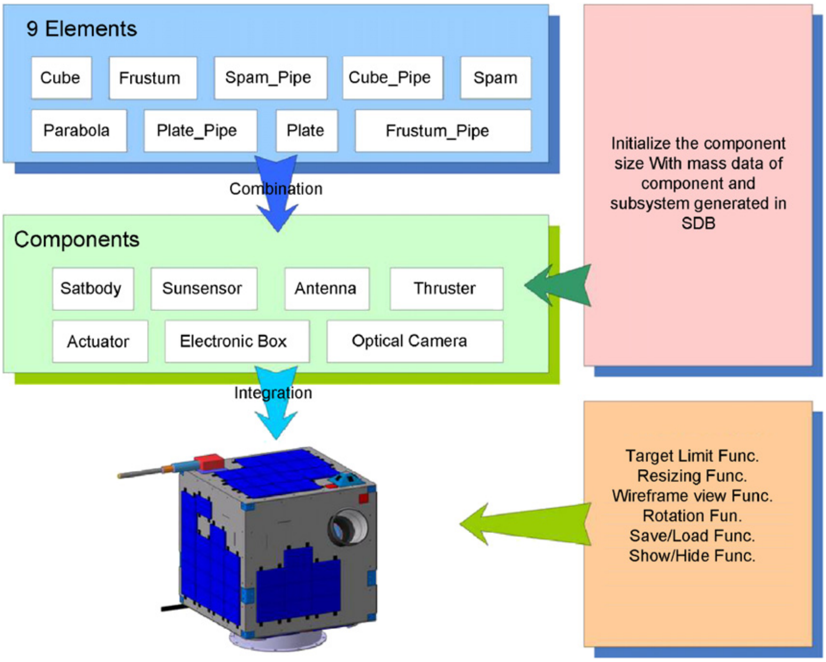


Fig. 16. Architecture of component sizing.

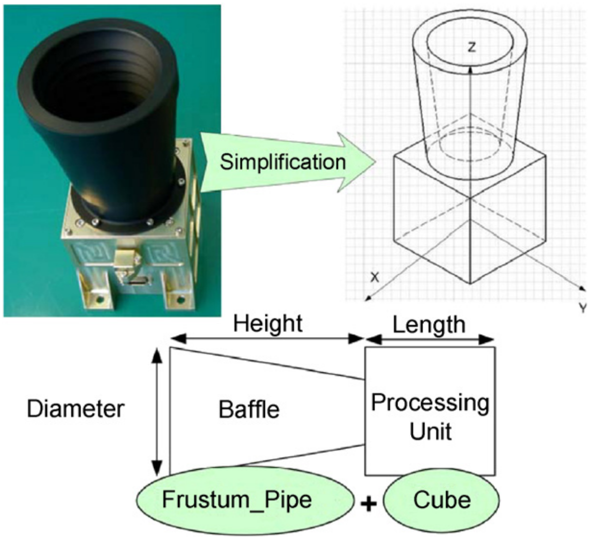


Fig. 17. Star tracker sizing.

consist of nine elements as shown in Fig. 16. This method enables easy updates for various components. A CTE initially determines the external size of a component. After that, VB combines some elements into the component. Fig. 17 shows the elements and sizing factors of star tracker components. In particular, antenna length is defined not by a CTE but by the communication frequency. If the component size is not available, the user can enlarge its volume or shorten its length. Users can adversely determine component size suitable for satellite configuration and size.

CTEs reflect development transition of satellite parts. Fig. 18 shows an example of CTEs for the elements, applied to star tracker sizing.

## 4. User-friendly GUI design

SEDT is designed by UML based on object oriented design (OOD) and coded by language of C + + in Object Oriented Programming. It is friendlier to users than Microsoft Excel worksheet implemented by former system engineering tools. The main screen of SEDT has four function fields as shown in Fig. 19. Menu Bar has a function of compiling the data to show the design results and to provide interface to VB. Design Tree Window displays overall structure of SEDT and helps users approach the satellite design window. Users can provide design values and confirm the results in the Main Design Window. The window is divided into input and output as shown in Fig. 20. Message Window serves a function for checking whether the values are provided correctly and whether any error has occurred.

Fig. 21 illustrates a 3D screen shot of the visualization environment. User can observe configurations of

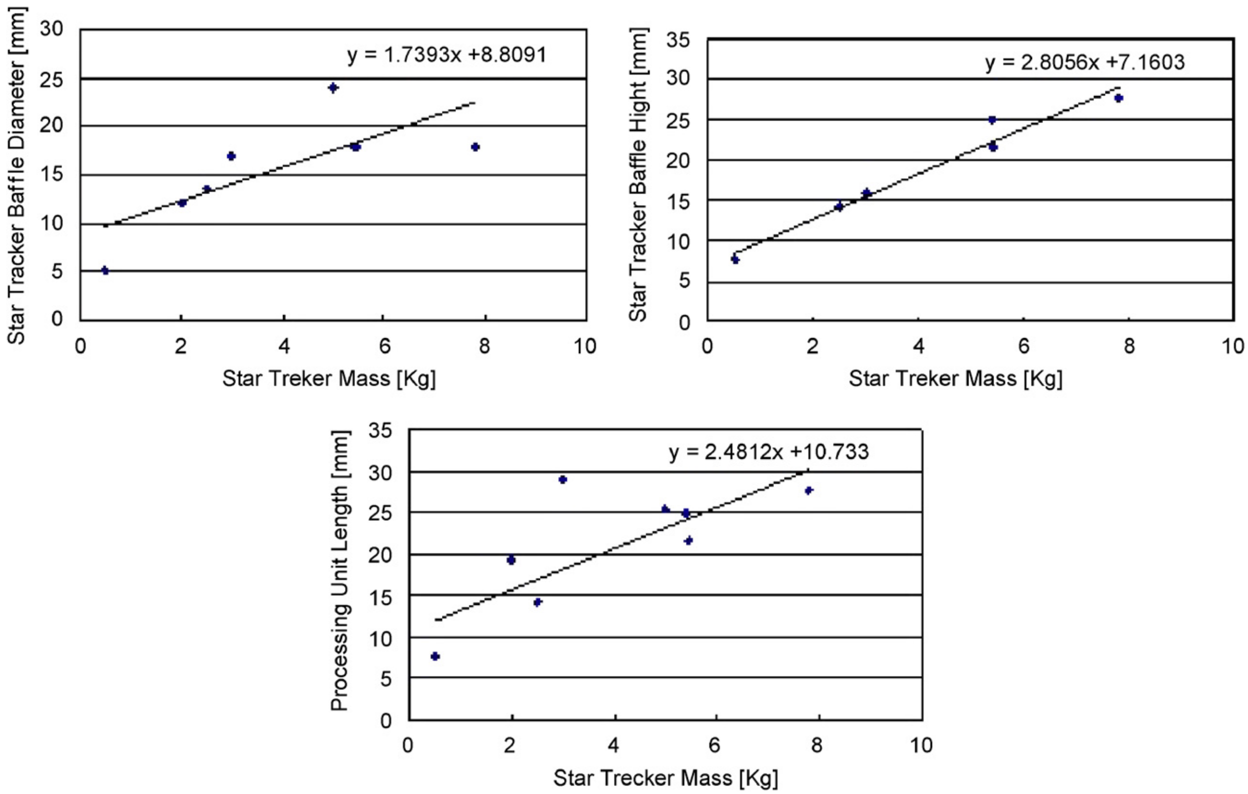


Fig. 18. CTEs of elements of star tracker component.

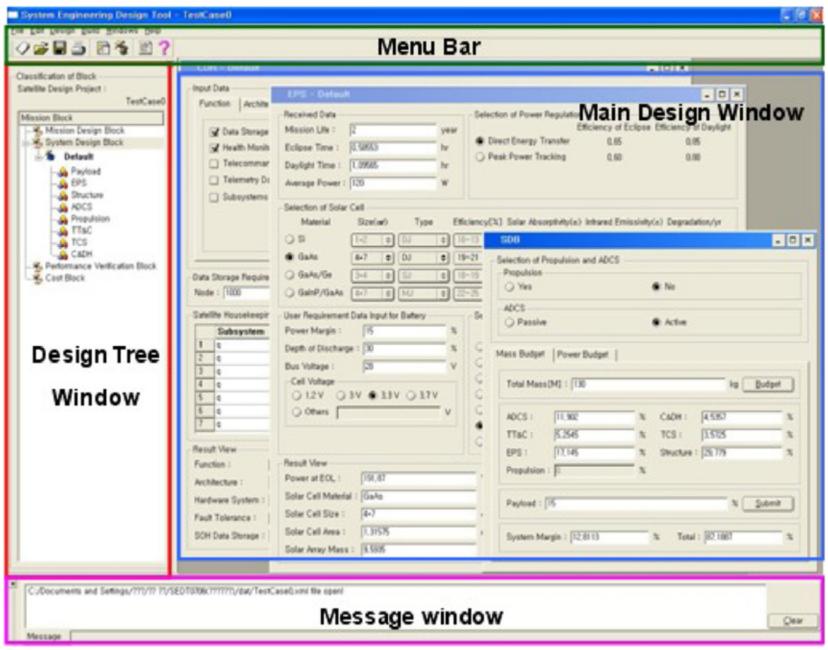


Fig. 19. Main screen of SEDT.

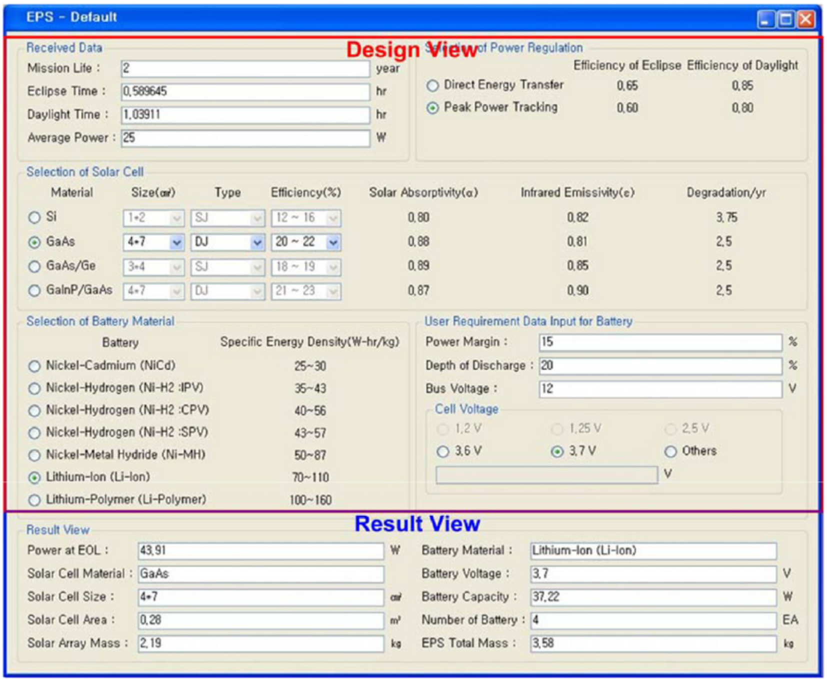


Fig. 20. Design screen of EPS.

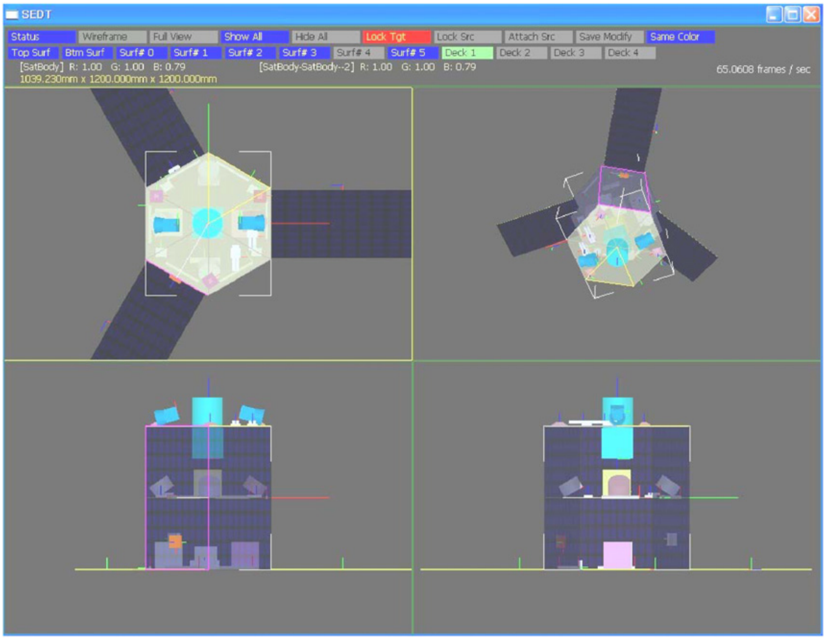


Fig. 21. VB screen.

the satellite or components in four divided screens. VB provides users with several icons for easy operation. Also, user can change the color of the selected components.

## 5. Estimation of satellite development cost

To predict the cost of satellite development is important at the satellite conceptual design phase. In early design step, development cost affects various factors such as satellite total mass, mission life, and performance such as pointing accuracy. Because cost will be largely driven by several factors (grade of parts (space, military, commercial grades), development duration, labor, etc.), it is difficult to estimate the cost with a high reliability. To resolve this problem, SEDT includes cost estimation relationships (CERs) which was developed by Aerospace Corporation. Although SSCM can use 17 technical parameters to estimate cost, SEDT has adopted 12 of these technical parameters. CB roughly estimates the cost of satellite bus and payload using some designed factors and inflation factors according to the development year [3].

## 6. Conclusion

SEDT is a useful tool that allows system engineers to design and analyze small satellites conceptually. The present SEDT is focused on designing satellite systems with single payload based on optical sensors. It is also a powerful tool where a system engineer can run design estimates, from mission concept to bus design, cost estimate, and even structure and component shape and sizing. The software also provides a great value as an educational tool for students interested in satellite systems design. It is the final objective of SEDT to ultimately enable one system engineer to conduct the small satellite conceptual design easily without requiring other references. It can also be applied in documenting the satellite conceptual design more rapidly in early satellite development proposal phases.

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