System Design and Project Management for University Satellites

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This paper focuses on university satellite projects that have spread all over the world in recent decades. In this study, a university satellite refers to a satellite project that is initiated by students. In most cases, university satellites are relatively small with a mass between 1 kg (10-cm cubic satellites) and 50 kg (50-cm cubic satellite). Although a university satellite has limited mission objectives because of severe budget constraints in and the amateur development environment, it often has impressive technical benefits. Moreover, university satellite projects can provide good educational opportunities for students to learn satellite engineering and management skills. This paper describes the system design concepts for effective development and the characteristics of project management based on the QSAT (Kyushu satellite) project experience.

Key Words: Small Satellite, System Engineering, Project Management, Practical Education

1. Introduction

Recently, developments of small satellites in universities all over the world have become very popular. The first university satellite was developed and launched by the University of Surrey, Guildford, UK, in 1981. That satellite is UoSAT-1 and its mass is 52 kg. UoSAT-1 had a CCD camera for Earth observation and amateur radio telecommunication equipment for amateur radio services.

Since that time, the interest in small satellite development in universities has gradually increased and extends now all over the world. In the last 20 years, more than one hundred small university satellites with a mass between 1 kg (10-cm cubic-size) and 50 kg (50-cm cubic-size) have been built and launched.

In Japan, the Whale Ecology Observation Satellite (WEOS) was developed and launched by Chiba Institute of Technology in 2002. This project was the first satellite mission initiated by students in Japan. This satellite was launched by the Japanese launch vehicle H-IIA in piggyback mode. One of the unique features of this project is that it was proposed by students learning satellite engineering and not by a space agency or company.

Afterwards, the University of Tokyo and Tokyo Institute of Technology developed two cube satellites (CubeSat XI-IV, and Cute-I), respectively. They were launched together by the Russian launch vehicle ROCKOT in 2003. In these projects, students not only proposed the mission and designed the satellite system, but also manufactured the satellite hardware, using Commercial-Off-The-Shelf (COTS) products, and developed the software. These projects demonstrate an effective concept of small-satellite development in universities. These successful projects have had an impact on education and research and have lead to satellite projects in many universities in Japan. [1-2)]

2. University Satellites

This chapter describes the characteristics of university satellites, mission categories, constraints of university satellite development, and examples of Japanese university satellite projects.

2.1. Definition and Characteristics of University Satellite

First of all, the definition of a university satellite project should be clarified. In this study, a university satellite is defined as a satellite project when it is mainly developed by students. This means that the main developers are undergraduate and/or graduate students of a university or technical college. In many cases, faculty and/or company people will join as project members. The many satellite projects, in which students form only a small percentage of the entire project team, are not classified as university satellite projects here.

The university satellite projects are categorized into two major groups based on their development styles. One refer to the small student-initiated projects like CubeSats. The other consists of university-initiated projects with some contractor involvements (in many cases, small regional companies) like 50kg-class piggyback satellites as typified by WEOS. The characteristics of each project are described as follows.

Case 1: Student-initiated projects like CubeSats. In this type of projects, students have the responsibilities for the entire development from system level to components supported by faculty. In some cases, local companies may support some developments of complicated units like telecommunication equipment or micro-computer electronics. The CubeSat concept was proposed by Prof. Twiggs originally. Basically, the CubeSat configuration is defined as 10 cm cube in size and 1 kg in mass. [3)]

Case 2: University-initiated projects with some contractors like 50kg-class piggy-back satellites. In this case, students are responsible for mission design, operation, system and subsystem developments. On the other hand, regional industries are participating in the subsystems design, component developments and in manufacturing. In some cases, not only educational value but also activation and growth of the potential of regional industry may be expected.

Table 1 shows the comparison of a typical agency satellite project and a university project based on development responsibility. In the case of an agency satellite project, the project team is often multiple and hierarchical. The boundary of each responsibility is strictly clear and decoupled. The development flow from the upper processes to the lower processes is well-phased. On the other hand, in the case of a university project, the responsibility distribution and the development flow are relatively flexible. Therefore, a more concurrent implementation of the project can be performed.

In the university project, the feasibility of the mission depends on the skills and capabilities of students. Therefore, the satellite mission may be very limited and focused compared with 'real' satellite missions. However, satellite projects in universities can provide good educational opportunities for students to learn satellite engineering skills (e.g., mission design, system design, integration, testing, and operation) and management skills (e.g., team building, communications, scheduling, task distribution, and progress control). For students, not only the final mission goals but also the experiences of the development process will be valuable. In many cases, the educational value may not be mentioned explicitly in the mission statement, but this aspect is often the main motivation for a university project.

2.2. University Satellite Missions

Table 2 shows a few of the major examples of Japanese satellite missions conducted by the Japanese space agency and by universities. When the satellite name is in brackets, it means that it will be launched in the future. To categorize a typical satellite mission, we define 8 mission categories: physical sciences, Earth observations, astronomy, planetary and deep space explorations, telecommunications, broad-casting, material sciences, and engineering technical demonstrations.

In many cases, university satellites have amateur radio telecommunications equipment that can provide amateur radio services as OSCAR (Orbiting Satellite Carrying Amateur Radio). Usually, the radio frequency communications subsystem is one of the high-cost elements for a university project. Therefore, the amateur radio frequency is often used because the characteristics of a university satellite mission are suitable for the special aspects of amateur radio (e.g., non-commercial, public purpose, and aiming for outreach). Furthermore, this concept is expected to lead to the collaboration with the amateur community. This is the great benefit for extending the operational capabilities.

Most CubeSat missions launched in the past had mainly for technical demonstration objectives, but the number of advanced missions is gradually increasing. For example, we refer to the piggyback satellites launched with GOSAT (Greenhouse gases Observing SATellite) in January 2009. One of those piggyback satellites is PRISM (Pico-satellite for Remote-sensing and Innovative Space Missions) developed by the University of Tokyo. This satellite's development was started as an evolutional project of two CubeSat missions (XI-IV and XI-V). This is now one of the most successful university satellites in Japan.[4)]

In addition, the inter-university project UNITEC (UNIsec Technological Experiment Carrier-1) developed by UNISEC (University Space Engineering Consortium) will be launched together with the Japanese Venus explorer, PLANET-C, as a piggyback satellite in 2010. During the trajectory to Venus, the investigation of On-Board Computer (OBC) survivability against the deep-space environment and some scientific observations will be conducted. This spacecraft will be the first student interplanetary object.[5)]

Generally speaking, the number of university satellite missions is limited because of various constraints in budget resources and amateur development environment, but they have potentially challenging technical benefits.

Table 1. Comparison of typical agency and university projects

Development Responsibility	Agency Satellite Project	University Satellite Project	
		Case 1: CubeSats	Case 2: 50kg class (QSAT)
User Mission Proposal	Agency or other Institute	Students	Students
Operations	Agency	Students	Students
System Design / Testing	Agency or Contractors	Students	Students
Subsystem Design / Testing	Contractors	Students	Students or Industries
Components Design / Testing	Sub-Contractors	Students	Students or Industries
Manufacturing	(Sub-)Sub Contractors	Students or Contractors	Industries

Table 2. Examples of Japanese satellite mission

Mission Category	Agency Satellite Missions	University Satellite Missions
Physical Sciences	GEOTAIL INDEX	SPRITE-SAT SOHLA-1 (QSAT)
Earth Observations	GMS, ALOS MTSAT-2 GOSAT	WEOS PRISM
Astronomy	ASTRO-F SOLAR-B	(Nano-JASMINE)
Planetary and Deep Space Explorations	MUSES-C SELENE (PLANET-C)	(UNITEC)
Telecommunications	WINDS	OSCAR CubeSats
Broad-casting	JCSAT	-
Material Sciences	USERS	-
Engineering Technical Demonstrations	ETS series	Cute & XI series SEEDS, HIT-SAT KKS-1, STARS

Table 3. Japanese University Satellites

Launch Date	Satellite Name	University	Launcher	Mass [kg]	Category*	URL
2002.12.14	WEOS	Chiba U	H-IIA-4	50	2: U+C	http://wwwlib.cc.it-chiba.ac.jp/kanta/
2003.06.30	XI-IV	Tokyo U	ROCKOT	1	1: U	http://www.space.t.u-tokyo.ac.jp/cubesat/
2003.06.30	CUTE-I	Titech	ROCKOT	1	1: U	http://lss.mes.titech.ac.jp/ssp/cubesat/
2005.10.27	XI-V	Tokyo U	COSMOS 3M	1	1: U	http://www.space.t.u-tokyo.ac.jp/cubesat/
2006.02.22	Cute-1.7 + APD	Titech	M-V-8	3	1: U	http://lss.mes.titech.ac.jp/ssp/cute1.7/cute1.7-1/
2006.09.23	HIT-SAT	HIT	M-V-7	2.7	1: U	http://www.hit.ac.jp/~satori/hitsat/
2008.04.28	Cute-1.7 + APD II	Titech	PSLV-C9	3	1: U	http://lss.mes.titech.ac.jp/ssp/cute1.7/
2008.04.28	SEEDS	Nihon U	PSLV-C9	1	1: U	http://cubesat.aero.cst.nihon-u.ac.jp/
2009.01.23	PRISM	Tokyo U	H-IIA-15	8.5	1: U	http://www.space.t.u-tokyo.ac.jp/prism/
2009.01.23	STARS	Kagawa U	H-IIA-15	8	2: U+C	http://stars1.eng.kagawa-u.ac.jp/
2009.01.23	KKS-1	TM College	H-IIA-15	3	1: U	http://www.kouku-k.ac.jp/~kks-1/
2009.01.23	SPRITE-SAT	Tohoku U	H-IIA-15	50	2: U+C	http://www.astro.mech.tohoku.ac.jp/SPRITE-SAT/
2009.01.23	SOHLA-1	Osaka U	H-IIA-15	50	2: U+C	http://www.sohla.com/
2010(TBD)	Negai	Soka U	H-IIA	1	1: U	http://kuro.t.soka.ac.jp/cube/what/index.html
2010(TBD)	K-sat	Kagoshima U	H-IIA	1.5	2: U+C	http://kasat.jp/
2010(TBD)	WASEDA-SAT2	Waseda	H-IIA	2	2: U+C	http://www.miyashita.mmech.waseda.ac.jp/Waseda-Sat2/
2010(TBD)	UNITEC-1	UNISEC	H-IIA	15	1: U	http://unitec-1.cc.u-tokai.ac.jp/
2010(TBD)	HoRyu	KIT	N/A	1.3	1: U	http://kitsat.ele.kyutech.ac.jp/
2010(TBD)	PROITERES	OIT	N/A	10	2: U+C	http://www.oit.ac.jp/elc/scl/oitsat/
2010(TBD)	Nano-JASMINE	Tokyo U	N/A	14	1: U	http://www.space.t.u-tokyo.ac.jp/nanojasmine/Index.htm
2010(TBD)	TAIKI	Hokkaido, HIT	N/A	50	2: U+C	http://www.hokkaido-sat.jp/
2011(TBD)	QSAT	KU, FIT, KIT	N/A	30	2: U+C	http://ssdl.aero.kyushu-u.ac.jp/

* 1: U means the student initiated project, 2: U+C means the university initiated project with some contractors.

In some cases, the university satellite mission can also provide educational and social outreach effects.

Table 3 shows all known Japanese university satellites. Since the WEOS launch, 13 university satellites have been launched. Aiming to be launched in the future, various satellite missions are under development now.

2.3. Constraints of University Satellite Development

In general, university satellites are expected to be launched in piggyback mode or in a cluster because most university satellite projects do not have sufficient budget resources. In all of these launch opportunities, constraints in terms of size and mass are imposed on the university satellites. In addition, the orbit is prescribed by the main passenger and cannot be modified by the piggyback satellites. For example, in the case of the Japanese launch vehicle H-IIA, the piggyback satellites must be designed within 50 cubic-cm in dimension, and must be less than 50 kg in mass. The Sun-Synchronous Orbit (SSO) (altitude 600 to 800km) is the most frequently used, because this orbit is favorable for Earth observation missions. In order to design the satellite system, students have to understand not only mission requirements but also the orbit constraints.

3. QSAT Project

As one of the projects mentioned above, in the Kyushu area, a small satellite project had been started under collaboration of three universities (Kyushu University (KU), Kyushu Institute of Technology (KIT), and Fukuoka Institute of Technology (FIT)) and regional industries since 2006. This project is named QSAT (Kyushu Satellite).

The QSAT project team consists of about 20 students and 10 faculty members from the three universities and experts from the industries who cooperate in manufacturing of the satellite hardware units. The QSAT spacecraft consists of 6 subsystems, Attitude Determination and Control (ADCS), Command and Data Handling (C&DH), Telecommunications, Power, Thermal, Structures and Mechanisms. A faculty member is responsible for each subsystem and two or three students are working on each subsystem development.

QSAT is based on a practical satellite design using low-cost COTS units and parts. The students have responsibilities to design electronics units and the mechanical devices in cooperation with the company experts. They have also responsibilities for software design and coding, the operations, and the application programs of the individual spacecraft functions. Furthermore, they perform functional, calibration and environmental tests of the units manufactured by regional industries.

QSAT is designed for H-IIA piggyback conditions. The size of the satellite is about 50 cm square and 30 cm tall. The present mass is about 30 kg. The orbit altitude is expected to be between 600 and 800 km, i.e., Sun-Synchronous Orbit, as defined by the main passenger. The orbit-average power generated by the solar cells is 14W, and the maximum is 30W. The QSAT primary mission objective is to investigate plasma and geomagnetic physics in the Earth's aurora zone for better understanding of spacecraft charging. More details of the QSAT Mission and the system characteristics are given in the references [6-7].

4. System Design Concepts for University Project

This chapter introduces some concepts of system design for the effective development of university projects learned from experiences of the QSAT project.

4.1. The Unitization and Distributed Processing Concept

This section describes our approach from the view-point of system architecture and integration. The complicated interfaces among the components may the cause trouble during the integration and functional tests. Therefore, it is useful to conduct stand-alone and interface tests for each component that has common elements and interfaces. The system constructed from these common units may not contribute to the optimization of the entire system, but the advantage of simplification of the integration and the reduction of complicated interfaces is more useful than the overall optimization for the small university satellite.

In this context, we proposed the unitization and distributed processing concept. The common electronics unit of QSAT consists of a common printed circuit board (PCB) called "Control Board" and specific PCBs called "Local Boards". The Control Board contains the same micro computer chip H8/2638 produced by Renesas Technology Corp., common interface ports and thermometer and heater attachment ports. On the other hand, the Local Board contains the devices to provide the individual functions, e.g., sensor elements, Analog/Digital converters, power devices, modem IC, memory IC. The Control Board and the Local Boards are connected by PC-104 stack-through connecters. [8]

Moreover, the bus-type connection of power supply and date interface between the units allows the satellite system to maintain flexibility and extensibility.

Figure 1 shows the distributed unit concept. The QSAT spacecraft subsystems consist of 5 kinds of major units; Main Unit, Tele-comm. Unit, Management Unit, Actuator Unit, Sensor Unit. In the past development, we developed the bread board model to validate the distribution processing by using the Controller Area Network Bus (CAN-Bus). Now, we are developing the engineering model units to conduct functional tests in the flight condition.

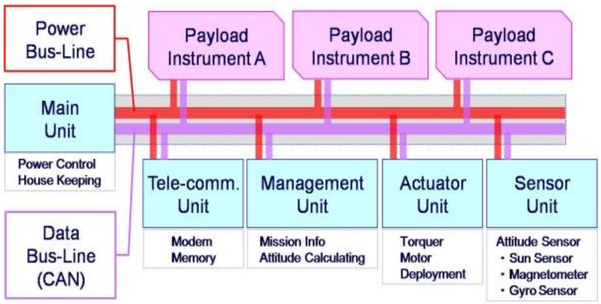

Fig. 1. The distributed unit concept.

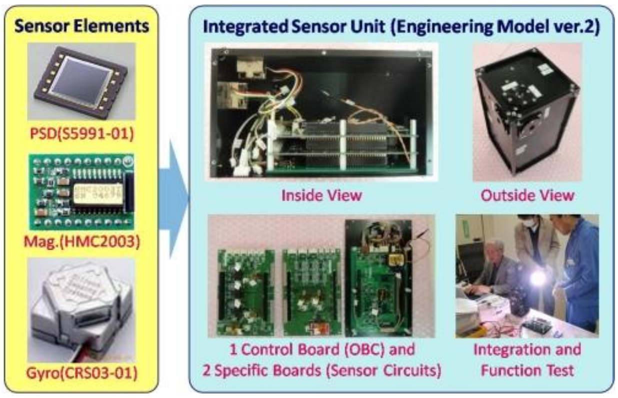

Fig.2. Sensor Unit for attitude determination.

4.2. Attitude Determination and Control

This section describes the characteristics of the attitude determination and control subsystem that provides effective attitude functions by using low-cost COTS elements.

The satellite attitude is determined by estimation algorithms using measurements from the three types of attitude sensors: sun sensors, the three-axis magnetometer and the gyro rate sensors. To detect the sun direction, we have developed a new sun sensor concept by using the two-dimensional Position Sensing Device (PSD) produced by Hamamatsu Photonics Co., Ltd. and a pinhole. Furthermore, the sensor unit contains the three-axis magnetometer provided by Honeywell, to measure the geomagnetic field vector as the second attitude vector, and the mechanical gyro rate sensors. Figure 2 shows the sensor unit developed as based on the unit concept mentioned the section 4.1. So far, we finished manufacturing, integration, and initial functional tests. Now, we are conducting the calibration tests of each sensor to verify its performance.

To achieve the on-board estimation that produces a reasonable accuracy, we established an efficient and straightforward estimator that combines a Weighted-Least-Square (WLS) preprocessing estimator with the sequential Linearized-Kalman Filter (LKF). By using this estimator, we can achieve the accuracy of less than a few degrees which satisfies the science mission requirements. Furthermore, we established various attitude determination strategies considering the combinations of sensor data in various conditions. For example, because sun sensor date is not available during eclipse, we established a specific algorithm by using the data of magnetometer and gyros. More details on the attitude determination are given in the references [9].

The attitude control consists of three-axis magnetorquers for control and a gravity-gradient extension boom for enhancement of the attitude stabilization. Magnetorquers are handmade units manufactured by students. So for, we completed the engineering model and conducted the calibration test by using the magnet-shield facility and the fluxgate magnetometer of ISAS (Institute of Space and Astronautical Science). Now, we are evaluating the test data for calibration.

QSAT has two main attitude-control phases. One is the de-tumbling to point one particular satellite axis roughly along the local Earth-pointing direction. The other is the normal mode to achieve accurate attitude stabilization by means of the magnetorquers after the boom extension. So far, we have established a few control algorithms for each of the phases and have evaluated their performances by simulations. More details on the attitude control are given in the references [10].

4.3. Operation Concept

QSAT mission is operated by using amateur radio telecommunications equipment as well as typical university satellites. The on-board system consists of the electronics unit for modulation/demodulation and the data storage function, the amateur radio transceiver, and the antennas. This on-board unit provides the data packet formatting based on the amateur radio protocol AX.25, Gaussian-Minimum Shift Keying (GMSK) modulation for downlink, Frequency Shift Keying (FSK) demodulation, and the data storage function. The telemetry data rate is 9,600 bps, whereas the command date rate is 1,200 bps. These properties are popular in amateur radio telecommunications. However, this is a very limited performance compared with the specifications of communications of traditional agency satellites (often Mega-bps class). Therefore, in the case of downlink of the large amount of mission data, effective planning of the operations is needed.

In this context, we established an effective operation concept. Figure 5 shows the mission sequence and specific modes in each lifetime phase. Specific modes are defined in order to provide for an effective operations concept. They represent a particular satellite system-level configuration. These modes guarantee the survival of the satellite and the proper execution of the required tasks during the mission. Table 4 shows the satellite mode definition.

The mission operations plan is based on the access times and access durations considering the limited performance of amateur radio telecommunications. Phase transitions are only conducted when certain specific criteria have been fulfilled. Moreover, these transitions can only be initialized by a ground-command. The QSAT mission consists of the main two phases after separation from the launch vehicle. More details of the operation concept are given in the references [11].

5. Management of University Projects

This chapter introduces the issues and lessons from the management of a university project based on the author's QSAT project experience.

5.1. Fundamental Techniques

Nowadays, many useful modern project management techniques exist. Some papers provide examples of successful management by using these techniques effectively.[12]

These techniques are important in many projects. The concept of project management is constructed systematically to give the appropriate solutions for complicated problems that may be encountered in real projects. Every project manager has to understand that importance of these techniques and apply them to his specific project, appropriately. Generally speaking, these traditional project management methods are effective for large and complex project teams. On the contrary, for university projects, these methods would not always be effective, because there are important differences compared with real projects as mentioned in the next section.

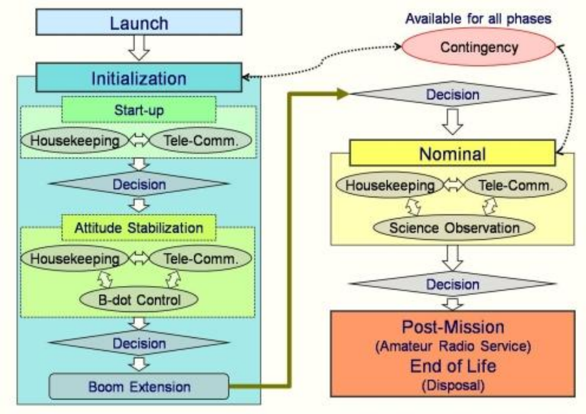

Fig. 3. Mission phases and satellite modes.

Table 4. Satellite mode definition

Mode	Describes
Housekeeping	Standard QSAT mode, basic operations are performed that are essential for survival
B-Dot Control	De-tumbling of the spacecraft
Tele-Communication	Mission data downlink, commanding, and uplink of software updates
Science-Observation	Acquisition of scientific data
Contingency	react to anomalies: power shortage, temperature levels, electronics unit troubles

5.2. Issues of University Projects

Table 5 shows the typical issues of a university project. The main issue is that most students have little or no practical experience. This issue is related to the student training. Usually, in the case of the university project, newcomers are joining the project every year. The senior students and faculty members have to take care of the training about not only the technical skills but also management disciplines for the newcomers. For a successful project, this training process should be defined systematically. The other important factor is the tolerance and permission to make mistakes. In many cases, the newcomers tend to make mistakes in their activities. Although the mistakes are undesirable issues for the project progress, it's necessary to learn the practical skills from the viewpoint of the student's training. When the project members make mistake, the manager must make sure that they learn from them and don't make the same ones again. Moreover, the manager has to coach the project members about the sources of problems and the meaning of their failures.

In addition, most students are not formally employed in the project. This is related to the management topic of student motivation-keeping. In the case of student management, the motivation factors should be understood by the manager, properly. For students, the important motivations factors are to be proud of our own work, to be interested in the assigned task, to feel achievement. If students were forced to work in the satellite project, it would be impossible to orient and keep the students' motivations. To distribute the proper tasks to the proper team member, the project manager must understand the member's personal biases including motivation and interests. Sometimes, psychological and sociological approaches may be needed.

Besides, most students have many activities like writing a thesis and/or classes. The period a student is engaged in a project could be shorter than the entire project lifetime. These issues are related to the task distribution and handover. As one of the solutions, considering the student life cycle, the manager should distribute the tasks.

Table 5. The Management issues peculiar to university project

Describes	Related Topics
Most students have little or no practical experience	Training, Teaming, and Study
The period a student engaged in a project is usually shorter than the entire project life time	Task Handovers
Most students are not employed in a project.	Motivation-keeping
Most students have multi-activities like a thesis and/or classes.	Task distribution

5.3. Key Concepts for Effective Management

This section describes some concepts for effective management in university projects. As mentioned in section 5.2, there are particular issues caused by the university environment. To cope with these issues, not only the techniques of project management but also the attitude and discipline of every project member need to be considered.

In most cases, the project team consists of different students like undergraduate students, graduate students (Master course, PhD course). The communicative environment and atmosphere should be set up by the senior students and faculty members before the kickoff of the project.

In a small-group development like a university project, it is necessary to take advantage of the small group characteristics (i.e., flexibility, direct and interactive work interface, easy communications among members). Of course, the project manager should be in the center of management for the entire project from the project kickoff to the end of mission. In addition, the delegation and empowerment of management activities to every member or every team should be conducted by the project manager, appropriately.

For example, in the case of the QSAT project, each team consists of a faculty and/or industry member and two or three students. We are conducting specific meetings for every team.

6. Conclusions

We focused on the university satellite projects that have spread all over the world in recent decades. We describe the characteristics of university satellites, mission categories, constraints of university satellite development, and examples of Japanese university satellite projects. Although the satellite mission may be very limited and focused compared with ‘real’ satellite missions, university satellite projects can provide good educational opportunities for students to learn valuable satellite engineering and management skills.

And furthermore, we introduce and describe the system design concepts for effective development and the characteristics and issues of project management based on QSAT (Kyushu satellite) project experience.

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