# Extensible Boom-Based Optical System for Nano-Scale Remote Sensing Satellite "PRISM"

Yuya Nakamura, Ryu Funase, Masaki Nagai, Akito Enokuchi,
Yuta Nojiri, Tsukasa Funane, Fumiki Sasaki, Shinichi Nakasuka
Department of Aeronautics and Astronautics, University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, JAPAN 113-8656; +81-3-5841-6608
{yuya, funase, nagai, enokuchi, nojiri, funane, sasaki, nakasuka}@space.t.u-tokyo.ac.jp

ABSTRACT: Intelligent Space Systems Laboratory (ISSL), the University of Tokyo is now developing the nano-scale remote sensing satellite named as "PRISM." This satellite aims at obtaining high resolution Earth images with 30m of ground resolution. Conventional remote sensing satellites have adopted reflective optical system using multiple mirrors to realize long focal length and large aperture. However, such system requires very high stiffness, machining accuracy and thermal management in order to maintain the designed light path. Thus we concluded that common reflective optical system cannot be applied to our nano-satellite, and adopted a totally different concept. PRISM deploys an extensible boom up to 800mm in space. The boom has a lens on its end, which realizes the desired long focal length. In other words, the boom works as a structure of telescope. Of course additional technological issues occur if we employ this methodology, such as how to keep focusing at the focal plane, and how to avoid the stray light coming into the optics. We are developing a kind of "auto-focus" system suitable for our nano-sized satellite, and light shade to be implemented on the extensible boom. PRISM is now at the engineering model phase, intending to be launched in 2006.

## INTRODUCTION

### *Our Previous Project – CubeSat XI-IV*

Intelligent Space Systems Laboratory (ISSL) succeeded in launching its first hand-made pico-satellite "CubeSat XI-IV" in 2003, and we have been operating it for more than two years. Through this CubeSat project we verified the availability of COTS-based electronic devices including the CMOS image sensor in space. The following images were taken by CubeSat XI-IV. Further information on our CubeSat project can be found at our web site.[1]

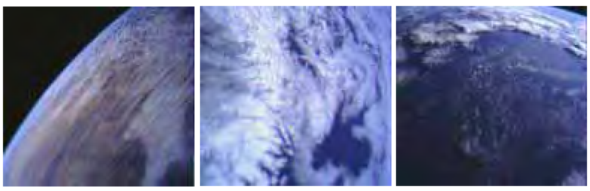

**Figure 1. Images by CubeSat XI-IV**

### *Motivation for a new generation nano-satellite*

Growing interest in the global environment requires more and more opportunities of Earth observation using satellites with lower cost. ISSL decided to start a next generation nano-satellite project with remote sensing mission after the success of CubeSat.

Several universities such as Surrey in the UK have already succeeded in developing remote sensing micro-satellites. However, the size of their satellites (50-100kg) is too large for us to develop in one laboratory level. What we pursue is the remote sensing mission by a nano-scale satellite whose mass is less than 5kg.

We named our new satellite "PRISM," which stands for "Pico-satellite for Remote sensing and Innovative Space Missions." PRISM aims to acquire Earth images with about 30m of ground resolution using the extensible boom-based optical system we propose here.

## OUTLINE OF PRISM PROJECT

### *Mission Overview*

Figure 2 illustrates the visual appearance of PRISM. One of the most characteristic points to this satellite is the extensible boom. PRISM deploys the boom up to 800mm in space, which enables PRISM satellite to obtain high resolution images by extending the focal length. The details on the optics and the extensible boom of PRISM will be hereinafter described.

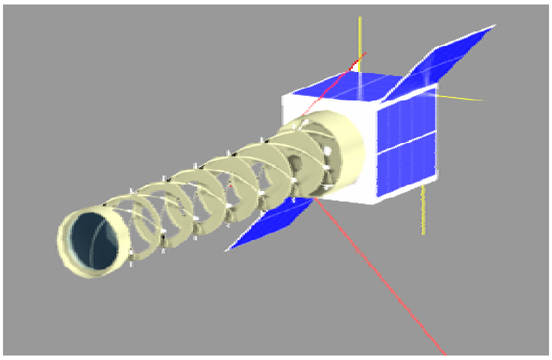

**Figure 2. Appearance of PRISM**

Main missions of PRISM can be summarized into the following three points.

(1) Establishing remote sensing technology for nano-scale satellites

It would be difficult for nano-scale satellites to obtain extremely high resolution images (less than 1m of ground resolution, for example) without further technological innovation. We do not pursue such high performance from the start of the project. If we can obtain relatively high resolution images (1m~50m) with a very low-cost nano-scale satellite, offering its images at affordable rates can become a promising business.

(2) Establishing technology to deploy a part of structure

As a piggy-back satellite, space-saving structure is attractive. Thus implementing deployable structure is a promising methodology to carry out various kinds of missions for small satellites.

PRISM deploys three parts of its structure. The first part is the extensible boom. It is indispensable for its remote sensing mission. The second part is solar array paddle. Deploying paddle doubles the generated electric power. The last part is antenna. Know-how of antenna deployment has been already achieved through our first CubeSat project.

Deploying structure, however, involves some degree of risk. To improve the reliability of deployment, we adopted the deployment mechanism making use of elasticity of the material itself, avoiding active actuation. Figure 3 is a conceptual rendering of the deployment of the extensible boom and the solar array paddles of PRISM.

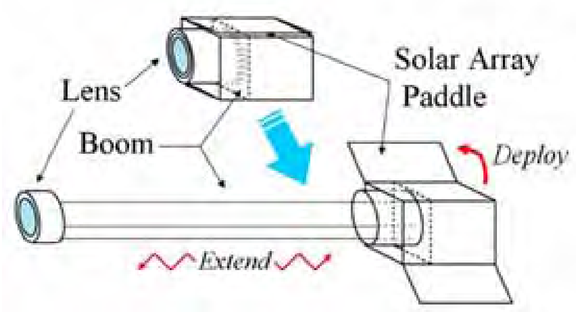


**Figure 3. Extensible Boom and Solar Array Paddles**

(3) Verifying improved bus technology

We adopted many kinds of new technology we did not use for CubeSat on PRISM bus system. CAN (Controller Area Network) inter-subsystem communication, three-axis active attitude control with magnetorquers, demonstration of a hand-made reaction wheel, high data rate communication (9600bps) and peak power tracking are their examples. Details are to be described in the latter part of this paper.

***Development of PRISM***

PRISM project consists of the following six subsystems, besides the ground station.

- Optics
- ADCS (Attitude Determination and Control System)
- C&DH (Command and Data Handling)
- Communication
- Power
- Structure & Thermal Design

Currently around 15 graduate and undergraduate students are engaged in PRISM project. We are now in the engineering fabrication phase, and the completion of the flight model is scheduled for next spring. We are looking for a launch opportunity in mid 2006.

## OPTICAL SYSTEM DETAILS

***Refraction-based Optical System***

In order to acquire high resolution Earth images, long focal length and large aperture are required. To achieve them, many conventional remote sensing satellites have adopted the optical devices mainly based on reflection using several mirrors. This kind of optical system is suitable for obtaining images of accurate resolution as pre-designed. Moving part is not necessary, and its reliability is also high.

However, the structure of optics requires very high stiffness and machining accuracy to manage the high-level request from the standpoint of optical design. Thermal control system may also have to be implemented to handle the thermal expansion or shrinkage of the structural material. In addition, reflective optical system requires much room inside the satellite. We cannot mount devices in the space where they intercept rays of light, and the optics and its peripheral devices will occupy the satellite internal room where otherwise can be used for implementing electronics or power equipment. Although this reflection-based optical system will realize high performance and reliability, it is likely to result in high cost and enlargement of the satellite size for above reasons.

Low cost is one of the most important goals for us, and we decided to adopt a completely different concept. PRISM selected the refraction-based optical system with a couple of lenses. That is, PRISM deploys an extensible boom with lenses attached to the tip of it in orbit. The boom extended up to 800mm works as a structure of telescope. This telescope-like extensible boom lengthens the distance between lenses and an image sensor, which can realize the desired long focal length within such a nano-sized satellite.

This optical system does not require high machining accuracy compared to the reflection-based system because the optical lenses are not position- and attitude-fixed to the main structure. We secure light path outside the main structure by deploying the extensible boom, and no internal-room-problem will arise on the refraction-based optical system of PRISM.

This refractive optical system has another merit. It is very tolerant of the deviation of the optical axis, while we need to compensate the deviation of the focal length. The deviation of the optical axis only results in the difference of the capture point and a little degradation of image quality. This may be critical for full-fledged remote sensing satellites. However we permit it to maximize the possibility of the success of our mission. If we adopted the reflection-based optical system, a slight position error of mirrors would cause the drastic degradation of image quality.

***Focal Length Compensation***

The deviation of focal length after the deployment of the extensible boom can be caused by various reasons mainly based on the flexibility of the boom. To avoid the degradation of image quality, we will install a focal length compensation system. The candidates are a micro stepping motor and a linear piezo motor. They move the electric circuit board on which the image sensor is mounted with a stroke of less than 5mm. We will adjust the position of the board by uplink or onboard in order to obtain focused images. Active feedback controller will not be implemented, because the distance between the lenses and the image sensor should not change significantly once the boom was deployed properly. This "auto-focusing" can be processed onboard by detecting the highest level of contrast.

**Table 1. Technical Data of the Linear Piezo Motor on the Table**

| **Item** | **Value** |
|---|---|
| Travel Range | Unlimited |
| Min. Incremental Motion | 0.1μm |
| Max. Speed | 800mm/s |
| Max. Push/Pull Force | 1N |
| Max. Holding Force | 2N |
| Weight | 10g |
| Operating Voltage / Current | 12V / 0.5A |

***Prevention of Stray Light***

Another concern about the extensible boom-based optics is the stray light coming into the image sensor. We prepared two measures against that.

The first one is the light shade covering the boom. Covering the entire boom is very difficult, and we decided to cover its root part with black light shade. To what extent the boom will be covered has been under active consideration.

The second one is the hole on the baffle disk to lead only the required light into the image sensor. The disk is originally used to enhance the rigidity of the extensible boom.

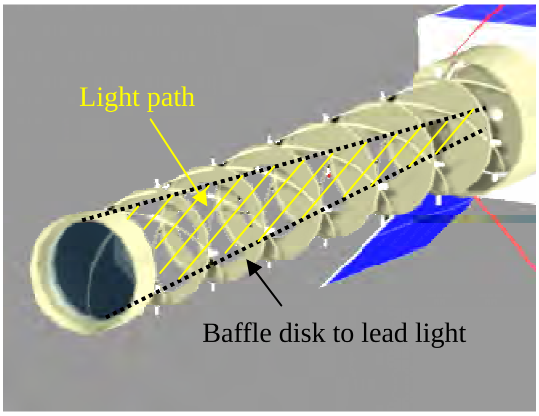


**Figure 4. Light Guide Baffle Disk**

***Optical Devices Specification***

PRISM has two kinds of cameras, NAC (Narrow Angle Camera) and WAC (Wide Angle Camera). Of course images using the extensible boom are captured by NAC.

For WAC, we use the same color CMOS image sensor as that of XI-IV. Its ground resolution is around 6km and the coverage area is about 600km at nadir view. WAC is to be installed at the side of NAC. Its wide field of view should catch the image of the extended boom inside it. Through images of WAC we can confirm the completion of the boom deployment. In addition, it can help us to identify where NAC captured.

**Figure 5. WAC Module**

NAC is the telephotographic camera system using the extended boom as the structure of telescope. Table 2 shows the specifications of NAC module and expected images.

SNR in Table 2 is calculated based on a possible sun-synchronous orbit at the altitude of 550km. CMOS imagers tend to have fixed pattern noise, and we are now designing the calibration system on ground. To realize the maximum value in the table, these calibrations should be perfectly successful. Additional calibrations in orbit may be required.

**Table 2. NAC Specifications**

| Item | Value | Remarks |
|---|---|---|
| Orbit Altitude | 550km | Estimation |
| Lens Aperture | 102mm | |
| Focal Length | 820mm | |
| Pixel Size | 6.7μm | |
| Photoelectric Conversion | CMOS | |
| Number of Pixels | 1280*1024 | |
| Quantization Level | 8bit | ADC: 10bit |
| Field of View | 0.6deg | 5km at ground |
| Ground Sample Distance | 9m | |
| Ground Resolution | 30m | Design value |
| SNR | 150 | Maximum value |

The collector optics for NAC consists of one group of apochromatic lenses made by fluorite, which are commonly used for telescopes. Color blurring can be compensated by using these multiple lenses.

***Image Processing***

The photo detector for NAC is COTS color CMOS image sensor with 1.3M pixels. A CMOS imager will be a better choice for nano-satellites than CCD, because driver circuitry for a CMOS imager tends to be simpler and the drive voltage to be lower. Low drive voltage enables a compact peripheral circuitry.

The product for NAC adopts Bayer pattern array. If we tried to obtain all image data without any compression, 1M byte data per image should be downlinked. However, most nano-scaled satellites have very low communication data rate. In the case of PRISM, it has only 9600bps data rate at the fastest. Thus we need to compress raw image data. JPEG or JPEG2000 compression methodology is to be implemented on PRISM to reduce the data amount to be downlinked.

## EXTENSIBLE BOOM DETAILS

### *Deployment Mechanism*

Before launch, the extensible boom is coiled and fixed to the main structure using clamps. The deployment will be conducted after receiving the specific command from ground. Unlocking the fixation, the boom starts extension by itself with its elasticity. Figure 6-8 describe this deployment sequence using the engineering boom model.

**Figure 6. Coiled Boom Model**

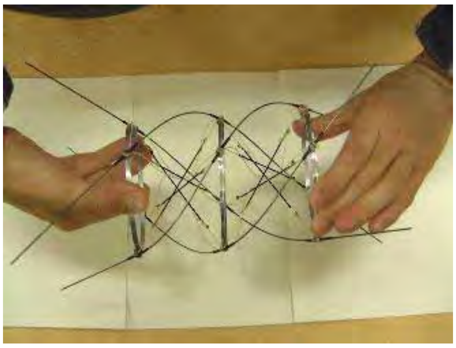

**Figure 7. Extending Boom Model**

**Figure 8. Extended Boom Model**

### *Materials and Structure*

As the material of longeron, we use GFRP (Glass Fiber Reinforced Plastics). It has high elasticity and small temperature coefficient. Note that we cannot use metal as the material of the boom, because a metal boom has an adverse effect on the RF performance.

In addition, we are going to use hemp line to prevent the complete extension of longeron. Longeron will stop extension with its elastic force remaining, which maintains the rigid boom. Figure 9 depicts the boom structure.

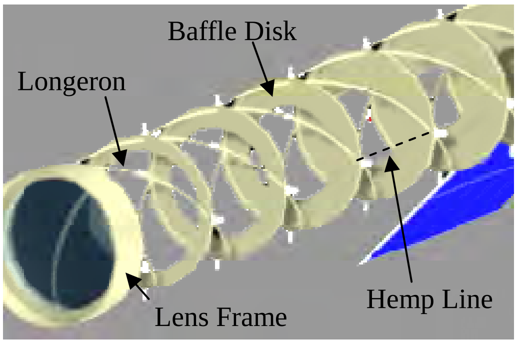


**Figure 9. Boom Structure**

### *Suppression of Boom Oscillation*

To obtain focused images, we should suppress the oscillation of boom structure. Structural damping can be effective, but it may not be enough in the direction perpendicular to the boom axis. Although the deviation of the lens position in that direction is acceptable to some extent due to the characteristics of the refractive optical system of PRISM, further measures should be required.

PRISM is capable of three-axis stabilized attitude control using three magnetorquers as actuators. Before capturing images, this attitude control will be activated to attenuate the oscillation.

## SATELLITE BUS SYSTEM DETAILS

### *ADCS*

ADCS controls the attitude of PRISM to satisfy the requirements from optics system. The extensible boom works as a gravity gradient boom, which lessen the burden of attitude control. However, attenuating the vibration will be still required.

We adopted magnetometers, gyros, sun sensors for attitude sensors, and magnetorquers for actuators. In addition, a hand-made reaction wheel is installed on PRISM for demonstration. For this reaction wheel, COTS flat type brushless motor is used to be put into the limited internal room of PRISM. Figure 10 shows the engineering model of the wheel. The diameter of this model is 65mm.

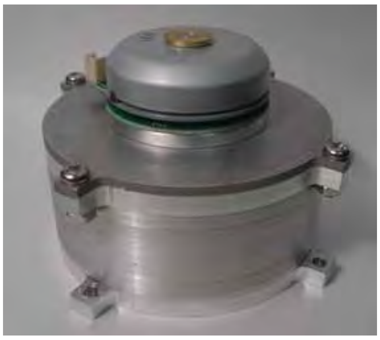

**Figure 10. Reaction Wheel Engineering Model**

ADCS will implement the following functions.

- Steering lenses at Earth

  It is possible that PRISM will be stabilized with lenses looking into the opposite direction after deploying the extensible boom. ADCS should recover such a situation. PRISM can find out whether if it looks into the correct direction or not by checking brightness of images taken by WAC.

- Attenuating oscillation

  In order to obtain high resolution images, PRISM should stop its motion as long as possible with respect to the surrounding space at the moment of image capturing.

- Steering in the desired direction

  ADCS tries to achieve this technology as an advanced mission. PRISM is always staring at nadir direction only with the attitude control to attenuate oscillation. By controlling its attitude and steering PRISM in the desired direction, PRISM will be able to capture the horizontal line of Earth or other astronomical objects such as the Moon.

### *C&DH*

C&DH system has the following functions.

- Interpreting and processing uplink commands
- Health monitoring
- Generating telemetry data for downlink
- Mutual monitoring with power system

  To enhance the survivability of the satellite, mutual monitoring between C&DH and power system is implemented. If an anomaly occurred in C&DH, power system will detect it and restart C&DH and vice versa.

- Storage of mission data

  Large amount of image data should be stored onboard. High-capacity flash ROM is used for this purpose instead of the serial EEPROM used on XI-IV.

- Task management using RTOS (Real Time Operating System)

  Functions of C&DH, ADCS and optics system are implemented into one chip. Management of multiple tasks is realized using RTOS.

### *Communication*

PRISM has three transmitters and two receivers.

They are custom-made models by a Japanese maker. One of three transmitters has been newly developed for PRISM, mainly used for transmitting image data. Its modulation type is GMSK. The other transceivers are the same products as those used on XI-IV.

PRISM is equipped with two receivers, and one of them will be for additional missions. At present we are planning to let ham operators uplink messages. Table 3 depicts the specifications of transceivers installed on PRISM.

**Table 3. Transceiver Specifications**

| | TX 1 | TX 2 | CW | RX |
|---|---|---|---|---|
| **Freq. Band** | 460MHz | 430MHz | 430MHz | 144MHz |
| **Modulation** | GMSK-FM | AFSK | Morse Code | AFSK |
| **RF Power** | 2-3W | 800mW | 100mW | --- |
| **Data Rate** | 9600bps | 1200bps | 50wpm | 1200bps |
| **Antenna** | Turnstile | Dipole | | Monopole |

***Power***

Power system takes charge of power supply to each subsystem, power management, and mutual monitoring with C&DH. Although we had no CPU for power system on XI-IV, a H8 microprocessor will be used on PRISM in order to deal with the complicated power management and the peak power tracking (PPT) mission. PPT is said to be a promising technology for small satellites, for one of the most critical factor limiting capabilities of small satellites is the electric power supply.

We use GaAs type solar cells, whose conversion efficiency reaches up to 25%. PRISM is also equipped with two solar array paddles to boost power generation significantly.

Lithium polymer type was chosen for the rechargeable batteries. This type of secondary batteries is relatively new even on ground. PRISM tries to verify its availability in space.

## CONCLUSIONS

PRISM is the second small satellite project for Intelligent Space Systems Laboratory. The main mission of PRISM is high resolution remote sensing. We try to obtain images with 30m of ground resolution within a nano-sized satellite.

To realize the long focal length required to obtain high resolution images with a nano-satellite, we proposed a new type of refractive optical system. That is, the satellite deploys the extensible boom with lenses at the tip of it. This mechanism lengthens the distance between lenses and an image sensor, without extremely high machining accuracy.

PRISM has many missions as a nano-sized satellite besides remote sensing, such as the verification of structure deployment mechanism and reinforced bus technology.

PRISM is now in the engineering fabrication phase, and the flight model is scheduled to be completed by next spring, intending to be launched in 2006.

## ACKNOWLEDGMENTS

One of the authors (Y. Nakamura) was supported through the 21$^{st}$ Century COE Program, "Mechanical Systems Innovation," by the Ministry of Education, Culture, Sports, Science and Technology.

PRISM project at the University of Tokyo ISSL is financially supported by UNISEC (University Space Engineering Consortium).[2]

## REFERENCES


1. CubeSat Web Site: http://www.space.t.u-tokyo.ac.jp/cubesat/
2. UNISEC Web Site: http://www.unisec.jp/
3. PRISM Web Site: http://www.space.t.u-tokyo.ac.jp/prism/
4. Yuya Nakamura, Shinichi Nakasuka, et al., "University of Tokyo's Ongoing Student-Lead Pico-Satellite Projects –CubeSat XI and PRISM–," IAC-04-IAA-411.4.06, 55th International Astronautical Congress, Vancouver, Canada, October 2004.