Space Camera Development Using COTS Technologies

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It is becoming imperative to have visual capabilities forspace activities. There are increasing opportunities to use visual images coupled with image processing technologies for spacecraft sensing and control. To fill this need, we have developed a small, low-cost, high-performance image acquisition and processing unit (HP-IMAP), which uses commercial off-the-shelf technologies. In this paper, we describe the HP-IMAP and discuss its qualification tests.

民生具品を活用した宇宙用カメラの開発

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衛星の形態やミッションが複雑になるに従い、搭載機器の状況を監視する監視カメラへの要求が高まってきている。展開構造物の状況確認や、ロボット操作の手先の状況監視など、多岐にわたる。カメラがより小型になればその需要はさらに広がると思われる。本発表では民生部品を効果的に活用することで構成した、超小型分散監視カメラシステムの概要を紹介する。

1. Introduction

Recently, there has been a growing need for the development of advance visual monitoring of spacecrafts operating in space. With recent advances in space system design and increasingly complex spacecraft and mission objectives, both telemetry and visual data are important for monitoring such systems1-4). In addition, visual capabilities can be used for sensing (e.g., star sensors 5-7)), and such data obtained can serve educational purposes. Small satellites, including some designed by universities, have become increasingly popular, and in such cases, having visual capabilities is considered to be important for educational purposes. Therefore, small, low-cost space cameras are required for various applications.

The Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS) spacecraft was launched on May 21, 2010; its mission is to evaluate the performance of solar power sails, which are large membranes that use sunlight for propulsion8). In addition to acceleration by solar radiation, a solar power sail obtains power from thin-film solar cells. When the sail is completely deployed, the size of IKAROS is significantly large; therefore, it is important for its status (e.g., orientation/alignment) to be visually monitored. Therefore, high-resolution images are desired for detailed monitoring and analysis of the deployed structure. However, transmission bandwidth available for such image processing and analysis is limited.

In general, there are limited resources available for implementing a visual monitoring system in space because in spacecraft design, parameters such as size, weight, and cost are strictly regulated. Particularly for IKAROS, because images of the entire spacecraft must be acquired using a small camera that can be ejected from the spacecraft, the camera must be as small as possible. Moreover, a high-performance processor is required for the monitoring system in order to enable image processing and compression prior to downlink transmission, because the available communication bandwidth for IKAROS is very limited. Therefore, the visual monitoring system for IKAROS must be small, low-cost, and intelligent.

We have developed a very small, high-performance image processing unit that is based on COTS technologies. It has a calculation capability of 500 million instructions per second (MIPS) in a single 50 mm × 50 mm printed circuit board, and it incorporates various interfaces using field-programmable gate array (FPGA) technology12). Using this image processing unit, we have developed a small, low-cost camera with image processing capabilities for spacecraft. The camera is called the high-performance image acquisition and processing unit (Fig. 1).

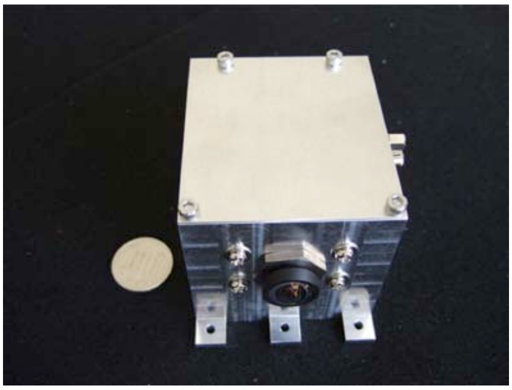

Fig. 1: High-Performance Image Acquisition and Processing unit (HP-IMAP)

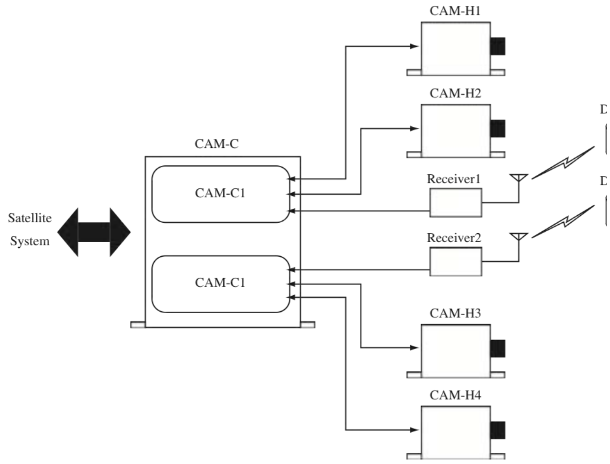

Fig. 2: System Structure of HP-IMAP for IKAROS

On the basis of HP-IMAP technology, we have subsequently developed a visual monitoring system for IKAROS, called the "HP-IMAP for IKAROS." This system acquires high-resolution 360 degree panoramic images of the deployed membrane using four high-resolution cameras known as CAM-H, while it acquires images of the entire spacecraft using two extendable cameras known as DCAM. The HP-IMAP for IKAROS was launched on IKAROS and has successfully supported IKAROS operations. Using the DCAM, we have obtained the world's first images taken by spacecraft itself. In this paper, we describe the HP-IMAP for IKAROS and present results obtained by demonstrating this technology on IKAROS.

2. Image Acquisition and Processing System (HP-IMAP) for IKAROS

2.1 System Structure

HP-IMAP for IKAROS consists of three units: CAM-C, CAM-H, and DCAM (Fig. 2). The CAM-H is a camera head fixed on the body of IKAROS for capturing high-resolution fixed-point images of the deployed membrane. In the HP-IMAP for IKAROS system, four CAM-H cameras, each having an angle of view greater than 100 degrees, are configured to face four directions. A panoramic view of the entire deployed structure can therefore be acquired using these four cameras. The CAM-C is a central controller for the HP-IMAP, and its most important function is to serve as a command and telemetry interface between the HP-IMAP and satellite bus system. It also manages power conversion from the satellite bus power line to the HP-IMAP and power supply control. The CAM-C uses two channels, which can be increased to a maximum of 12, for capturing analog video. NTSC analog video signals that are transmitted from the DCAM are converted into digital images. The CAM-C can also record data and is equipped with a 1-Gbyte SD memory card for storage of the acquired and processed images.

IKAROS has a flexible deployable structure, and for acquiring images of the entire structure while in orbit, we use the DCAM which when extended from the body of the satellite in orbit, acquires a complete image of IKAROS. Once the DCAM is extended, the images captured by it can be transmitted to the CAM-C using a wireless link. The size of the DCAM must be small enough to ensure that its extension does not affect the satellite's main structure. Therefore, UHF analog frequencies are adopted for transmission of the images from the DCAM to CAM-C. The acquired images are encoded into the NTSC analog video signal in the DCAM and the CAM-C decodes the analog video signal into a digital data stream. This structure is similar to that of a wireless monitoring system.

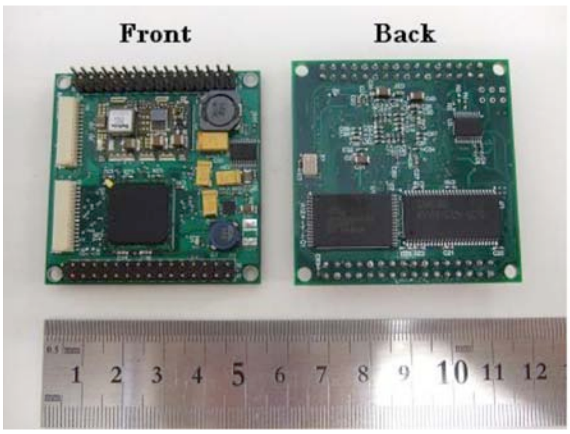

Fig. 3: T he processor board microprocessor unit,

2.2 Modular Design of the Processing Board

To efficiently develop high-performance processing capabilities, both CAM-H and CAM-C are equipped with the same processing board by using FPGA technology and open source software.

The processor board microprocessor unit was implemented using a Xilinx CPU core FPGA Virtex-II Pro (Fig. 3). Using the flexibility of FPGA's peripheral interface, we achieved 500-MIPS calculation capability and 64-Mbyte synchronous, dynamic, random access memory in a 50 mm × 50 mm processor board. We also installed an 8-Mbyte flash memory chip for programming and operational system storage (Fig. 4). Furthermore, FPGA enables

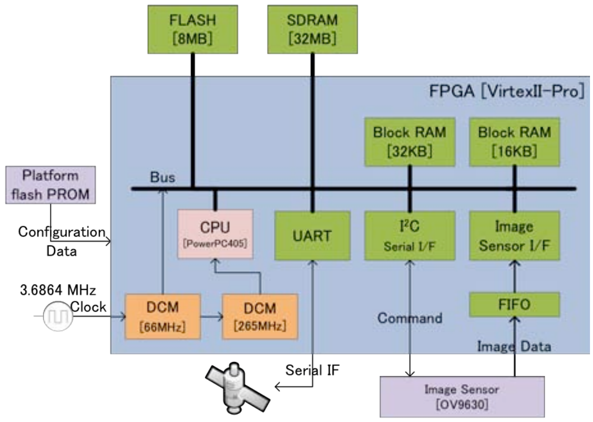

Fig. 4: Block Diagram of HP-IMAP

the processor board to support various protocols for the imager interface and for interfacing with satellite systems. The optimum interface can therefore be selected depending on the satellite system. We are experienced with the installation of universal synchronous/asynchronous receiver/transmitter (USART), controller area network (CAN), inter-integrated circuit (I2C), system packet interface (SPI), and Ethernet interfaces.

Incorporating an operating system for the built-in computer system greatly increases software productivity, although considerable memory and computational resources are consumed for the processing. Device drivers and function calls enables us to call complex functions using simple statements, while a cross-platform operating system enables us to use software resources from different platforms.

Regarding the use of software, COTS technology effectively enhances software performance while reducing cost. We use the Linux operating system, which is one of the most commonly used free operating systems, for the image processing unit. For HP-IMAP, from among the various free software resources developed for Linux, we installed the free software applications for JPEG compression and binary data compression. In addition to the original applications and device drivers that were developed in-house, we can utilize other resources such as documentation on the Linux operating system. These resources and free software therefore help reducing the development costs, work load, and development time for the on-orbit system.

2.3 CAM-H

In general, the customized design and development of optical systems are costly, so we preferred to use the relatively less expensive COTS camera lenses for the on-orbit camera. However, when using COTS camera lenses in orbit, we must consider the problems of contamination and degradation that may result from outgassing and poor mechanical durability.

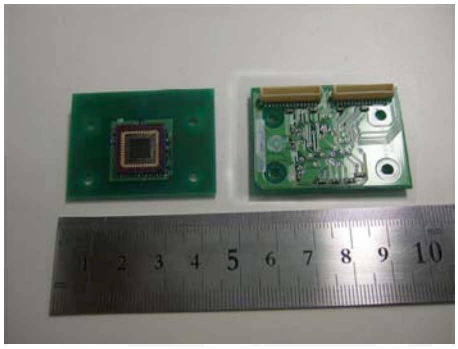

Fig. 5: Imager Board

Small COTS cameras often use plastic in the design of lenses and structural parts. However, under ultravacuum conditions, the solvent that is present in the plastic material may evaporate (i.e., outgas), thus resulting in degradation of the material. Optical performance and transparency are adversely affected by outgassing, especially in case of plastic lenses. The solvent that evaporates may contaminate and damage other components, especially other optical sensors.

Sakai Glass Engineering Co. Ltd. supplies a series of board-camera lenses that are made of glass and metal and not plastic. Therefore, outgassing or degrading of lenses in an ultravacuum environment is avoided. Because several types of lenses are aligned within the focal length, and the F factor is based on the same mechanical interface, the specifications of the optimal lens can be selected according to the application.

To make the camera mechanically durable using a simple structure, the camera wall is designed to serve as the lens tube. Because the focal length of the board-camera lens is rather short, using the camera side wall as a lens tube increases the side wall thickness up to a maximum of 10 mm. The side of the lens cylinder is equipped with M13 pitch, single-thread screws. The lens is attached to the camera wall using double nuts to prevent lens motion and maintain the focal length. The lens hole in the camera side wall remains securely fixed in position because the four side walls and the camera flange are made from a single aluminum block by scraping out the interior of the camera body. In addition, the small lens mass and the lens position with respect to the camera board affect mechanical durability, as verified by vibration tests.

A mega-pixel CMOS imager OV9630 is installed at the center of the imager board (Fig. 5). The imager board is connected to the processor board via the imager data lines and the I2C control-interface line. Because we have developed several types of imager boards using the same electrical and mechanical interfaces to the processor board, the best imager may be selected based on the mission's requirements. For example, a high-speed global shutter imager board can be used to capture fast motion, and a high mega-pixel imager board can be used for high-resolution applications. For applications

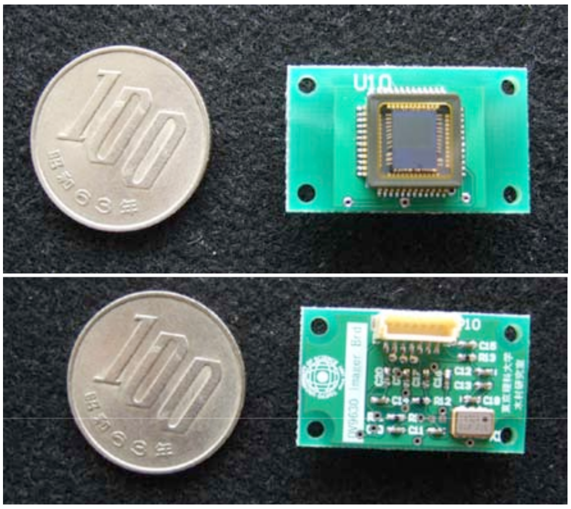

Fig. 6: Analog Imager Board

requiring very high resolution, such as Earth observations, an 8 mega-pixel imager may be used.

2.4 DCAM

DCAM is ejected from body of IKAROS and gets whole images of IKAROS. The camera separation system consists of a separation mechanism and the DCAM. As the separation mechanism rotates, the DCAM extends away from the satellite frame. The separation mechanism also acts as a receiver for UHF data images transmitted by the DCAM. The data is demodulated into an analog video signal and is then passed on to the CAM-C analog video decoder. Two camera separation systems are installed on the top surface of IKAROS. Each DCAM camera can be individually extended. Because the DCAM extends from the satellite's body, it should be small enough to prevent any negative impact on the satellite's weight distribution or rotation.

The DCAM's function is to convert captured digital images into NTSC video signals, which are then transmitted via UHF frequencies. The OV7950 CMOS imager, which is capable of converting digital images into NTSC video signals using one chip, is adopted for this function. The OV7950 CMOS imager is widely used in automotive applications and is suitable for operation over a wide temperature range. OV7950 a 1.6 cm × 2.8 cm tiny imager board was developed using OV7950 imager and installed in the DCAM (Fig. 6). Once power is supplied, the imager board automatically transmits the NTSC video signal in an optimal image acquiring mode. The board automatically adjusts the luminescence level and the white balance.

2.5 CAM-C

To achieve a redundant structure, CAM-C consists of two sets of the same functional unit, CAM-C1 and CAM-C2 (Fig. 7). Each unit consists of three boards: the processing, power, and interface boards.

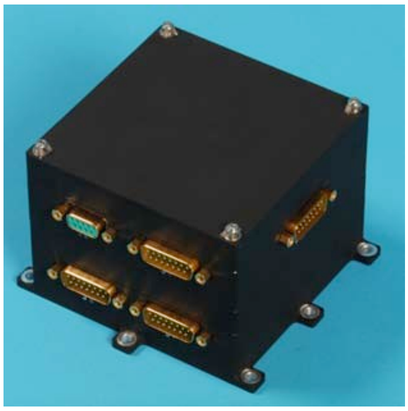

Fig. 7: CAM-C with two sets of the same functional unit.

As mentioned above, the processing board is the same as CAM-H, and it is equipped with an additional interface function based on the FPGA technology.

The power board manages voltage conversion and stabilization from the satellite bus power line to the 5V HP-IMAP system. The power board also manages the power on/off function for both CAM-H and DCAM depending on the signal from the processing board.

The interface board has two functions: (1) a serial interface between the CAM-H and satellite mission processor (MP), and (2) an analog video interface with the DCAM. With respect to the serial interface, a 57600 bps UART base low-voltage differential signaling interface is equipped with five channels. Each unit has two channel interfaces for the CAM-H and one channel MP. The decoder chip ADV7180 is adopted for the DCAM. A 1-Gbyte SD memory card is also placed on the interface board and is connected to the processing board through an SPI interface.

3. RESULTS

3.1 CAM-H

After the IKAROS was launched, more than 1000 images successfully captured by CAM-H. Fig. 8 show examples of images captured by CAM-H. These images act very important roles to decide operation of IKAROS.

3.2 DCAM

DCAM1 and DCAM2 are ejected in June 14 and June 19 respectively. Fig. 9 show examples of images captured by DCAM. Combination of DCAMs and CAM-C successfully capture sequences of images in almost one frame per second. Part of images shows saturation in luminescence level according to sun direction to the membrane, it can be reduced by the luminescence level adjustment algorithm

4. CONCLUSION

Using the COTS technologies, we developed a small, low-cost camera called the HP-IMAP that includes image processing capabilities for spacecraft. The HP-IMAP technologies are being utilized in IKAROS, which was launched on May 21, 2010. IKAROS became the world's first successful solar power sail craft that uses both photon propulsion and thin-film solar power generation during its interplanetary cruise. HP-IMAP technologies are being used successfully to acquire images of IKAROS and support its operations.

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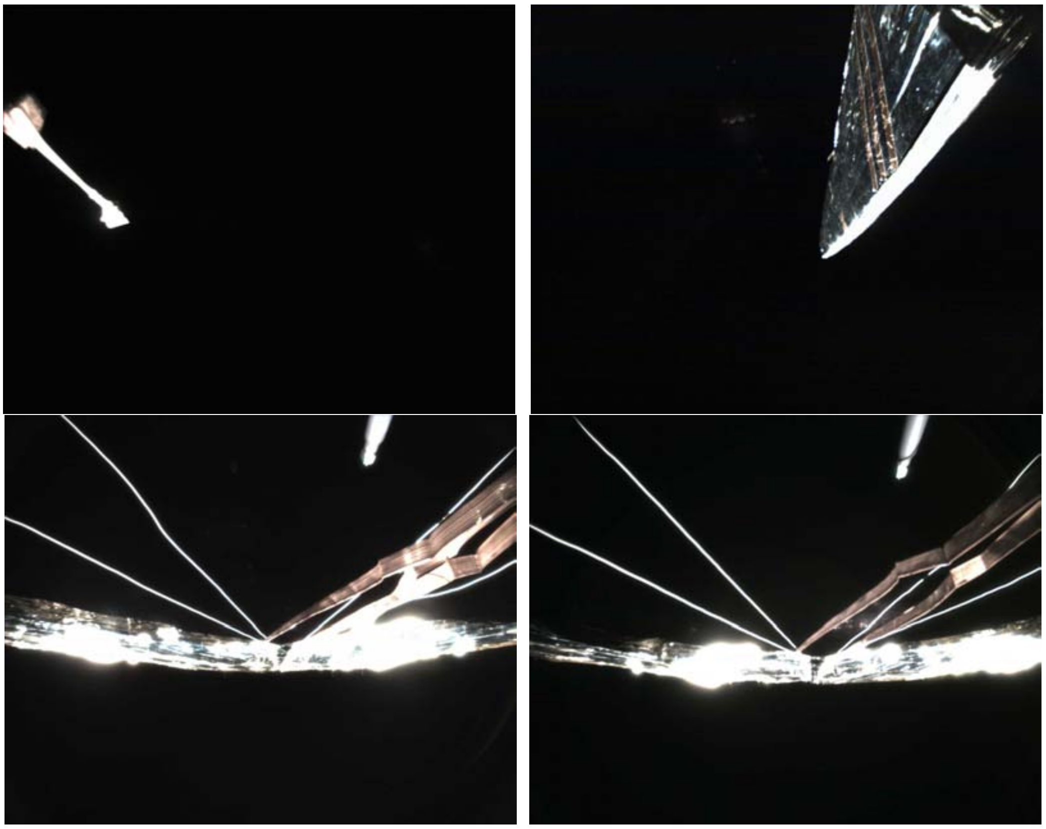

Fig. 8: Examples of Images Captured by CAM-H

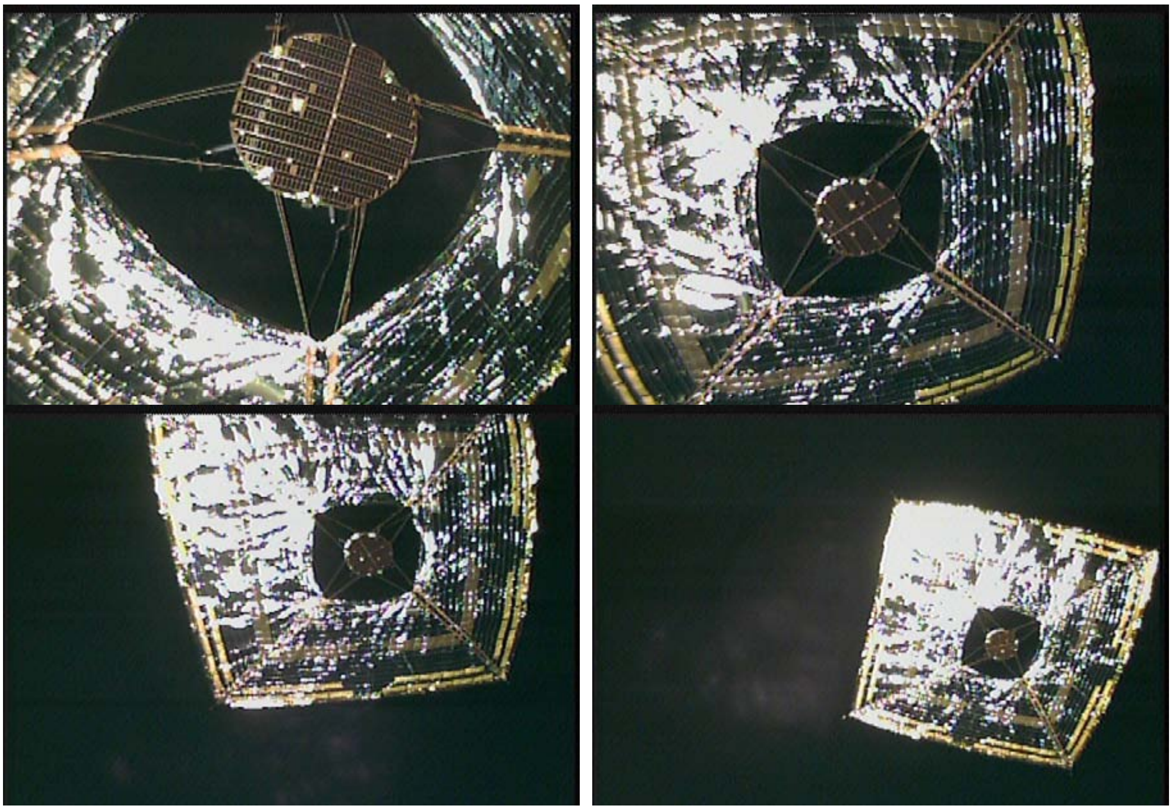

Fig. 9: Examples of Images Captured by DCAM