HIGH-PERFORMANCE IMAGE ACQUISITION AND PROCESSING SYSTEM FOR SPACE DEBRIS MITIGATION

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ABSTRACT

Recently, problems involving space debris have become more serious. According to NASA, the volume of space debris is projected to increase, even if no new satellites are launched. Therefore, debris-removal satellites must be developed immediately. A mandatory function of a debris-removal satellite is to recognize and approach the target debris. Thus, visual guidance using image processing is being considered as an effective means of guiding debris-removal satellites toward unresponsive targets. A small satellite is suitable as a debris-removal satellite; however, because of weight and/or size limitations, the installation of certain cameras in small satellites is difficult. Thus, we have developed a compact camera system that can perform on-board image processing, by expanding the functionality of an existing camera system to enable it to acquire the multidirectional images required during the satellite-debris rendezvous process. To overcome these difficulties, we have developed a compact camera system called KITE-CAM that can perform on-board image processing. Further, we demonstrated its performance on the H-2 transfer vehicle (HTV) as part of an electrodynamic-tether (EDT) experiment. Based on the experimental results of the KITE-CAM, we developed an image acquisition and processing system for space debris mitigation for an on-orbit demonstration. In this paper, the outline of the image acquisition and processing system for space debris is introduced and compared with the KITE-CAM.

1 INTRODUCTION

In recent years, problems associated with space debris have become more serious, as space development has become more active. Furthermore, because collisions among existing debris generate new items of debris, the volume of space debris is projected to exponentially increase, even if no new satellites are launched. If these fragments collide with the International Space Station (ISS) or other satellites, serious problems will arise. In fact, impact damages have already been observed on the ISS.[1] Thus, the management of spacecraft activity in orbit is difficult without debris surveillance. Further, according to a research conducted using the NASA long-term debris evolutionary model, LEGEND, it is necessary to remove five large-sized items of debris per year to maintain the current space environment.[2] Therefore, satellites for debris removal must be developed immediately. Owing to such a critical situation, not only the governmental public approaches but also commercial private approaches have emerged.

An imperative function of a debris-removal satellite is to autonomously recognize and approach the target debris by sensing its distance and movement. The debris-removal satellite cannot be expected to communicate with the debris; further, owing to additional communication limitations, the real-time remote operation of the debris-removal satellite from ground stations is impractical. Thus, visual guidance using image processing is being considered as an effective method of guiding debris-removal satellites toward unresponsive targets. For example, image processing can be used to estimate the distance between a debris-removal satellite and the items of debris, or to estimate the debris movement.

A small satellite is suitable as a debris-removal satellite, because it can be realized at a very low cost and within a short period. In addition, small satellites are often equipped with a camera for situation monitoring, and such satellites have many launching opportunities. However, because of the weight or size limitations, the installation of certain cameras in small satellites is difficult.

To overcome these difficulties, we have developed a compact camera system called KITE-CAM that can perform on-board image processing. Further, we have demonstrated its performance on the H-2 transfer vehicle (HTV) as part of an electrodynamic-tether (EDT) experiment.[3]-[6] In debris-removal operations, the rendezvous process has two phases: the debris-removal approach phase, which requires high-resolution images to acquire detailed information about the debris, and the homing phase, which requires wide-area images to locate debris over a large area. Therefore, the developed camera system can perform two types of real-time image processing, using the HRCAM (High Resolution CAM) or WACAM (Wide Area CAM). In the context of the HTV mission, the estimation of the tether–endmass distance during the tether–endmass ejection was planned using the HRCAM; this corresponds to the debris-removal approach phase. The second operation involved tether motion recognition to detect a marker attached to the tether; this operation required the use of the WACAM and corresponded to the target recognition and orbit estimation processes during the homing phase of a debris-removal mission. Using this camera, we acquired images of the ISS, when the HTV rendezvoused with the ISS. [6]

Based on the experimental results and heritage of KITE-CAM, in cooperation with Astroscle, we developed an image acquisition and processing system for space debris mitigation for an on-orbit demonstration. Utilizing the advantages of KITE-CAM as much as possible, the new system is improved in the following three aspects:

1) Improvement in resolution utilizing 3M pixel monochrome imager.

2) Improvement in acquiring frequency and real-time performance.

3) Improvement in image processing capabilities by combining FPGA and software.

Herein, the outline of the image acquisition and processing system for space debris is introduced and compared with the KITE-CAM heritage.

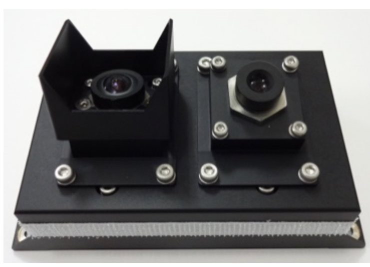

Figure 1: KITE-CAM.

2 KITE-CAM

2.1 Structure

As mentioned above, the two phases of the rendezvous process, i.e., the debris-removal approach phase and the homing phase, require high-resolution images to yield detailed information on the debris and wide-area images to locate debris over a large area, respectively. Owing to the applicable weight or size limitations, however, the installation of certain cameras in small satellites is difficult. Thus, for compactness, the camera system should employ a single processing system that controls the two image lens systems (HRCAM and WACAM). Using a single processing system simplifies the electrical interfaces of the data handling unit, the telemetry and command interface, and the power conditioner unit. To control both of these image lens systems via the processing system, the developed camera system utilizes an IF board. Fig. 2 shows the "KITE-CAM"; the system specifications are listed in Table 1.

Table 1. KITE-CAM specifications.

Size (excluding optics)	124 × 66 × 32 [mm^3]
Mass	0.35 [kg]

The KITE-CAM missions can differ widely in terms of target, distance, or direction. Thus, we designed and developed image lens systems that can be employed in each scenario through the application of image processing techniques.

For example, during the tether–endmass ejection, the endmass is first imaged at distances of up to 100 m from the HTV. High-resolution images are required to allow the estimation of the tether–endmass distance from the endmass area. Therefore, the HRCAM image lens system is equipped with a telephoto lens with an 8-mm focal length, and its optical axis is inclined by +10°.

Next, markers within 2 m from the base of the tether are imaged. Wide-area images are required to allow the tether to swing by ±60° in the orbit plane. Therefore, the WACAM image lens system is equipped with a wide-angle lens with a 2-mm focal length, and its optical axis is inclined by -15°.

Table 2. KITE-CAM optics specifications.

	HRCAM	WACAM
Focal length	8 [mm]	2 [mm]
Row resolution	1280 [pixel]	
Column resolution	1024 [pixel]	
Vertical field-of-vision (FOV)	37.087 [°]	106.606 [°]

2.2 Electrical System

The developed camera system has the two image lens systems described above, and employs an IF board to control these systems using a processing system. The wiring is reduced compared to the IKAROS design through using a serializer and deserializer, and alternates between the two image lens systems via a bus switch. Fig. 3 shows the system diagram.

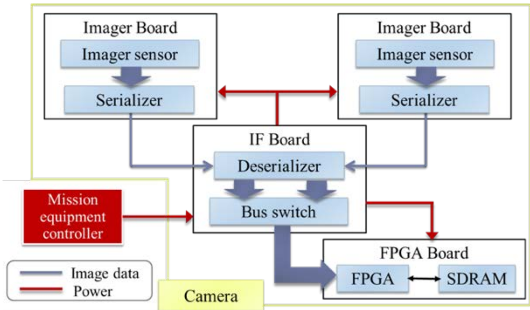

Figure 2: System diagram. FPGA: Field-programmable gate array; SDRAM: Synchronous dynamic random access memory.

The two image lens systems contain the same type of imager board. The image sensor (OV9630, OmniVision) is identical to that used in IKAROS. The IF board is equipped with deserializers and bus switches.

Fig. 4 shows the field-programmable gate array (FPGA) board. A Xilinx FPGA Virtex-2 Pro is employed as the primary camera processor. The reliability of this FPGA has been proven on the IKAROS mission. The logic synthesis file of the FPGA is based on the IKAROS camera and is modified to suit the KITE-CAM IF board. This FPGA board can connect to the IF board in a 5-mm stack.

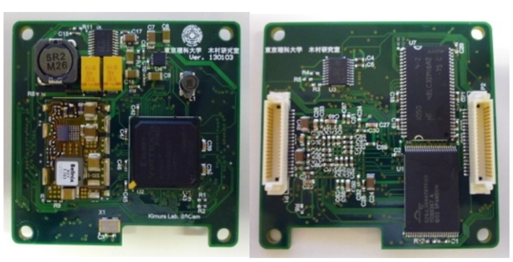

Figure 3: FPGA board

2.3 Software Development Environment

The Linux (Kernel 2.4) OS is employed in the image processor. Linux is highly flexible and various free open-source applications can be utilized effectively with this OS, which can shorten the development period. In addition, using a memory management unit and Linux, which are installed in the central processing unit (CPU), can ensure powerful memory protection and prevent the sudden destruction of important data.

3 IMAGE ACQUISITION AND PROCESSING SYSTEM FOR SPACE DEBRIS MITIGATION

3.1 Improvement in Resolution Utilizing 3M Pixel Monochrome Imager.

In the KITE-CAM, we adopted the 1 Megapixel OV9630 imager because the OV9630 is space proven in various forerunning missions such as the IKAROS. The imager resolution is essential for the image acquisition. Especially in visual guidance and navigation, the resolution of the imager affects not only the identification resolution of the target but also the sensitivity in long distances or very small targets. Moreover, the dithering process also affects and decreases the image resolution because the OV9630 is a color imager using a Bayer pattern filter.

Meanwhile, we qualified a monochrome 3 Megapixel imager using a radiation qualification test and successfully obtained its radiation tolerance performance. Therefore, we decided to utilize the 3 Megapixel monochrome imager to improve the image resolution. We developed a camera head board using the imager in the same interface. Because almost all interfaces such as the mechanical, optical, and electrical interfaces are the same as the previous OV9630 imager board, we can select each board according to the application requirements.

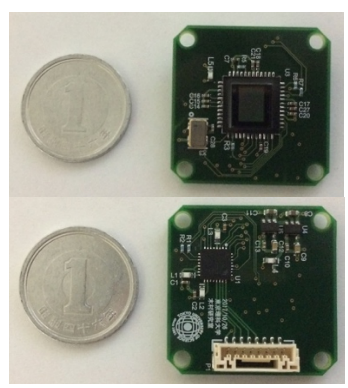

Figure 4: 3M pixel camera head board

3.2 Improvement in Acquiring Frequency and Real-time Performance.

Based on the KITE mission requirement, the image capture timing of KITE_CAM is controlled by a CPU based on a time scheduler. However, in some cases, such architecture causes timing overhead and we could not increase the capturing frequency because the time scheduler timing is not perfectly synchronized with the image capturing timing of the imager. Moreover, because we are to design and tune the capture timing using software, it is difficult to maintain the real-time feature of the image to be captured.

Therefore, to improve real-time feature of the capturing process and to ease the software design, we designed the capturing process to slave the image frame signals of the imager and the software process is also evoked by the interruption of the image frame signals. Using such architecture, we can easily harmonize image capturing in the imager and image processing, and maximize the image capturing frequency.

3.3 Improvement in Image Processing Capabilities Combining FPGA and Software

In a KITE mission, the image processing requirement is rather simple, such as target position identification or target size identification. In the case of visual guidance and navigation applications, the system is to cover various types of processes such as motion estimation and orbit identifications.

To meet these requirements, we used an FPGA for part of the image processing, thereby combining hardware logic and software logic for the image processing. An FPGA can realize various processes in hardware logic by coding using the hardware definition language and its performance is much better than that of software coding. Therefore, if we implement part of the image processing logic as a pipeline process during image data transmission, we can execute the process at high speed and the CPU need not perform these image processing processes.

We implemented a rough target identification process using a histogram analysis in the FPGA during the image data transmission process. Therefore, the CPU can be dedicated to higher-level image processing processes such as shape and feature point identification or motion and orbit determination.

4 CONCLUSION

In this paper, the outline of an image acquisition and processing system for space debris is introduced and compared with the KITE-CAM heritage. The system is expected to demonstrate its visual guidance and navigation performance in space-debris mitigation demonstration missions.

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