Space Telemetric Panomorph Imaging System for micro/nano Satellite

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ABSTRACT

For many years, many microsatellites (satellites in the 10-100 kg mass range) and nanosatellites (in the 1-10 kg mass range) missions have been designed, built and launched having the objective of technology demonstration. Recently, due to the advance of technologies over the past decade, a new trend is to use them in more demanding space missions such as space science, earth observation, flying formation and space surveillance. In micro/nano satellites applications, the need for size, mass, power consumption and cost reduction is critical. This is why there is an effort toward the development of specialized and integrated hardware. Among space hardware for satellites, the development of optical imaging payload and miniaturized attitude sensors are of great interest for space surveillance and space science applications.

We proposed the development of a panomorph lens optical module designed to record wide and broadband images of a panoramic scene around the satellite. A key requirement of the optical module is therefore to be able to manage the field coverage properties to distinguish true element that can be used for star tracking, earth horizon sensing and related tracking functionalities. The optical module must provide all usable telemetric information for the satellite. The proposed technology consists of a concept of space telemetric imaging system, which will combine optically imaging for surveillance/visual monitoring of space and attitude determination capabilities in one compact and low-power consumption device for micro/nano satellite applications.

Keywords: Space telemetry, micro satellite, panomorph lens, nano satellite, attitude determination

1. INTRODUCTION

For many years, many microsatellites (satellites in the 10-100 kg mass range) and nanosatellites (in the 1-10 kg mass range) missions have been designed, built and launched having the objective of technology demonstration. Recently, due to the advance of technologies over the past decade, a new trend is to use them in more demanding space missions such as space science, earth observation, flying formation and space surveillance. Several planned and launched missions, such as XMM, SNAP-1, CanX-1 and 2, MOST, BRITE, CHIPSat, ION-F, which are developed by space civilian, military and university organisations have used or plan to use as payload imaging sensors for visual telemetry, Earth imaging, astronomical observation and for attitude determination applications [1,2,3,4,5,6].

In micro/nano satellites applications, the need for size, mass, power consumption and cost reduction is critical. This is why there is an effort toward the development of specialized and integrated hardware. Among space hardware for satellites, the development of optical imaging payload and miniaturized attitude sensors are of great interest for space surveillance and space science applications.

Within the framework of the present paper, the goal of reducing size, mass and power consumption may be achieved by combining and integrating different optical hardware for micro/nano satellite platforms.

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2. THE CONTEXT

In the Canadian context of the space program and industry, the micro satellites technology constitutes a way to reach for less expensive space missions [7]. In Canada the development of optical imaging hardware for micro/nano satellites is very limited. Some activities are mainly performed by a University research laboratory (UTIAS-Space Flight Laboratory), which has undertaken the building of a series of nanosatellites (CanX program) for different applications. Some military applications also exist, such as formation flying of nano satellites for sensing of moving target, digital terrain surveying and surveillance of space [8]. From civilian side, the Canadian Space Agency (CSA) has established a small and micro-satellite program. This program will require the development of new satellite platforms and instrumentations. A series of small and micro satellites will be developed in order to maintain bus design, fabrication and integration capabilities.

A niche regarding the development of optical space hardware for imaging and attitude determination is not fully exploited by Canadian industry and by other countries. Considering the increasing number of micro/nano satellites in development in the world, a very interesting market will develop for the Canadian industry.

The demand for images from space will certainly increase due to Internet and other media (news and meteo channels). A virtual Earth composed of a multitude of remote sensing images is currently available on the Internet through Google Earth. Other similar products will emerge from multimedia companies, so the need for images will dramatically increase. The number space imaging providers is limited by the current operational satellites. The lifetime of those satellites imposes that other imaging platforms will be launched in the coming years. Micro/nano satellites developed for imaging in space will be used as cheap mean to get those images from various orbits, altitudes and ground spatial resolutions. Also, the US space shuttle provided a lot of images of space, but its retirement in 2010 or even before will reduce significantly imaging of space capabilities. The ISS would be a good platform for providing images, but its utilization is not clarified yet.

Imaging and attitude determination systems (ADS) have already been developed in the past for space missions. These existing systems might not be suitable for future Canadian micro/nano satellites missions because both their cost and availability cannot be confirmed. Also, these units would most likely require customization on micro/nano satellite bus. As such, it is proposed to investigate into a new miniature and low power consumption imaging/attitude determination system. This novel unit must fit in a low mass/volume satellite and it must have a high performance to cost ratio. Compared to the capabilities of the existing systems, it is proposed to develop one with visual and enhanced imaging functions for multi-tasks capabilities, such as surveillance and attitude determination.

3. SPACE TELEMETRIC IMAGING SYSTEM CONCEPT

The following sections will describe the concept of the space telemetric imaging system (STIS) and the COTS technologies available for producing it.

3.1 General system concept

The basic concept of the system is composed of a self-contained module with the following components (Figure 1): an optical head (OH) and an electronics unit (EU).

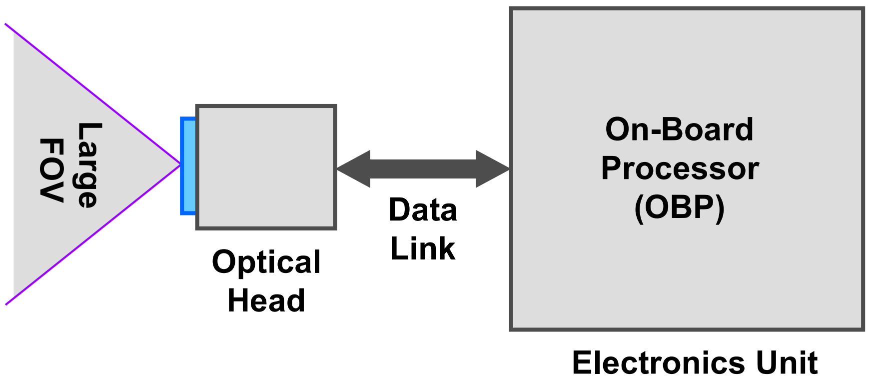


Fig.1 Block diagram of the space telemetric imaging system

The OH module will provide two specific angular fields: a wide field of view (FOV) for imaging and narrow field of view coverage for the ADS functions. Figure 2A presents the OH with an imaging subsystem (the use of one or two imaging modules will be discussed in the next section). The imaging module will be composed of a detector array, an imaging optics and a baffling element for stray light shielding. The OH module will be designed in such a way that it is used as a fix-head device on the satellite.

The EU module will be composed of an electronic card for the on-board processing (OBP). The functions of the EU will be the following: image acquisition and processing, attitude determination functions, timing and control and telecommand/telemetry. Figure 2B shows the bloc diagram of the EU.

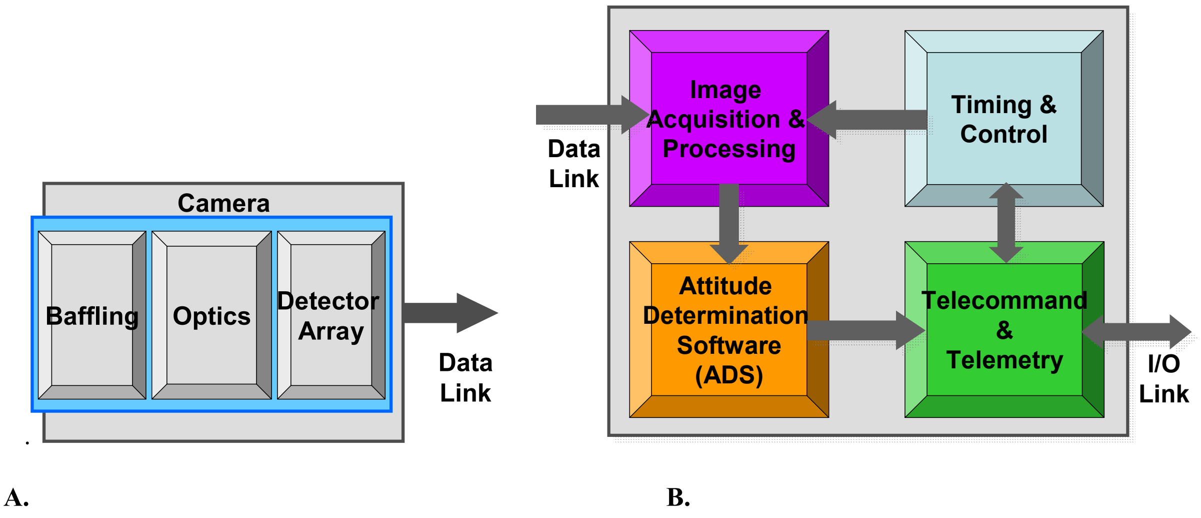


Fig.2 A. Block diagram of the Optical Head (OH); B. 3 Block diagram of the Electronics Unit (EU).

3.2 System functionalities

The primary purpose of the optical module is to record wide and broadband images of a scene around the satellite. A key requirement of the optical module is therefore to be able to use the field coverage properties to distinguish true element that can be used for star tracking, earth horizon sensing and related tracking functionalities. The optical module must provide all usable telemetric information for the satellite.

The space telemetric system will provide data through its imaging and ADS functions. The data accessible to users and for the control of the satellite will be under the form of raw images, processed images, tracking positions and attitude data. Telecommand functions will allow selecting the desired type of information from the system. In the case of the imaging data, the communication downlink speed will set the quantity of images per second that can be displayed on ground for visualization. It would be desirable to reach video rate (at least 30 images/sec.) for operations requiring visualizing the deployment or separation of spacecrafts or for flying formation. Figure 3 shows an example of a monochrome image that would be taken from space when the system is on the satellite. The wide FOV will be mainly used to take pictures of a space scene with objects like the Earth, Moon and other satellites. The narrow FOV will be used for performing ADS functions like star tracking and Earth horizon sensing.

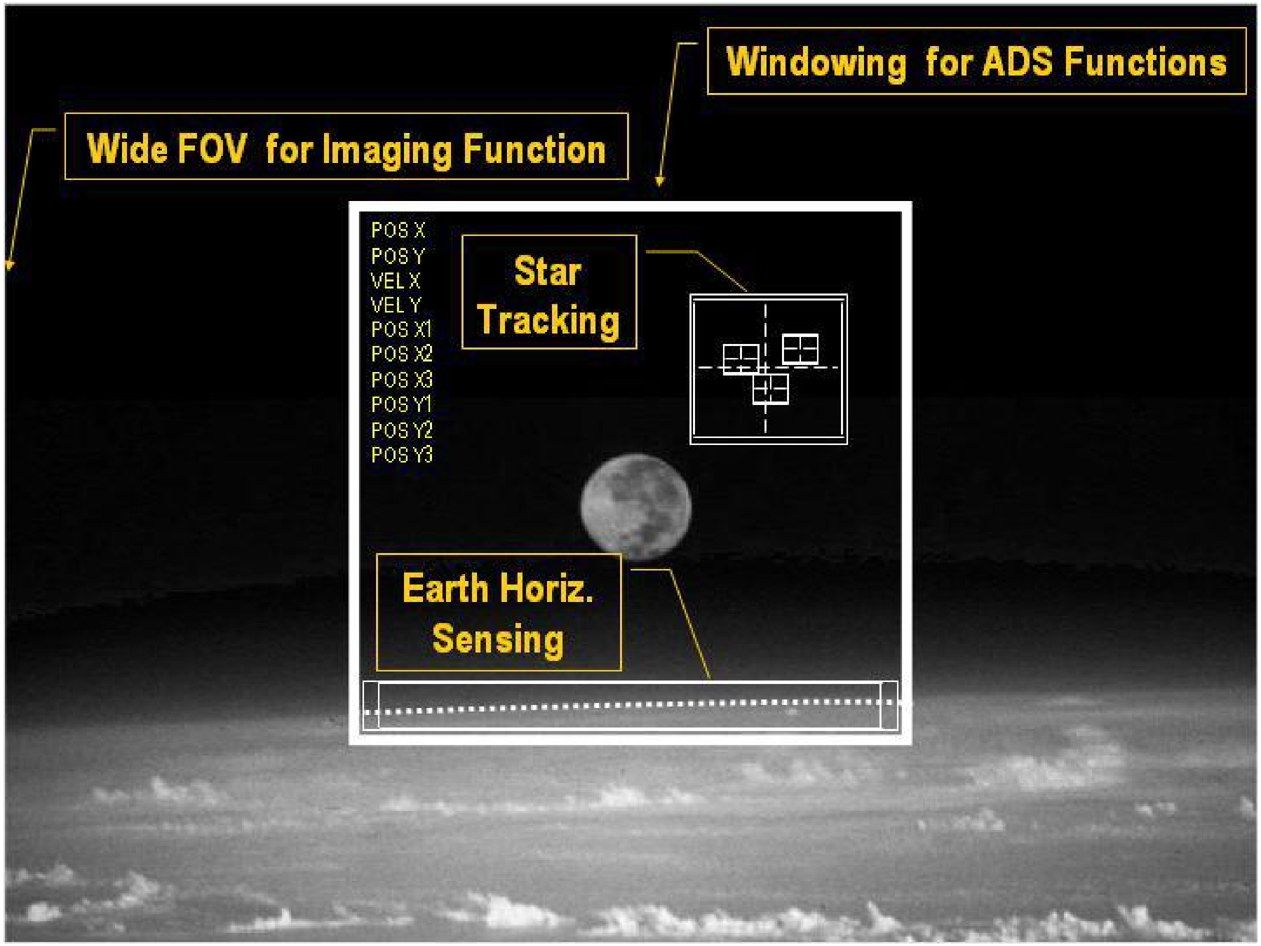


Fig.3 Example of an image of space with the proposed functionalities

3.3 Optical design considerations: The benefit of using a Panomorph lens

Two concepts can be used for the imaging optical module:

1) a two camera optical module (wide field and narrow field coverage);
2) a single wide angle camera unit with an enhanced resolution for the central field (high resolution narrow camera) and a lower resolution for wider field.

The first concept that uses two independent cameras is interesting because of the flexibility. However the second concept seems an excellent approach since it can provide all telemetric parameters because it reduces the number of piece as well as the overall size and complexity. The second concept uses a patented technology from ImmerVision. This technology has been developed in order to provide optimal pixel coverage in digital imaging.

This technology permits to provide higher resolution in the zone of interest by reducing the resolution where is not required.

It is proposed to use the second concept. It provides a compact and more robust solution. The panomorph lens concept is based on a new capability. It is possible to design a new type of wide angle objective to feed a single camera that can provide the same telemetric information. The lens will use the distortion control as a design parameter. By managing optical distortion and pixel coverage we can significantly improve the imaging properties of the camera in order to reduce the vision system hardware from two to a single camera [9].

In is simplest expression, the distortion is a transverse deformation of an image. If a grid is used as an object, its image in a system with distortion will be a grid of curved lines. This is due to the change in the transverse magnification in a system as a function of the distance from the optical axis. When the magnification decreases as the distance from the axis increases, a barrel shaped image occurs. If the magnification increases with the distance, a pincushion image is obtained. Visually most people do not notice distortions of less than a few percent however for precision digital imaging applications optical distortion will result in a significant resolution penalties. But managing distortion can be interesting because it is possible to make major performance improvements by questioning assumptions that have crept in at the very beginning of the design process. Using such a design philosophy can produce new type of optical design, and in particular using distortion.

Today, many challenging digital imaging systems can enhance their imaging capability by managing the distortion. The distortion now becomes a new degree of freedom for optical designers. Since much of the persons working with optical software have a little or no background in optics, using distortion as a design variable is not an easy task. Those persons attack new problems not from a fundamental understanding but based on their past experience. However using imagination and theoretical background, a qualified specialist can design a new variety of optical systems that can enhance the use of digital imaging systems. By controlling the distortion, we can manage the relation between the field of view and the pixels for a given application.

Although the choice of the distortion profile may be complex, the factors that must be taken into account are relatively straightforward: minimum acceptable resolution and applications. Other factors, such as wavelength range, light level and environment, also must be considered.

The next figure shows a graphical representation of the distortion profile uses for the resolution calculation. Each circle corresponds to the chief ray positions of the detector plane. The left hand side represents an ideal linear distribution (f-theta). The right side shows some field compression from 0 to 36 degrees and a field expansion between 54 and 72 degrees. In our telemetric application, we should do exactly the inverse. We must have a field expansion (higher pixel per degrees coverage) for the central 40 degrees (rough number) and the rest of the sensor will be used equally for the remaining field of view. Figure 4 represents a chart for a 180 degrees camera.

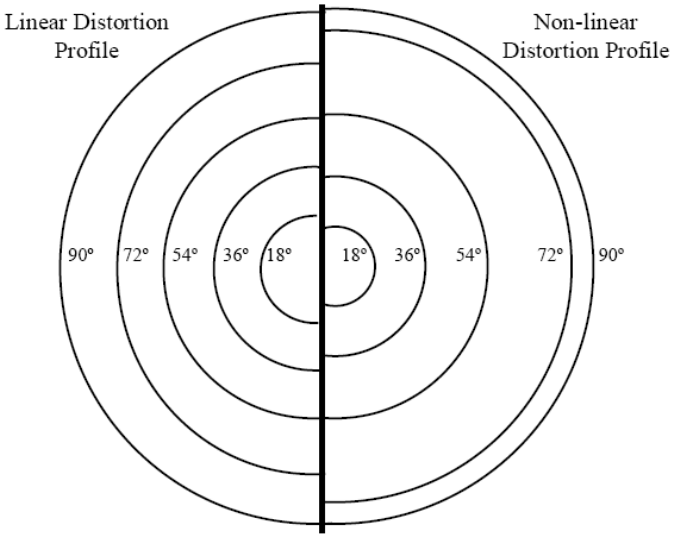


Fig. 4 Fields positions on the detectors for two distortion profiles

Figures 5A and 5B show an image on the sensor with a central increased resolution compared to a standard image taken by a non corrected objective. The correction is not software but at the hardware level.

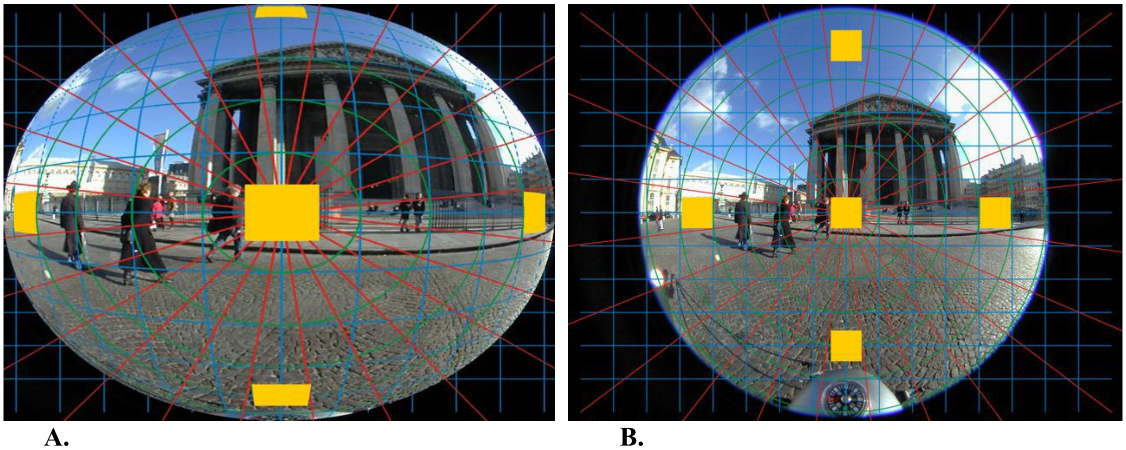


Fig. 5A Standard 180 degrees images (on the sensor); B. same image with an increase resolution in the center

In Figures 5A and 5B, an axial stretch in the image is shown. To get better pixel coverage, an anamorphic correction can be included in the optical design. This anamorphic correction provides by the anamorphic component in the panomorph lens will provide 30% increased image coverage. Consequently, a panoramic imager that used a panomorph approach will make a better use of the pixels available on the sensor. This is particularly important for space applications.

Figure 6 shows an optical layout of a panomorph lens which has an enhanced central field resolution. The lens is mainly composed of a wide angle afocal attachment mount on a typical camera unit. A stop (pupil) is positioned in order to provide more or less light depending of the application (indoor or outdoor). The typical size of the objective is about 3 cm long and 2 cm in diameter. However the size will depend on the design as well as the sensor dimension.

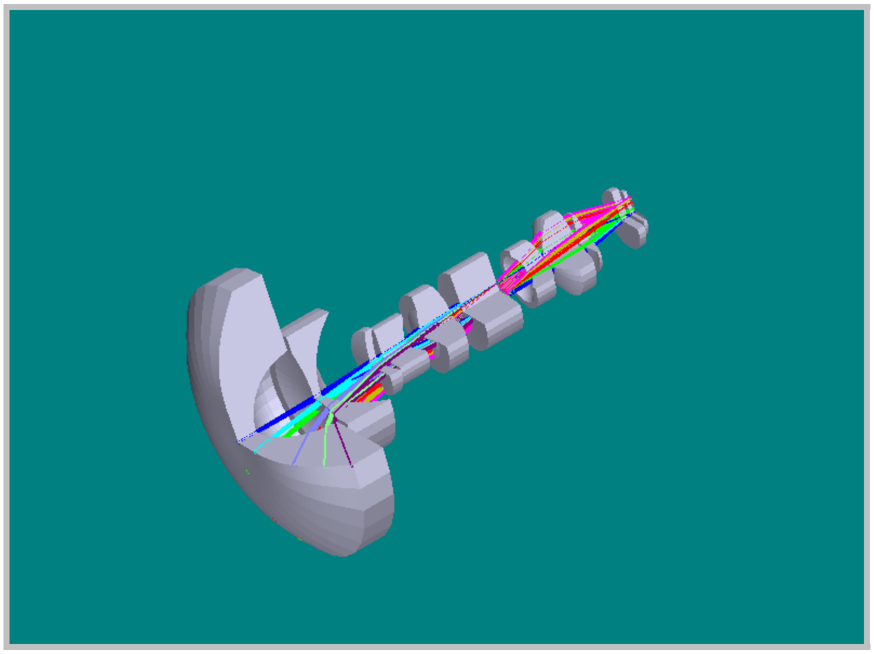
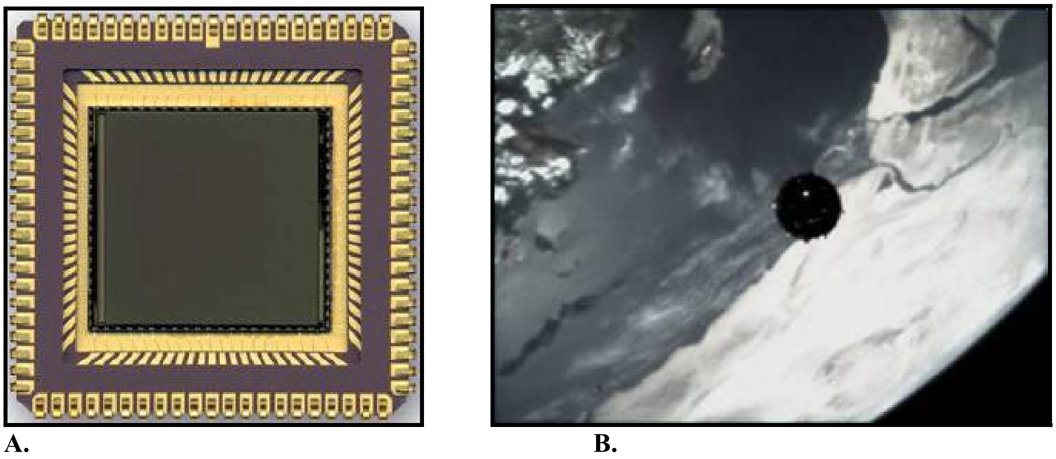


Fig. 6 Wide angle objective with enhanced resolution

The field of view coverage can be from nearly 0 degree to 230 degrees. The second approach using enhanced field of view is clearly a good candidate to reduce the complexity of such imaging system for space applications.

3.4 CMOS image sensors

The recent developments in imaging sensors based on CMOS technology make them very attractive for space applications. They now get into domains where traditional CCDs are used for high-end applications. CMOS imagers, named APS (Active Pixel Sensors) CMOS, have already been tested in space mainly for imaging applications. Recently, their use in attitude determination hardware has been proposed for various missions (BRITE, ION-F, Bepi Colombo). In Figure 7A, a CMOS imager chip with 1024 x 1024 pixels is shown and Figure 7B presents an image taken from a satellite using a CMOS imager.



A. **B.**

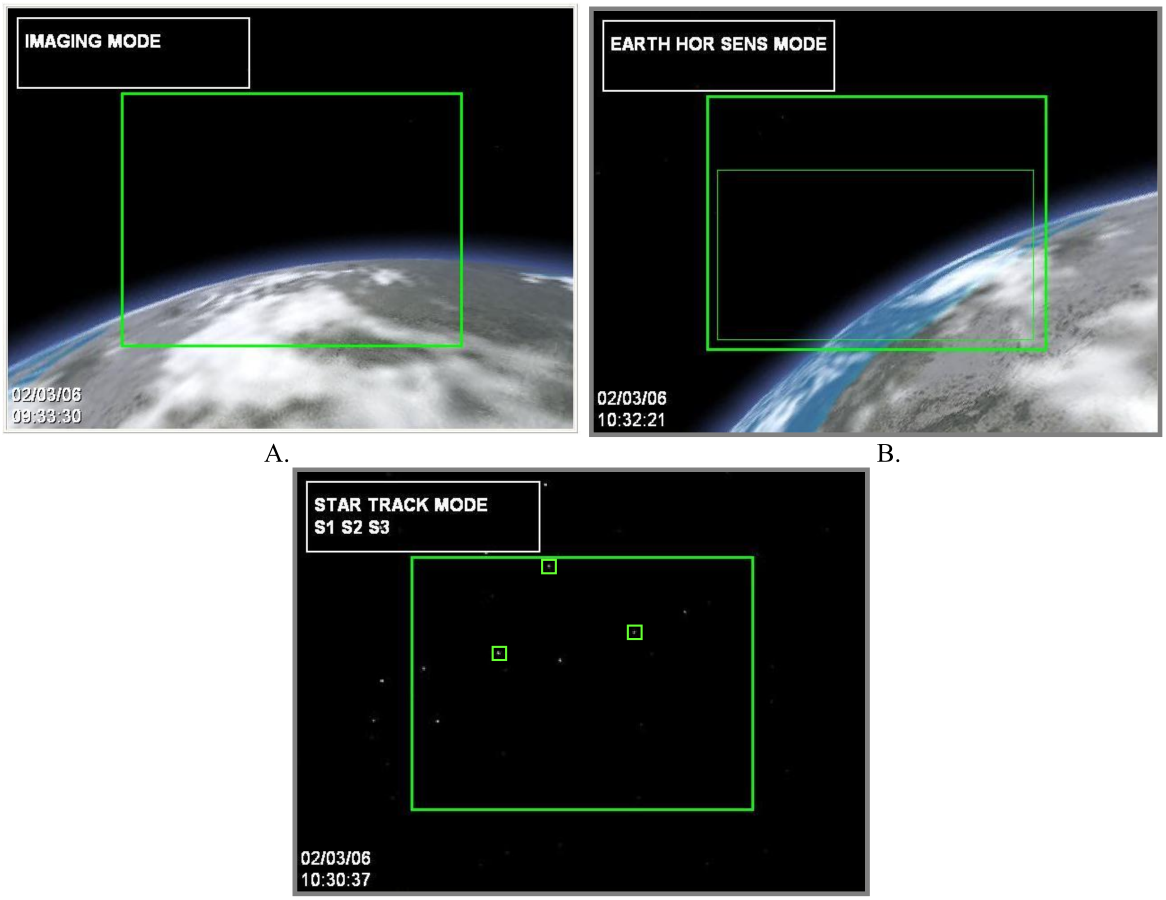
Fig. 7 A. 1024 x 1024 pixels radiation–hard CMOS image sensor produced by FillFactory (acquired by Cypress Semiconductor Corp.); B. Example of an image of a satellite taken from space with such CMOS imager.

APS CMOS imagers are the preferred candidate for the proposed concept. They offer several advantages over CCDs: reduced size and weight suitable for miniaturization, low power consumption, can be manufactured radiation-tolerant, allow a versatile access to the image plane, enabling functions like windowing, subsampling, analogue pixel binning, etc. However, they suffer some disadvantages over CCDs: low fill factor, lower quantum efficiency, worse noise performance, high dark current, shuttering limitation [10, 11].

New developments in CMOS sensors have increased their performances, so their use for high-end imaging applications is possible today. Today, many more manufacturers offer high-quality CMOS sensing products.

3.5 Preliminary system definition

The STIS would operate in different modes for performing imaging and attitude determination functions. The imaging payload would provide to a spacecraft both wide field imaging capability for surveillance and attitude determination. The wide field imaging mode where scenes like space environment objects such as Earth, Moon and artificial objects can be visualized and recorded. In the other modes, a ROI window is used for performing image processing and feature extraction. The attitude determination modes include wide field imaging, horizon sensing and star sensing modes. Figure 8A, 8B and 8C show a simulation of the operation of the system in the different modes.



A.

B.

C.

Fig.8 Simulation showing the operation modes of the system: A. wide field imaging, B. horizon sensing, C. star sensing.

The main characteristics and benefits of the system are the following:

System characteristics
• Simple imaging device • Compact, multi-functions, low power consumption • Wide field of view imaging capability • Raw video images and basic attitude determination data • Single sensor with multi-tasks capability
Applications
• Visual monitoring for formation flying, spacecraft separation, solar arrays deployment • Attitude sensor for micro/nano sats
Imaging payload preliminary specifications
• Size: 10x10x10 cm • Sensor Dim.: 1024 x 1024 pixels • Spectral Range: 400-1000nm • Field of View: Wide field (panomorph lens)

Figure 9A illustrates a mechanical conceptual design of the system which includes the lens window, connectors and the alignment cube for system axes referencing. Figure 9B shows the definition of the mechanical reference frame (MRF) and alignment reference frame (ARF) for sensor mounting during its integration to a spacecraft body using an optical cube.

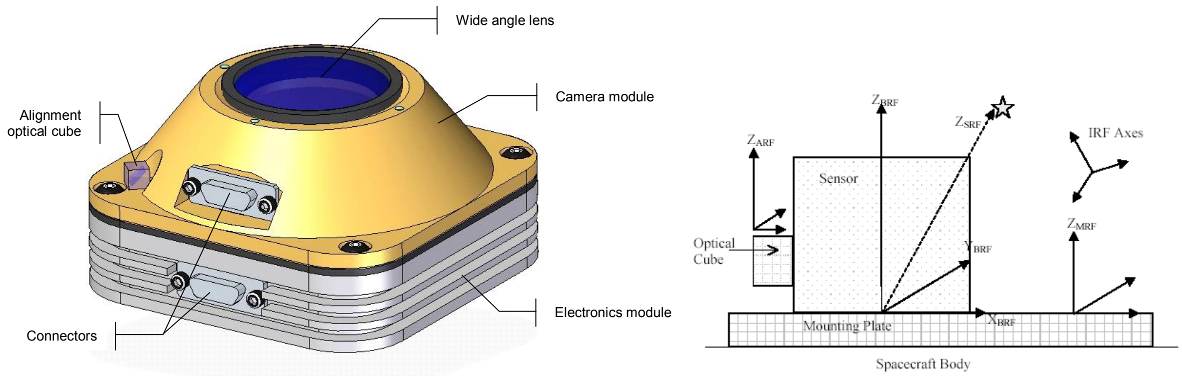


Fig.9. Mechanical conceptual design of the system and. System axes referencing.

3.6 ADS and imaging functions expected performance

High performance optical attitude hardware, such as star trackers, can achieve few arc-seconds accuracies with stars brighter than $M_v < +3.5$. Those devices are used for high precision attitude determination in applications such as Earth resources, communications and weather monitoring. Spacecraft attitude control can be performed by other types of attitude hardware like the horizon sensors. Those sensors provides pointing performance in the range of 0.1 – 1 deg. of accuracies. It depends on the sensor type and the spectral range of detection [12]. For micro/nano satellite applications, the attitude determination accuracy requirements vary in function of the space mission objectives.

According to [13,14], low cost attitude sensors based on CMOS can achieve significant attitude accuracies in the range of 1 arc-minute for star tracking and 0.5–1.0 deg. for Earth horizon sensing. A careful analysis of expected accuracies is required, taking into account centroiding and edge detection algorithms.

4. CONCLUSION

The proposed space telemetric imaging system offers innovations at two levels:

Integrated system level: the proposed system will be designed as a self-contained module that could be installed on any satellite platforms or series of platforms, so that the product will not have to be custom designed each time for space missions.

Optical subsystem level: the proposed system will introduce a patented technology developed for producing better pixel coverage in digital imaging. This technology allows for providing higher resolution in the field of interest by reducing the resolution where is not required. Using specially designed optics, one detector array can be used for different tasks or applications by optical control of distortion for producing a redistribution of the light in desired pixel regions of the array. This innovation will allow for producing optical instruments which will have less power consumption, reduced size and volume/mass of the system for micro/nano satellite applications. Moreover, the system will be used as a plug and play device for mounting on a spacecraft body.

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