CubeSat Camera System (C2S) - Research

Overview

Developing a bespoke low-resolution camera for a 1U CubeSat to capture imagery of cities from low Earth orbit (LEO) as part of the CubeSat 1 mission.

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1.1 The Planetary CubeSats Symposium, 2018

[2] Developed under MSSS IRAD, the Engineering Camera (ECAM) is a modular space camera platform built to strict NASA standards. While it was originally targeted towards engineering applications, ECAM systems have been used for:

1. In-flight diagnostics
2. Deployment/actuator monitoring
3. Space sitiuational awareness
4. Science observations
5. Public outreach
6. Optical navigation

ECAM architecture uses DVR interfaces between cameras (power, data, commanding). DVR processes and stores data (Bayer pattern interpolation, compression, and buffering - frmo 8 to 32 Gbytes of flash). DVR provides one power (28V) and one data interface to the S/C. DVR baseline I/F is SpaceWire, but it can accommodate any customer specified four-line LVDS or RS-422 interface. DVRs can be daisy-chained, making a DVR8 or DVR12, still with a single S/C command/data interface.
The smallest of the three ECAMs is ECAM-IR3a, a VGA format uncooled microbolometer. It has a pixel pitch of $17 \mu m$ pixel pitch (640 x 480) with an optional calibration flag. The larger two use a colour or B/W CMOS sensor with decreasing pixrl pitch and resolutions of (2592 x 2048), however, this is acheived with larger optic barrels.
ECAM system components meet the requirements of NASA EEE-INST-002, Level 2. ECAM ahrdware can be customised for different environments. Systems have been delivered for:

1. Deep space (OSIRIS-REX)
2. Low Earth orbit
3. Geosynchronous orbit

The MSSS ECAM architecture provbides viable options for CubeSat applications where high reliability, heritage, and performance are required. ECAM system components are built to NASA reliability standards and are now flying on multiple missions. ECAM systems can be cutomised for a range of environments, applications and configurations. This shows that imaging systems with science-driven performance that meet NASA deep space requirements can be compatible with CubeSat missions.

1.2 The Main Features of the CubeSat Camera

[4]

1. **Imaging Sensors** The first question is, how does a satellite take pictures? CubeSat cameras employ imaging sensors like charge-coupled devices (CCDs) or complementary metal-oxide-semiconductor (CMOS). They convert light into electrical signals, capturing images with varying resolutions and sensitivities.

2. **Resolution** The CubeSat camera resolution refers to the level of detail it can capture in an image. Higher resolution allows clearer and more detailed pictures but may come with increased data storage and transmission requirements.

3. **Radiation resistance** Space environments expose satellites to various forms of radiation. CubeSat cameras are constructed to resist these harsh conditions through radiation-hardened components and protective means to ensure the endurance of the imaging system.

4. **Data compression** The cameras include built-in data storage to store captured CubeSat images for some time before transferring them. Efficient data compression algorithms are usually included to decrease the amount of data that needs to be transmitted, considering the limited bandwidth available.

5. **Connection systems** CubeSat cameras are equipped with communication systems to transfer captured images back to any ground station on Earth or elsewhere. Usually, this involves radio frequency communication systems operating in various bands.

6. **Power economy** CubeSat cameras' system is designed to operate within the power limits of CubeSats. This involves using energy-efficient components and technologies to boost the utility of the available power.

7. **Onboard processing** Some CubeSat cameras include built-in processing, which means they perform initial data analysis or image processing before transmitting the data. This can help reduce the amount of data that needs to be passed on and improve the efficiency of the whole mission.

8. **Customization** CubeSat camera design is created to meet the specific needs of their missions. For example, Earth survey CubeSats may prioritize high-resolution imaging, while scientific CubeSats may focus on observing specific phenomena in space.

1.3 Satellite cameras and optical payloads

[3] When selecting any piece of technology for your mission it is important to be aware of costs, lead times, integration and testing requirements, as well as the physical requriements of your system. In addition, here are some of the key performance criteria to consider when assessing satellite cameras on the global market, to see which could suit your needs:

1. **Spatial Resolution** - a measure of the smallest object that can be resolved by the optical payload.

2. **Spectral Resolution** - the number and width of spectral bands that the sensor can collect from reflected radiance.
3. **Swath** - the area imaged by the optical payload.
4. **Radiometric Resolution** - this indicates how much information is in a pixel and is expressed in units of bits.
5. **SWaP Factor** - the size, weight, and power of the satellite or sub-system.

Interoperability throughout the entire communications and data capture chain is also vital, particularly if you intend to operate a competitive commercial service. Of the listed C2Ss the following are viable for PAST's mission:

1. **Gecko** Designed for 1U CubeSat systems, Gecko has a standard RGB spatial resolution of 39m at 500km. Includiong electronics, it weighs less than 500g. It uses snap shot as the imager type and stores data in either 8-bit or 10-bt. It has an integrated mass data storage of 128 Gigabytes and compresses to RAW, J2K or lossy. It uses SpaceWire as its interface and SPI, I2C, CAN and RS485 as its TMTC interface. At the most, it requires <6W to images and <4W to readout. It only operates in the range +10 to +30C and can survive between -20 to +55C.
2. **Lynx-4MP** Lynx4MP is a 4MP RGB/Monochrome CMOS camera electronics backend designed for space applications. The camera technology is at TRL9. Lynx4MP is mechanically compatible with the standard CubeSat form factor and can support precise image capture timing requirements. The system has been qualified for thermal vacuum, vibration, and shock and tested up to 40kRad TID. Lynx4MP camera backend electronics can be combined with different optical assemblies to suit a range of space applications. This C2S is more conservative than Gecko and requires 2.75W to image and 1.75W idling. It uses SPI and UART as its data interface, can capture up to 13fps. Its operating temperature is between -40 to 85C.

There exist monitoring camera options, however they do not have the required specifications to meet requirements and are only designed to image the internal components.

1.4 A Survey of Camera Modules for CubeSats - Design of Imaging Payload of ICUBE-1

[6] Small sized low resolution CCD or CMOS imaging sensors are camera modules are generally used in CubeSats for imaging applications. Both types have their pros and cons. For exmaple, it has been observed that CCD sensors generally consume more power as compared to CMOS cameras. Similarly, data retrieval mechanism differs in CCD and CMOS. Data can be fetched quicker in CCD but that data is more prone to errors. On the other hand, CCD technology is more mature than CMOS which is still an evolving technique. The breakdown of each camera and can be found from the source. The following table is an analysis of each camera listed in the source.

TABLE I. CAMERA COMPARISON: A) IDS UI- 1646LE B) C3188A C) MCM20027 D) PC67XC-2 CCD E) MICROCAM TTL F) PB-MV13 G) PB-MV40 H) OV7648FB I) HDCS-2020

Camera	a	b	c	d	e	f	g	h	i
Power consumption	--	++	++	---	++	++	+	+++	++
Resolution	++	+	--	-	++	--	+	+	+
Price	--	++	+++	-	++	---	---	+	-
Size	+	+	+	++	+	+	+	+	+
Weight	+	+	+	++	+	+	+	+	+
Availability	+	+	+++	+	++	+	+	++	++
Interface	-	---	+	-	+++	-	-	+	+
Voltage level	-	-	++	---	++	+++	+++	++	++
Temperature range	+	+	+	-	+++	++	++	+	++
Space History	+	++	+	+	--	+	+	+	+
Data Acquisition Speed	-	+	+	--	++	+++	+++	++	+
Compression	-	-	-	-	+++	-	-	-	-
Total	**-1**	**7**	**13**	**-7**	**21**	**7**	**9**	**15**	**12**

Figure 1: Each camera has been rated for different criteria. The rating varies from — as the least rating to +++ as the best. The criteria have also been weighted after considering their importance to the project ICUBE-1.

The best rated camera, MicroCAM TTL is a family of scpecial integrated serial canera modules designed for very compact embedded imaging applications. This camera consists of an OmniVision CMOS coloured sensor, built-in lens, and JPEG compression chip with the capability of utilising direct serial interface for ensuring direct serial communication with any host microcontroller via UART or any PC COM port based solutions. It has a pixel size of $5.6\mu m$ and can capture low resolution RAW images (160x120 or 80x60) or higher resolution JPEG images (640x480 or 420x240).
The next best sensors, H, C and I are all CMOS cameras with similar resolutions and pixel sizes.

1.5 Cameras and Sensors

1.5.1 MCM20027 Chip

[5] This chip is manufactured by the well-known firm Kodak . It has a resolution of 1.3mill pixel, which as above gives a resolution of 78m x 98m. It comes for about 22$ when buying 10.000 units. The price for one unit is not known but it is expected to be much cheaper than the Photobit chips above. [7] The MCM20027 is a fully integrated, high performance CMOS image sensor with features such as integrated timing, control, and analog signal processing for digital imaging applications. The part provides designers a complete imaging solution with a monolithic image capture and processing engine thus making it a true “camera on a chip”. System benefits enable design of smaller, portable, low cost and low power systems. Thereby making the product suitable for a variety of consumer applications including still/full motion imaging, security/surveillance, and automotive among others. The imaging pixels are based on active CMOS pixels using pinned photodiodes that are realized using Motorola’s sub-micron ImageMOSTM technology. A maximum frame rate of 10 FPS at full resolution can be achieved, further the frame rate is completely adjustable without

adjusting the system clock. Each pixel on the sensor is individually addressable allowing the user to control "Window of Interest" (WOI) panning and zooming. Control of sub-sampling, resolution, exposure, gain, and other image processing features is accomplished via a two pin I2C interface. The sensor is run by supplying a single Master Clock. The sensor output is 10 digital bits providing wide dynamic range images.

1. SXGA resolution, active CMOS image sensor with square pixel unit cells
2. 6.0mm pitch pixels with patented pinned photodiode architecture
3. Bayer-RGB color filter array with optional micro lenses
4. High sensitivity, quantum efficiency, and charge conversion efficiency
5. Low fixed pattern noise / Wide dynamic range
6. Antiblooming and continuous variable speed shutter
7. Single master clock operation
8. Digitally programmable via I2C interface
9. Integrated on-chip timing/logic circuitry
10. CDS sample and hold for suppression of low frequency and correlated reset noise
11. 20X programmable variable gain to optimize dynamic range and facilitate white balance and iris adjustment
12. 10-bit, pipelined algorithmic RSD ADC (DNL +0.5 LSB, INL +1.0 LSB)
13. Automatic column offset correction for noise suppression
14. Pixel addressability to support 'Window of Interest' windowing, resolution, and subsampling
15. Encoded data stream
16. 10 fps full SXGA at 13.5MHz Master Clock Rate
17. Single 3.3V power supply
18. 48 pin CLCC package

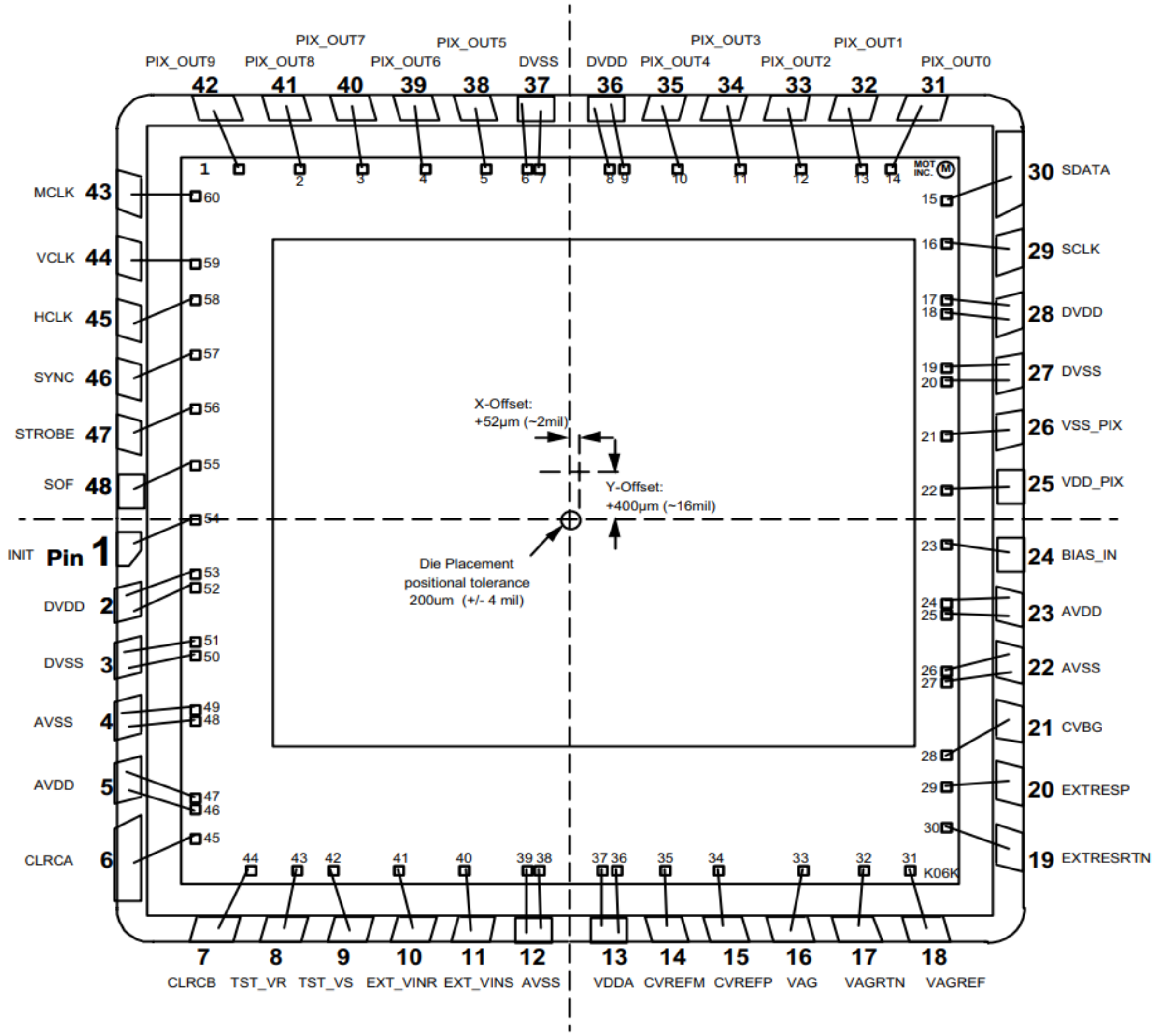

Figure 2: Center of the focal plane array with respect to the die cavity (top view)

1.5.2 piCAM

[8] The **piCAM** is the World's First SpaceFriendly™ Digital CubeSat Camera module, specially designed to provide colorful imaging in JPEG format and VGA resolution aboard small satellites with an external flashlight control signal.
The unit enables the possibility to trigger a signal for an external LED-based flashlight to illuminate nearby objects of interest in dark orbital periods, such as solar sails, booms, deployable structures, tethers, etc.
The camera can be delivered pre-configured with various optics. By default, optics with a ∼60° Field-of-View (diagonal) with an IR-cut filter is attached and fixed, set to focus on infinity. Other configurations or focus adjustments can be requested prior to the manufacturing process.

HIGH ALTITUDE BALLOON (HAB) IMAGE SAMPLES

There are three examples of the image captured using imagery mode "Middle", 60° FoV optics and IR-Cut filter during the HAB flight at an altitude of ~25 km above ground. Residual atmosphere is visible in Fig. 6.

Fig. 6 **High Altitude Balloon flight image data with residual atmosphere, 60° FoV Optics with IR-Cut filter.**

SUN SYNCHRONNOUS ORBIT IMAGE SAMPLES

The plot in Fig. 7 shows data from the Sun Synchronous Orbit (SSO) 530 km flight of the CubeSat spacecraft (NORAD ID 44406), identifying several regions over Europe, including direct sunlight image capture.

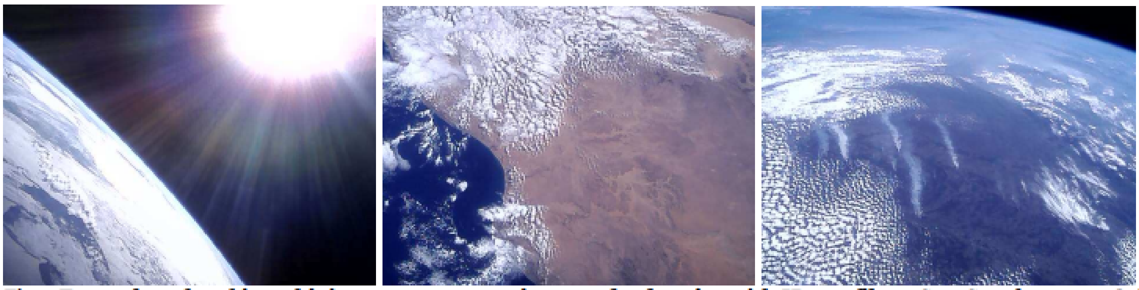

Fig. 7 **Examples of real in-orbit image captures using standard optics with IR-cut filter, Sun Synchronous Orbit. [Lucky-7 Spacecraft mission].**

Figure 3: Center of the focal plane array with respect to the die cavity (top view)

1.5.3 Mira220 Sensor

[1] Mira220 is a 2.2 MP NIR enhanced global shutter image sensor with a small 2.79 μm pixel size. It has excellent low light sensitivity made possible by a state-of-the-art stacked BSI technology. With an effective resolution of 1600x1400 and a maximum bit depth of 12 bits, the sensor supports on-chip operations like external triggering, windowing, horizontal or vertical mirroring. The maximum frame rate is 90 fps at full resolution and bit depth. The sensor has a MIPI CSI-2 interface to allow easy interfacing with a plethora of processors and FPGAs. On-chip registers can be accessed via the standard I^2C interface for easy configuration of the sensor. Due to its small size, configurability and high sensitivity both in visual as well as NIR, the Mira220 is well suited for 2D and 3D applications, which include Active Stereo Vision, Structured Light Vision for Robotics and AR/VR. High sensitivity in NIR enables increased measurement range and allows overall system power consumption optimization which is key for battery powered consumer and industrial applications.

Benefits	Features
Compact size with high resolution and bit depth	• 1/2.7” • 1600x1400 • 8/10/12-bit • 2.79 μm
High speed applications	90 fps global shutter with CDS
Use in low light conditions	High sensitivity
Compact size	Small die size achieved via state-of-the-art stacked BSI technology
NIR enhanced with high sensitivity	Class leading QE at 940 nm combined with high sensitivity. Industry leading PLS at 940 nm
On chip noise reduction	Digital CDS and row noise correction
Reduced off-chip processing	• On chip defect pixel detection and correction • On chip image statistics generation
Multiple variants	Available as Mono, RGB or RGBIR variant. Orderable with AR coated or plain glass and protective film
Extended battery operation	Low power consumption

Figure 4: Mira220 Sensor Specifications

2 Review

After reviewing a range of sources, it can be concluded that the camera system will require the following components:

1. **Optical System**
   - **Lens Assembly**: Focuses light onto the image sensor.
   - **Filters**: Such as Neutral Density (ND) filters, to control light intensity and prevent overexposure.
2. **Image Sensor**
   - **CMOS or CCD Sensors**: Convert light into electrical signals; CMOS sensors are often preferred for their lower power consumption.
3. **Processing Unit**
   - **Microcontroller or FPGA**: Manages image processing tasks, including initial data handling and compression.
4. **Data Storage**
   - **Onboard Memory**: Stores captured images temporarily before transmission to ground stations.
5. **Communication Interface**

- **Transmitter and Antenna**: Facilitate the transmission of images and data back to Earth.

6. **Power Management**

   - **Power Supply Unit**: Ensures the camera operates within the CubeSat's limited power budget.

7. **Thermal Control**

   - **Thermal Management Systems**: Maintain optimal operating temperatures in the extreme conditions of space.

8. **Structural Housing**

   - **Protective Enclosure**: Shields internal components from environmental hazards like radiation and micrometeoroids.

Based on current requirements, a CMOS C2S with a sensor size of $6\mu m$ and focal length $15mm$ using SpaceWire, I2C, SPI and UART are best suited for CubeSat 1. The camera will produce images with an approximate spatial resolution of $\approx 160m$ which is detailed enough to capture images of Perth and other urban cities. Moreover, using a CMOS camera opposed to CCD, it is possible to use a colour sensor rather than a B/W since the power requirements of CMOS is far more accomodating.

References

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