Multi-purpose active pixel sensor (APS)-based microtracker

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ABSTRACT

A new, photon-sensitive, imaging array, the active pixel sensor (APS) has emerged as a competitor to the CCD imager for use in star and target trackers. The Jet Propulsion Laboratory (JPL) has undertaken a program to develop a new generation, highly integrated, APS-based, multipurpose tracker: the Programmable Intelligent Microtracker (PIM). The supporting hardware used in the PIM has been carefully selected to enhance the inherent advantages of the APS. Adequate computation power is included to perform star identification, star tracking, attitude determination, space docking, feature tracking, descent imaging for landing control, and target tracking capabilities. Its first version uses a JPL developed 256×256-pixel APS and an advanced 32-bit RISC microcontroller. By taking advantage of the unique features of the APS/ microcontroller combination, the microtracker will achieve about an order-of-magnitude reduction in mass and power consumption compared to present state-of-the-art star trackers. It will also add the advantage of programmability to enable it to perform a variety of star, other celestial body, and target tracking tasks. The PIM is already proving the usefulness of its design concept for space applications. It is demonstrating the effectiveness of taking such an integrated approach in building a new generation of high performance, general purpose, tracking instruments to be applied to a large variety of future space missions.

Keywords: active pixel sensor, APS, microcontroller, star tracker, target tracker

1. INTRODUCTION

The CCD represents a mature technology which is widely produced and universally accepted as the standard solid-state image detector in star trackers. However, it has disadvantages of requiring complex fabrication processes, special drive waveforms and voltages, and relatively high total power consumption. In the search to alleviate these problems, the Jet Propulsion Laboratory (JPL) has developed a new, CMOS image sensor, which is fabricated with standard processing, does not require special drive waveforms, nor voltages (it operates with a single 5.5- or 3.3-V power supply), and it consumes substantially less power. This new image detector is the active pixel sensor, or APS[1].

In response to the ongoing development of the APS, JPL has initiated the design of a new class of autonomous microtrackers to capitalize on its advantages. The other key component is the microprocessor. A modern 32-bit, RISC microcontroller has been selected for use with the APS. It has sufficient computational power to enable a variety of tracking tasks to be performed. These include star field identification, star and target tracking, attitude determination, tracking of simple target features, space docking with cooperative targets, and descent imaging for planetary body landing. The new instrument has been named the Programmable Intelligent Microtracker (PIM). A multi-year program has been established to design, test and prove the concept. The first, development model of the PIM has been designed and built. It is currently in the coding and test phases.

Today, commercial star trackers for space applications are instruments with masses of 3 to 7 kg and power consumptions in the 7 to 17 W range. The majority of them are first-generation, non-autonomous units which output sensor referenced coordinates of a few bright stars in the field-of-view (FOV). Single-axis accuracies are an inverse function of FOV and range for over 100 arcsec for wide FOV units to less than 3 arcsec, rms for narrow FOV units. The emergence of microprocessors, which are more powerful than those used in first-generation designs, has allowed the state-of-the-art in star trackers to advance to second-generation autonomous units[2,3]. These second-generation units compare a star field image to an internal star catalog. They then autonomously calculate and output an instrument attitude relative to the celestial sphere. With their

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incorporation of multi-star tracking of up to 200 stars per frame, the single-axis, rms accuracy of wide FOV designs has moved into the 3-arcsec category[4].

Future space missions, with their greater emphasis on autonomy, modularity, small size and lower cost will require additional functionality from trackers, while demanding reduced power consumption and mass. Distant rendezvous and landing missions will require significantly more on-board data processing to support tracking operations of docking, landing, and navigation to target bodies which are simultaneously imaged with their background stars.

JPL has chosen the APS to be the basis of the PIM because of the advantages that have been cited, and preliminary tests demonstrating its suitability for star tracking[5]. The microcontroller was chosen because it has sufficient computing power, is highly integrated, and has low power consumption. The APS/microcontroller combination makes it feasible to construct the PIM with unprecedented low power and mass. The goals here are a mass of no more than 400 g and a power consumption of no more than 400 mW, in its flight version. The existing JPL 256×256-pixel APS is used in the developmental model of the PIM. Previously, a less integrated version of it achieved a relative accuracy of 8 arcsec, rms, per star, in each pointing axis, with a FOV of 5.5×5.5°[6]. This is 10% of the angular subtends of one pixel, which is comparable to CCD-based instruments. Since the star tracker version of the PIM will use multi-star techniques to improve accuracy, its accuracy goal is 3 arcsec, single-axis, rms, which is competitive with second-generation CCD based instruments.

2. APS TECHNOLOGY

The image sensor is the critical element of a tracker. The newly developed CMOS imagers feature low power consumption, a high level of possible integration of the associated CMOS circuits, up to and including the microcontroller, window access, and area-specific signal integration capability[7]. Further, they eliminate CCD charge transfer, and with it the increasing signal loss caused by radiation displacement damage. On the debit side, they tend to have somewhat lower sensitivity, higher noise, and larger pixel-to-pixel response variation.

The JPL DICE256 (Fig. 1) is an experimental digital APS image sensor, which has been used in the first developmental model of the PIM. It has a 256×256-pixel format and a 20.4-µm pixel pitch. It is a photogate device with a 10-bit integrated analog-to-digital converter (ADC). The imager is commanded through a serial interface which controls image integration time and window and subsample parameters. It has both serial and parallel digital-signal outputs. The PIM implementation of the APS uses a serial command input with internal sensor operation logic and parallel data output.

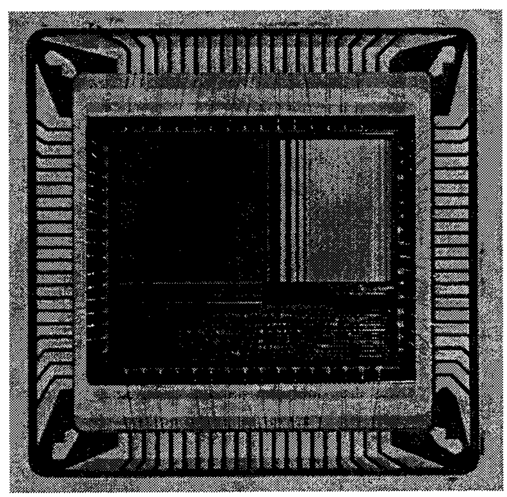

Figure 1. The DICE256 APS

The reasons for incorporating APS detectors in the next generation of star trackers are illustrated by the following list of their advantages over CCDs:

1) **Simplified hardware**—A CCD requires various bias and drive voltages, while an APS operates on a single 3.3- or 5-V power supply. Thus, an APS uses a greatly simplified power supply. A CCD requires complex, externally generated, driver waveforms for proper operation and specialized analog circuitry to generate the waveforms. An APS does not and thus eliminates them. Because of the specialized processing required to fabricate a CCD, it is incompatible with CMOS circuits and cannot be integrated with them on the same piece of silicon. An APS is a CMOS circuit and can be fully integrated with all associated CMOS circuits. In principle, it is possible to build all of the electronics, and the detector, on a single integrated circuit (IC), and thus have a complete tracker on one IC, plus the optics and associated mechanical parts.

2) **Very-low power consumption**—A CCD and its support circuits consume >0.5W of power. The power consumption of an APS can be <20mW. In addition, it is possible to implement an onboard A/D converter, which facilitates direct communication to the data system. This will be significant in the construction of star trackers for future microspacecraft where power consumption and mass are critical.

3) **Ultra-wide dynamic range**—The performance of most CCD-based star trackers tend to degrade rapidly when bright objects are present in the FOV. In the case of overload, this is due to blooming and is caused by charge spread in the CCD. This effect can significantly decrease sky coverage and it also prevents simultaneous tracking of bright bodies and dim stars in the same FOV. While the use on anti-blooming CCDs in star trackers is possible, this merely clips the signal. It does not permit linear range operation for accurate simultaneous tracking of bright bodies and dim stars. APS area integration will enable this.[8]

4) **Greater radiation resistance**—APS technology is inherently more radiation resistant than CCD technology because the pixels are directly addressed. This eliminates the charge transfer efficiency (CTE) degradation that affects CCDs subjected to proton irradiation. The use of commercially available radiation hard processes in APS fabrication, which is being implemented, should offer certain other improvements including the minimization of latchup and single event upsets (SEU).

3. CAMERA CONFIGURATION AND PROJECTED PERFORMANCE

The developmental model of the PIM is shown in Fig. 2. The DICE256 APS is a JPL design, which is an imaging system fabricated as a single, monolithic, integrated circuit. It contains an imaging array, 256 ADCs, D/A bias generators, digital control of its operation, and interface circuitry. Its power consumption is 20 mW. Signal gain, offset bias, and exposure time over the range of 64 μs to 69,000 s are set through the digital command interface. The PIM pixel readout rate is 1 MHz which results in an image transfer time of about 90 ms. There is one, 10-bit, ADC per column.

The lens used in the this model of the PIM is a 25-mm focal length, f/0.95 Schneider-Kreuznack with an FOV of 11.9×11.9°. There will be differences in star tracking accuracy between the earlier, analog APS and the DICE256 APS. The work with the analog APS was done with an external, precision, 12-bit ADC. This contrasts to the integral, 10-bit ADC of the DICE 256 APS. The latter's true, monotonic performance is probably in the range of 5 to 8 bits and possible signal offset may further limit the performance of this prototype device.

The actual performance of the PIM will be measured in two phases. The first one will be a laboratory measurement of photometric parameters through the integral ADC. The test set-up for this is shown in Fig. 3. The second phase will be done with real sky tests at JPL's Table Mountain Observatory. It is planned to complete both phases by the end of September 1998. Figs. 4 and 5 show a star field image taken with the earlier JPL-designed APS[6], and a test image taken with the developmental model of the PIM, respectively.

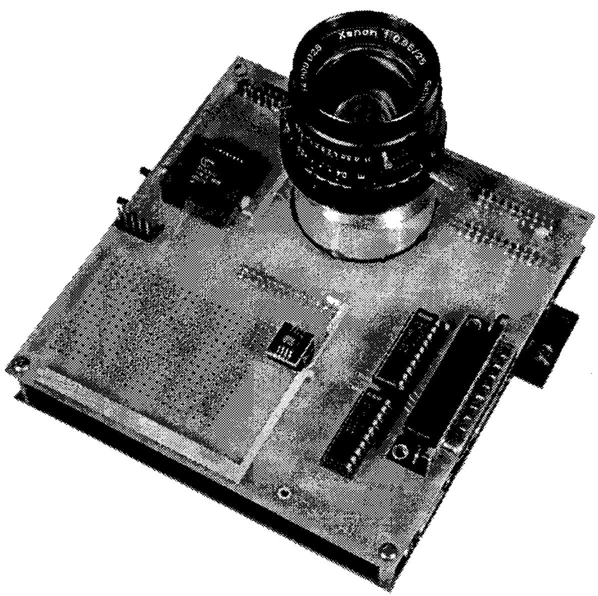

Figure 2. Developmental model PIM

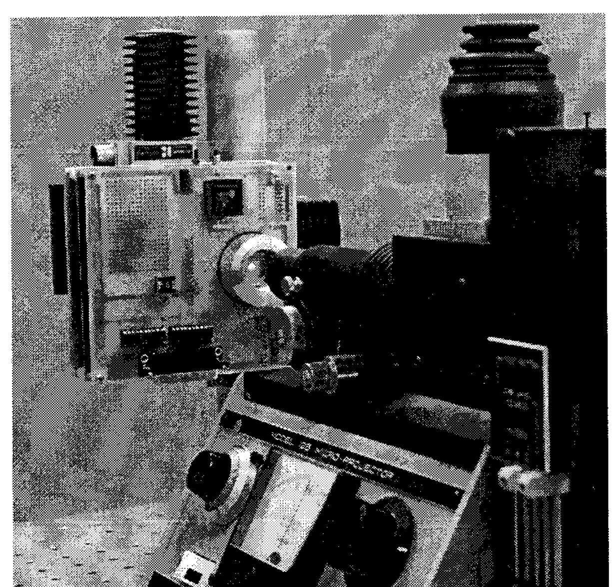

Figure 3. Developmental model PIM in laboratory calibration set-up

Figure 4. Real sky star field image taken with an earlier, analog-output 256×256-pixel APS[6]

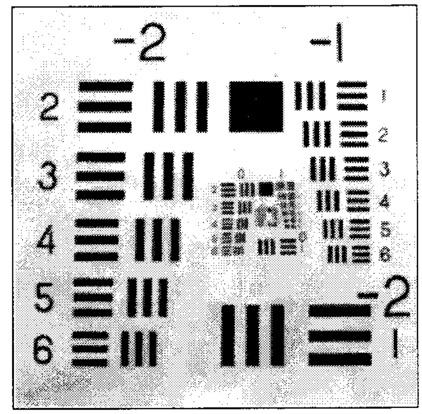

Figure 5. Resolution test chart image taken with the developmental model PIM

4. PROCESSOR CONFIGURATION

Realizing the low-power, low-mass, modular, and multi-functional goals of the PIM task requires incorporating the most recent technological innovations in processor architecture, semiconductor devices, and algorithms. This is illustrated by the design and implementation of the first, or developmental, model. It makes use of the highly-integrated and low-power devices to keep the component count down and to reduce overall power consumption. A block diagram is shown in Fig. 6. The PIM processor must provide adequate computation power to accomplish the task of the autonomous star tracker and flexibility to handle device interface and host communication. Since the overriding concern is power consumption, the selection of processors has been limited to RISC devices. RISC architecture lends itself better to pipelining and requires far fewer gates for implementation[9,10].

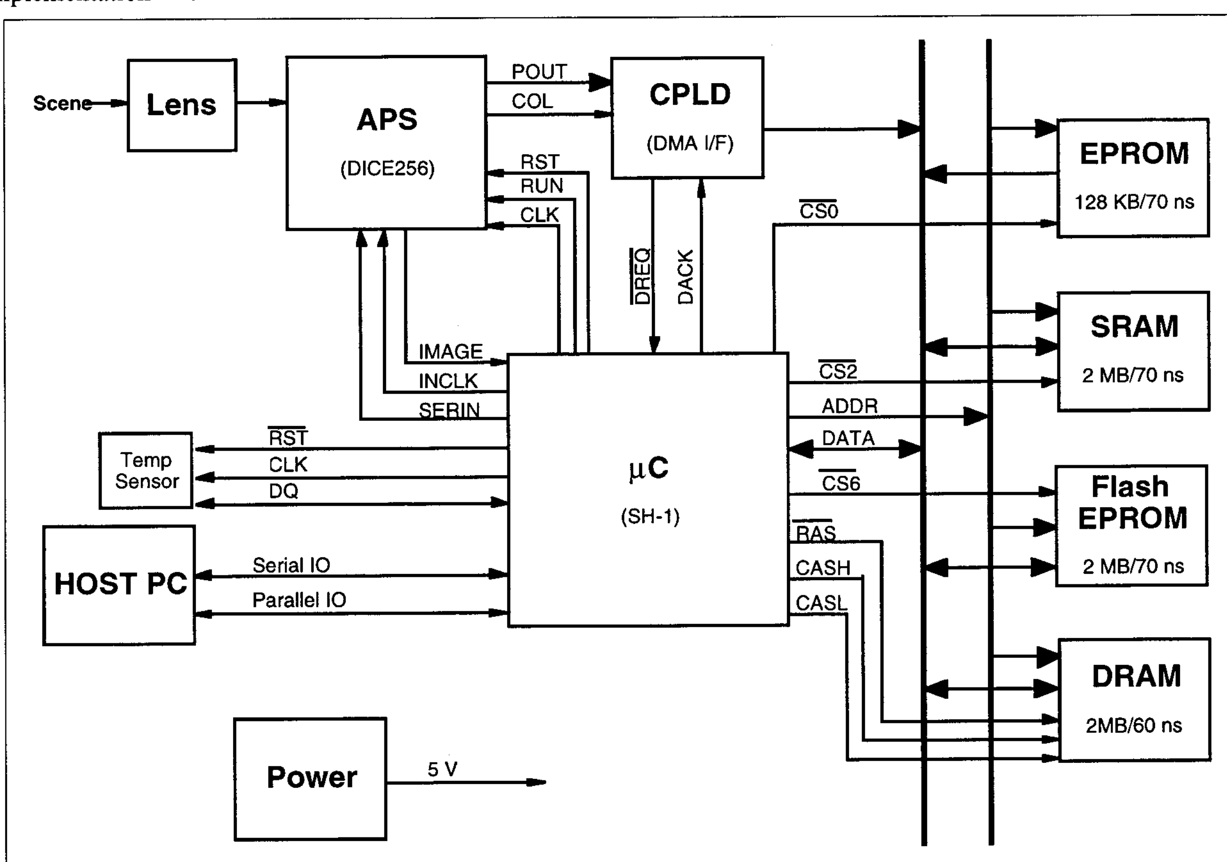

Figure 6. Block diagram of developmental model PIM

A microcontroller was chosen in favor of the microprocessor because of its ease of use and its abundance of built-in peripherals. Sophisticated ASICs are unnecessary to implement controllers for DMA, memory, timers, I/O etc., which would increase component count and power. Since RISC processors have a small CPU core, they usually have more silicon real estate left to include these peripheral features, which are software configurable and adapt easily to different hardware architectures. Most of the peripheral features are similar among varying microprocessors, which makes a transition between them easy.

In the interest of efficiency, the choice was further limited to processors which are supported by the GNU™ tool chain and available on a variety of host platforms, including Linux. The GNU tool chain is familiar to most developers and thus reduces the effort of porting the software.

Some of the prominent 32-bit RISC processors designed for embedded applications are MIPS, ARM, and Hitachi's SH series. They are similar in many ways; e.g., they are designed for handheld computers and are the engines of some popular video game stations. The SH-1 processor was chosen for the first implementation because it has a good set of peripherals and achieves good code density with its 16-bit instruction encoding. It is inexpensive and readily available, and with some existing code for it including bootstrap code and a real-time OS.

Some of the features of the SH-1 processor are:

- 16 Dhrystone MIPS at 20 MHz
- 8 Kbyte on-chip RAM
- DRAM controller
- 4 DMA channels
- 5-channel 16-bit integrated timers
- 40 I/O channels
- 2 serial channels
- watchdog timer
- 9 external interrupt sources
- 8 10-bit ADCs
- 500 mW at 5V
- power down mode

Lacking a floating point unit (FPU) could be a serious handicap for achieving high-speed update rate. Floating number operations are emulated in software. It is yet to be determined if the desired 1–2 Hz update rate is achievable and if software can be optimized to minimize the impact of this shortcoming. The high-end processors in the same family do offer FPU, but the trade-off is power and peripherals.

The addressable memory space of SH-1 is divided into four main areas so that only one memory area is turned on at one time. Memory space is assigned as follows:

- 128-KB 70-ns EPROM
- 2-MB 60-ns fast page DRAM
- 2-MB 70-ns SRAM
- 2-MB 70-ns Flash memory

The UV erasable EPROM is not necessary and will be replaced by Flash memory, but it is included in the development phase for the programming ease.

The tracker has an interface with a host personal computer (PC) printer port to transfer data. This is a simple and versatile link, and it requires no special hardware on the host side. The PC receives data from the printer port's status bits. Transfer speed is about 100 KB/s in the nibble mode and 130 KB/s in the byte mode.

The SH-1 CPU can be powered down to sleep mode (reducing power consumption by 33%), while the peripherals continue to run. The CPU is awakened by interrupt. The standby mode, which also shuts down the peripherals, reduces current drawn to a minuscule amount, but the CPU can only be awaken by the NMI or reset.

The SH-1 is well supported by the GNU tool chain, which includes C/C++ compiler, assembler, linker, debugger, and the standard C libraries. Currently, gcc-2.7.2.1, gdb-4.16, binutils-2.7, and newlib-1.7.1 (a version of standard C libraries for embedded applications) are used and are configured to generated COFF output. Both UNIX and Windows versions are available. A very flexible evaluation board is used to allow experimentation with its various features and code low-level drivers.

The entire system operates on a single 5-V power supply. The system is divided into two boards stacked vertically through interconnect. One board hosts the imager and the processor occupies the other. This construction allows different combinations of imagers and processors.

5. APPLICATIONS

The PIM can be extended (with little or no modification to the hardware) to perform many imaging and image processing tasks beyond tracking stars, including:

Space docking. Space docking can be performed in a final approach phase (<100 m) with a cooperative target which has an active or passive geometric pattern. The PIM is capable of recognizing the geometric pattern by comparing it to the corresponding pattern stored in memory and calculating the target object orientation and distance.

Target and feature tracking. If the target is a bright point source, a defined shape, or has a simple geometric pattern, the PIM can identify it in the field of view and track it. Also, simple planetary features can be tracked within the limitations of the algorithms and the processor throughput.

Image compression. The PIM can be used as a "space surveillance camera." It is capable of acquiring a sequence of images at time critical moments of a mission such as those that occur during flyby, boom deployment, or microprobe ejection. It will then compress and store the images in real time. Later at a non-mission critical moment, the PIM can down load the compressed images through a low bandwidth channel.

Sun sensor. If the PIM is equipped with a neutral density filter and either a "fish eye" or pin hole lens, it may be operated as a wide-angle sun sensor by calculating the centroid of the solar image.

Mars rover locator. The PIM can be used as a sensor to provide information to locate a rover on the surface of Mars. It would do this by identifying and locating the two Martian moons, Phobos and Deimos to determine the position of a rover on the Martian surface.

Stellar position determination on Mars. Another approach to determining position on the surface of Mars is to use the PIM in its star tracker mode. In principle, location can be determined from stellar pointing knowledge and the plumb-line which may be measured by accelerometers.

Non-stellar object tracking. When the PIM is operating as a star tracker, it compares real star images to an internal star catalog. In this process point sources in the real image, which cannot be matched to the internal star catalog, include distant non-stellar objects such as spacecraft, planets, moons, asteroids, debris, etc. These objects can be identified by their image motion characteristics and then tracked.

Optical navigation. The non-stellar object detection can also be utilized for deep space missions. The PIM can identify and calculate pointing vectors to other planets and moons, with known orbital elements, and/or against a stellar background. It can also be used with bright, resolved bodies against a stellar background in area integration mode, when it is close to the target object.

Micro-probe tracking. It is possible to identify and track the ejection, or capture, of a microprobe by using the non-stellar object tracking described above.

Planetary Landing. The PIM can perform as a nulling landing sensor by operating it as a differential feature tracker.

6. CONCLUSIONS

The availability of the APS image detector and powerful microcontrollers have made it possible for JPL to undertake the development of the PIM. The path to integrating these essential elements and all others on a few integrated circuits has been shown. Their functionality will depend on programming, which can be reloaded in flight. It is possible to implement a wide range of functions in a true micro-power, micro-mass, autonomous instrument.

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