A Low-cost Robotic Imaging System for High Precision Photometry

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ABSTRACT

We present early results of an experimental low cost robotic imaging system recently deployed at the Mauna Loa observatory (Hawaii). A key goal of this system is to explore the suitability of a low-cost approach using mass produced imaging components for scientific astronomical imaging. A commercial digital single lens reflex (DSLR) camera body and lens are mounted on a commercial equatorial mount. The system produces 3-color images with an etendue (product of field of view and collecting area) equal to 1 $deg^2.m^2$ for a total hardware cost below $10k. Measurement of the detector characteristics shows that the CMOS array used in the DSLR is of sufficient quality for scientific imaging. Custom data reduction algorithms are developed to make scientific use of the color images, exploring in particular algorithms to perform high precision photometry for study of variable stars and exoplanet transits

Keywords: Robotic Telescope, CMOS, photometry

1. SYSTEM OVERVIEW

The system discussed in this paper is a small experimental low-cost robotic wide field imaging system for astronomy and atmospheric science. The project is a collaboration with the NSF-funded Variable Young Stellar Objects Survey (VYSOS) project,[1] and is located at the Mauna Loa Observatory, an excellent site for nighttime astronomy. This project is aimed at exploring a low-cost approach to perform a scientifically useful all-sky 3-color imaging survey. A 1-year duration will be used to evaluate scientific performance and system reliability, as well as develop data reduction algorithms which will process the 1-yr data set. This project focuses especially on:

- Low surface brightness, large size features (atmospheric and astronomical)
- High precision photometry in 3 colors simultaneously (variable stars, exoplanet transit photometry)

The system consists of a commercial digital camera (model Canon 500D, with IR-blocking filter replaced to increase sensitivity in the red channel) with a 85mm focal length lens at F1.2 (Canon EF 85mm f/1.2L II USM). The camera is mounted on a 2-axis motorized equatorial mount (Orion Atlas EQ-G). The system (camera + mount) is computer controlled with a laptop. The data is stored on the laptop hard drive and copies to an external hard drive. The main system characteristics are:

- 150 square degree per frame (10 x 15 deg)
- 10 arcsec square pixels
- Able to reach $m_V \approx 15.5$ sensitivity over full visible sky each night (no Moon)
- 70mm aperture
- Simultaneous 3 color imaging (RGB Bayer pixel array)

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Figure 1. Two views of the system, which is mounted on the side of the VYSOS computer building. The total volume of the system is a 67 cm diameter, 35 cm tall cylinder (painted white). The bottom part of the volume consists of the electronics plate, the top part is a platform which holds the mount and the camera. The laptop computer is located inside the building on which the unit is mounted. In both images, the camera is pointing down, which is the nominal position when not observing (daytime or bad weather).

- 4 mn individual exposures (no moon illumination), photon-noise limited on sky background
- 120 exposures per night, > 40% of full sky can be imaged each night
- 2 GB raw data per night

The data volume is approximately 2 GB per night, stored locally. The data is physically retrieved every 2 month by copying it to an external drive (2 month of data = 120 GB). The average total power consumption is about 20W (including approximately 10W for laptop) at night, and 10W during the day

The imaging system is built using mass produced commercial components to minimize cost, and does not include any custom electronics or machining (other than cutting and drilling). The durability of the system is a big driver in its design. To keep the system simple and low cost, it does not have a dome: the camera points down when it rains or snows or when there are clouds. The large cylinder around the camera keeps wind down to ensure stable pointing during windy conditions, but also keeps wind from blowing rain particles upward to the camera lens during rainy weather. As the rain falls down into the cylinder, it can drip down the side of the large aluminum plate: there is a gap between the bottom of the cylinder and the top of the aluminum plate, so that the cylinder does not fill up with water. Electronics and power supplies are mounted directly below the aluminum plate so that they are protected from rain and snow. The gentle heat generated by the electronics also hels melt ice and snow on the aluminum plate. The system includes several sensors to determine if the weather is suitable for observing:

- Three webcams acquire images every minute, and are used to automatically confirm nighttime (which is primarily derived from the Sun altitude below the horizon, according to the computer clock). Visual inspection of the webcam images can also identify snow or ice on the mount or camera.
- Temperature probes facing the sky and the ground are used to detect clear sky at night: if the sky is clear, the upward looking temperature probe is colder than the downward looking probe (thermal radiation to the sky). If this temperature difference is larger than a preset limit, then the sky is deemed clear and observing can start.

- A humidity sensor is used to identify wet and humid conditions

In addition to these sensors, the weather information provided by the VYSOS observatory and the the Mauna Loa observatory are downloaded evry minute from the network. Decision to observe is made from all sensor values. The system is designed to minimize the long-term impact of weather :

- No exposed plastic (to avoid UV degradation of plastics)
- The mount has been sealed against water with silicone
- The camera is sealed (cover) except at the front (lens) which points down when weather is bad
- Use of weather-resistant materials when possible: Aluminum instead of steel when possible, Stainless instead of standard steel for bolts/nuts, use of Kapton tape when tape must be exposed.

2. DETECTOR, SENSITIVITY

The camera system uses a Canon 500D camera body, with a 15Mpix CMOS sensor. Detector characteristics were measured and used to derive the system sensitivity and optimal photon-noise limited exposure times and ISO setting.

2.1 Measured detector characteristics

The detector noise was measured by differencing two short exposure dark frames at 800 ISO. The RMS deviation between the two images is divided by sqrt(2) to compute the readout noise. The Gain was measured by differencing two images taken with a background level of 1200 ADU (after subtracting bias), using green pixels only. A quadratic subtration of readout noise is performed to isolate and measure photon noise. Scaling to other ISO values is done assuming linearly of gain with ISO setting.

Table 1. Measured detector noise and gain for different camera ISO settings. The last column of the table shows the count level for which readout noise is equal to photon noise.

	ISO 100	ISO 200	ISO 400	ISO 800	ISO 1600
Readout Noise [ADU]	10.8959	11.6364	13.9445	19.8761	32.2658
Gain [e-/ADU]	1.36	0.68	0.34	0.17	0.085
Readount Noise [e-]	15.8	7.91	4.74	3.38	2.74
Readout Noise = Photon Noise level [ADU]	161.5	92.08	66.11	67.16	88.49

Results of the measurements are given in table 3 and are in agreement with previous measurements.[2] The last column of the table shows the count level for which readout noise is equal to photon noise. Exposures should be sufficiently long to ensure that the background counts are above this level to ensure photon-noise limited performance.

2.2 Sky background

The sky background level was measured under dark sky (no Moon), with the 85mm lens at F1.2 and ISO 800 setting. Values are given in the table below for each of the 3 color channels.

- RED pixels: 8.9 cnt / sec / pix @ 800 ISO = 1.513 e- / sec / pix
- GREEN pixels: 11.1 cnt / sec / pix @ 800 ISO = 1.887 e- / sec / pix
- BLUE pixels: 6.8 cnt / sec / pix @ 800 ISO = 1.156 e- / sec / pix

The blue pixels have the smallest counts. The minimum exposure times to ensure photon-noise limited performance are given by combining the sky background count levels with the previously derived minimum count level to ensure photon-noise limited sensitivity. Table 2 shows that under dark conditions, this exposure time ranges from 6.5 sec at ISO 1600 to 190 sec at ISO 100

Table 2. Exposure time required to achieve photon-noise limited sensitivity on background (readout noise = photon noise) on a dark night.

	ISO 100	ISO 200	ISO 400	ISO 800	ISO 1600
Exposure time	190.0 sec	54.2 sec	19.4 sec	9.9 sec	6.5 sec

2.3 Dynamic range as a function of ISO setting: optimal exposure time per frame

The dynamical range is the ratio between noise and saturation for a single pixel. All values are given here for a 1hr observation, assuming that the exposure time is chosen such that readout noide = sky background photon noise under dark conditions, and that readout time is much less than exposure time.

Table 3. Detector dynamical range with optimal exposure time

	ISO 100	ISO 200	ISO 400	ISO 800	ISO 1600
Single frame exposure time	190.0 sec	54.2 sec	19.4 sec	9.9 sec	6.5 sec
Number of exposures (per hr)	18.95	66.4	185.6	363.6	553.8
Saturation level [e-/frame]	22282.2	11141.1	5570.6	2785.3	1392.6
Saturation level (e-/hr)	0.422e+06	0.740e+06	1.0339e+06	1.013e+06	0.771e+06
Dynamical range (1 hr)	6542	11471	16026	15702	11951

The best dynamical range is achieved by co-adding exposures taken at ISO 400 or ISO 800, with indivual exposures of approximately 20 sec (@ ISO 400) and 10 sec (@ ISO 800). In practive, this optimal exposure time cannot be sustained for a long survey: at 20 sec per exposure, 10 hr observation per night, the shutter lifetime (rated at 90000 exposures) corresponds to 50 nights of observation. Single frame exposure time is therefore a compromize between shutter lifetime and dynamical range . The imaging system currently operates at ISO 100 with exposure times longer than 200 sec in dark time to optimize shutter lifetime, and operation without shutter is being explored.

2.4 Dark current

The dark current for this detector is extremely low, and difficult to measure. It is several orders of magnitudes lower than the sky. An upper limit on the dark current is obtained by measuring the flux on a moonless night when the camera is pointing down. This gives an upper limit of 0.0044 e- / sec / pix (to be confirmed by more accurate measurement), measured at temperature = 3 C. With this value, it would take a 55 days long exposure to saturate the detector at ISO 100. The dark current level is about 300x lower than sky background on a moonless dark night.

3. HARDWARE AND SOFTWARE DESIGN FOR ROBOTIC OPERATION WITH NO DOME

For simplicity and cost, the camera system was designed with no dome or cover. The camera, lens, motorized mount and electronics (except the laptop computer) are outside, exposed to large temperature changes, wind, rain, snow and sunlight. The hardware and software were designed to operate in this environment, and much attention was paid to avoiding failures and bugs that could damage hardware :

- The camera must never point at the Sun: with a 70mm diameter aperture, this would destroy the camera and probably the lens as well
- The camera must not point up when raining
- The mount should not be allowed to rotate past its limits

3.1 Hardware: Protecting the camera, mount and electronics

The camera body and mount are sealed using layers of plastic film, aluminum tape and weather-proof silicone to keep water away from electronics in the mount and camera body. Most of the electronics is mounted on an aluminum plate just under the main plate supporting the mount and cylinder. A rubber foam tube is wrapped around the lower plate, making a seal with the upper plate to keep water from entering the electronics. The few connectors which are exposed to the outside are sealed with Silicone to keep moisture out.

3.2 Power failures

The full system is on a dedicated UPS, which provides about 2 hrs of power in case of a power failure. An AC to DC converter upstream of the UPS produces an analog signal (nominally about 4.5V) which is monitored by the electronics (using an analog to digital converter). If the system detects that power is out, the camera is parked and waits until power is back up to resume observations. This ensures that if a long duration power failure occurs, the camera is not left pointing up when the UPS runs out of power. Power to the mount and camera is turned off to extend UPS battery time in case of a long (more than a few minutes) power failure.

3.3 Mount

The mount used for the project does not come with limit switches, so mechanical limit switches had to be added to both axes of the mount. The limit switches are read by the computer through a digital I/O board. When homing the mount, a slow slew command is issued, and only interrupted when the mount hits the limit switch(es). Under this scheme, if a hardware failure occurs on a limit switch, or if the computer crashes during the homing routine, the mount will go past the limit switch potentially leading to hardware damage. To prevent this, a second set of limit switched is installed past the first set, and this second set is hardwired to the power of the mount: if the mount reaches one of these limit switches, it will loose power and stop. If that happens, it is possible to recover the mount remotely (but not automatically) thanks to a relays that bypass the limit switches to power back up the mount, and then issue commands to move the mount out of these limit switches. This is done while checking the webcams for mount motion, and it is essential to watch the webcam in order to know which way the mount should be moved, and how to move it back to a safe position (parked). This happened once so far: due to a software error, the mount RA axis went into the second limit switch. The mount was recovered remotely with the steps descibed above.

3.4 Software safety: Weather

Weather conditions are read from multiple sources:

- Sensors on the unit: humidity, temperature (2 sensors, differential measurement detects low- level clouds), light (3 webcams)
- VYSOS sensors: humidity, wind, rain, cloud sensor
- Mauna Loa Observatory tower weather sensors

If any of the sensors shows high humidity of rain, the camera is parked. The camera can operate if communication to outside sensors is lost, in which case is relies entirely on the sensors on the unit. If the humidity or light sensors on the unit are not returning proper signal, the camera is parked.

3.5 Power and heartbeat

As described in the hardware section above, an analog signal is monitored to check that AC power is getting into the UPS. If the power goes down, the system is parked and partially powered off (power to laptop and essential electronics left on). When executing the main loop, the software regularly updates a file (”touches it” with the unix touch command). A separate monitoring program is checking that this hearbeat is beating. If the main program crashes, the heartbeat will stop and the monitoring program takes control of the mount to park it into a safe position, and then terminates. This leaves the mount in a safe position with neither program running

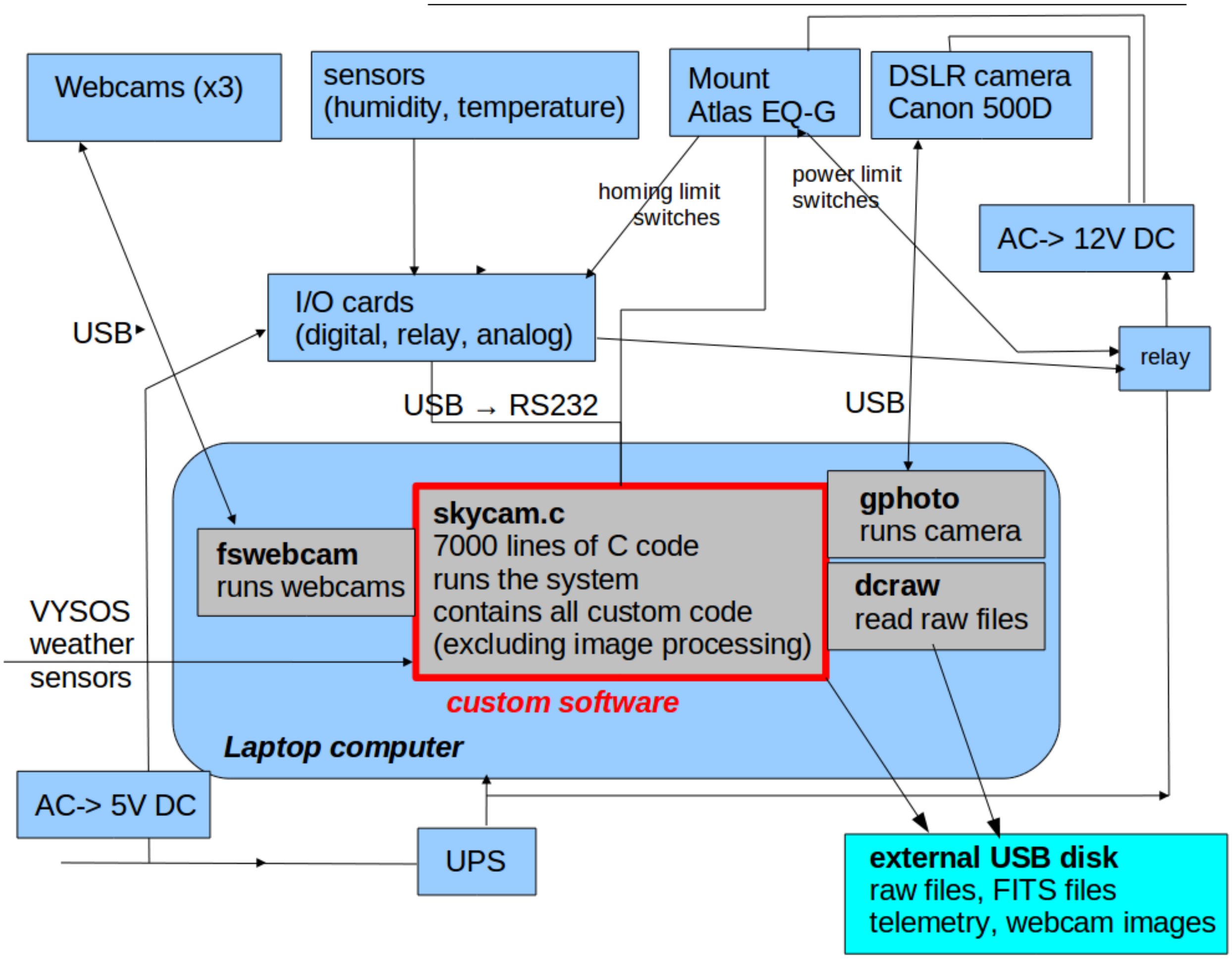

Figure 2. Software architecture. All components and software are off-the shelf, except for a single C program (7000 lines of code)

3.6 Safe mode in software

If the main loop detects an abnormal behavior, the system enters safe mode: the mount is parked and the program is terminated. The failures or behaviors that trigger safe mode include:

- Malfunction in the humidity sensor
- Failure to read or write to essential files on disk
- Timeout while waiting for an exposure to be be completed (camera failure)
- Large number of consecutive failures to talk to a device (communication failure)
- Internal software bug: the software is written to continously track which file descriptors are open and closed, and if it detects a mismatch (for example, and attempt to open a file which is already open), it will enter safe more and exit. This prevents having coding errors produce unforeseen and potentially dangerous results.

The overall electronics/software system architecture is shown in figure 2.

4. SYSTEM COST

Table 4 estimates resources needed to duplicate the system, excluding data analysis and costs associated with site (access to power, network). The total cost is $7713 per unit in hardware, and approximately 56hr of manpower to assemble, test and deloy the system.

Table 4. System cost and effort level

	Cost	Time effort (recurring)	Time effort (non-recurring)	Notes
Camera body	$549	-	-	Canon 500D
Camera lens	$1920	-	-	Canon 85mm F1.2
Mount	$1499	-	-	Atlas EQ-G
Laptop Computer	$800	-	-	-
Digital I/O board	$59	-	-	Weeder Technologies WTDIO-M
Analog I/O board	$109	-	-	Weeder Technologies WTDAC-M
Relay board	$69	-	-	Weeder Technologies WTSSR-M
Camera filter	$88	-	-	Baader astro DSLR filter
Camera filter change	-	3hr	-	Includes focusing test
Power supplies	$200	-	-	12V, 5V
UPS	$170	-	-	-
Metal stock	$200	-	-	plates, bars
Screws, bolts	$50	-	-	-
Cables and connectors	$200	-	-	includes USB-¿RS232 cable
Webcams	$150	-	-	3 USB webcams
Sensors	$150	-	-	limit switches, temperature and humidity
Paint, tape, Silicone	$150	-	-	-
Cutting, drilling	-	3hr	-	-
Cabling, assembly	-	3hr	-	-
Mechanical assembly	-	3hr	-	-
Software installation	-	3hr	16hr	install OS, software
Testing	-	20hr	-	-
Installation, debugging	-	20hr	-	Excluding travel
TOTAL	$7713	56hr	16hr	-

5. EARLY RESULTS, FUTURE WORK

5.1 Current status

The system started operating continuously in early Feb 2011. As of May 1, 2011, 10256 on-sky images totalling 398 hr of exposure time have been acquired.

An example image acquired by the system is shown in Figure 3, with minimal processing. The image quality is very good across the full field, with FWHM less than 2 pixel (20 arcsec). Figure 4 shows for each of these exposures the median pixel flux (bias-subtracted), normalized to a 1 sec exposure at 800 ISO.

Figure 3. Image of a field centered near Antares, March 1, 2011 (UT). Single 362 sec exposure at ISO 100. The full image (top) is 10x15 deg, with 10 arcsecond pixels. Bottom: portion of the field.

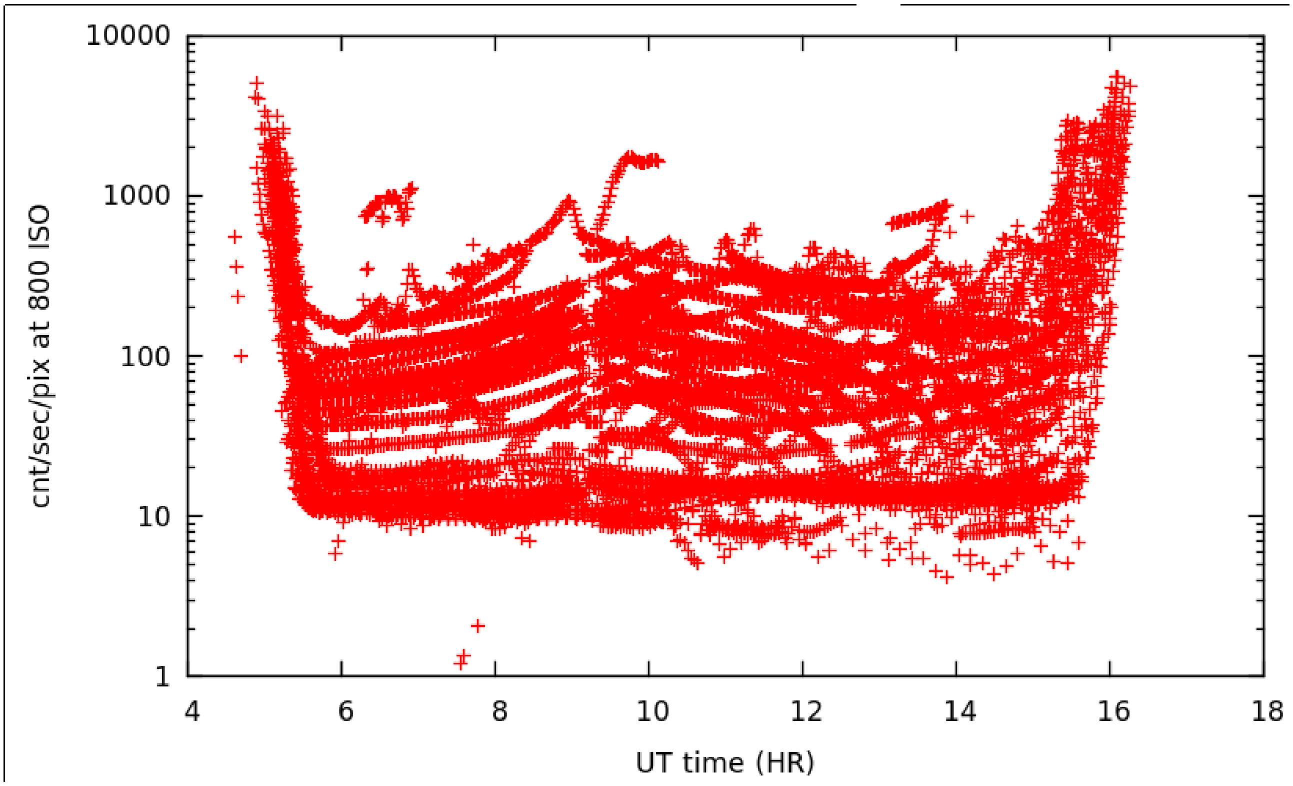

Figure 4. Median flux for each of the 10256 images acquired as of May 1, 2011. Residual daylight is visible on both ends of the night, and the large scatter in the nighttime values is due to moonlight and weather.

5.2 Photometry

Data analysis software is currently under development, and must take into account the color nature of the detector, with 3 types of pixels (R, G and B). Automatic identification of point sources in the image is first performed by subtracting background and extended sources from the image and finding groups of pixels well above the noise in the image. On the green channel of the image shown in Fig 3, this first step identifies approximately 20000 sources. The brightest sources are compared to the Hipparcos catalog to derive the astrometric parameters of the image, including field distortions due to the lens and atmospheric refraction.

Accurate photometry requires sub-pixel understanding of the chromatic PSF, which varies continuously across the field of view. Algorithms to perform this last step are currently under development, and will be described in future publications. Previous photometry work has been reported with a color CMOS array found in DSLR cameras[3] to be suitable for low accuracy photometric work. Without detailed modeling of the PSF and color pixel effects, photometric error of about 0.05 mag have been previoudly reported.[4] Smaller millimagnitude level photometric error can be achieved by defocusing the image,[5] which is unfortunately not suitable for the system discusssed in this paper due to the loss of angular of resolution.

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