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THE FLY'S EYE CAMERA SYSTEM

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RESUMEN

Hacemos una introducción del Fly's Eye Camera System, un dispositivo de monitorización de todo cielo con el propósito de realizar astronomía de dominio temporal. Este diseño de sistema de cámaras proveerá conjuntos de datos complementarios a otros sondeos sinópticos como LSST o Pan-STARRS. El campo de visión efectivo se obtiene con 19 cámaras dispuestas en un mosaico de forma esférica. Dichas cámaras del dispositivo se apoyan en una montura hexapodal que es completamente capaz de hacer seguimiento sidéreo para exposiciones consecutivas. Esta plataforma tiene muchas ventajas. Primero, sólo requiere un componente móvil y no incluye partes únicas. Por lo tanto este diseño no sólo elimina los problemas causados por elementos únicos, sino que la redundancia del hexápodo permite una operación sin problemas incluso si una o dos de las piernas están atoradas. Otra ventaja es que se puede calibrar a si mismo mediante estrellas observadas independientemente de su ubicación geográfica como de la alineación polar de la montura. Todos los elementos mecánicos y electrónicos están diseñados dentro de nuestro instituto del Observatorio Konkoly. Actualmente, nuestro instrumento está en fase de pruebas con un hexápodo operativo y un número reducido de cámaras.

ABSTRACT

We introduce the Fly's Eye Camera System, an all-sky monitoring device intended to perform time domain astronomy. This camera system design will provide complementary data sets for other synoptic sky surveys such as LSST or Pan-STARRS. The effective field of view is obtained by 19 cameras arranged in a spherical mosaic form. These individual cameras of the device stand on a hexapod mount that is fully capable of achieving sidereal tracking for the subsequent exposures. This platform has many advantages. First of all it requires only one type of moving component and does not include unique parts. Hence this design not only eliminates problems implied by unique elements, but the redundancy of the hexapod allows smooth operations even if one or two of the legs are stuck. In addition, it can calibrate itself by observed stars independently from both the geographical location (including northen and southern hemisphere) and the polar alignment of the full mount. All mechanical elements and electronics are designed within the confines of our institute Konkoly Observatory. Currently, our instrument is in testing phase with an operating hexapod and reduced number of cameras.

Key Words: techniques: photometric — instrumentation: miscellaneous — telescopes — surveys

1. INTRODUCTION

Nowadays, larger and larger telescopes are being built and the number of space telescopes are also increasing. These instruments have very good resolution but collect information from only a relatively small area, even if we consider time domain observations. However, there are many projects and initiatives to perform all-sky surveys such as Pan-STARRS (Kaiser et al. 2002) or the Large Synoptic Survey Telescope (LSST, Ivezić et al. 2008). These projects have larger sky coverage but less frequent image sampling.

Our goal is to design, build and operate an all-sky camera system performing high cadence time domain survey with high sky coverage. However, high cadence and coverage come with lower optical imaging resolution than the previously mentioned survey projects. The scientific goals of our project cover dozens of astrophysical phenomena, as it is described in Pál et al. (2013). We aimed to achieve millimagnitude level of photometric precision for $r \approx 10^{\mathrm{m}}$ stars. The all-sky camera performs sidereal tracking during the exposures and resets its position between the subsequent image acquisitions. In order to achieve this goal, we have designed a hexapod (Stewart platform) mount. This mount is rarely used as primary astronomical mount, but rather for positioning and adjusting secondary mirrors on larger telescopes (see e.g. Geijo et al. 2006). It has many advantages

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compared to an equatorial mount, for instance its usability is independent from geographical location. In this paper we describe the outline of the design and summarize the results of the first tests.

2. THE HEXAPOD DESIGN

Hexapods are a type of parallel robots with 6 internal degrees of freedom. These instruments have a good usability in flight simulators, machine tool technology and astronomy as well. In astronomy, these are mainly used as a support of secondary mirror on larger telescopes and there are a few examples for primary mount (Chini 2000; Koch et al. 2009). However, hexapods have never before been used as a primary mount in optical imaging.

2.1. *Mechanics*

This system involves six identical linear actuators with two universal joints mounted on both ends. Our choice of electromechanical actuator features a jack screw in order to transform rotary motion into linear one. To extrude or retract the actuators NEMA23 stepper motors are used. There is a 1:25 gear ratio between the stepper motor and the linear actuator's jack screw. This means that 25 full turns of the stepper motor shaft will retract or extrude the legs by 4 mm and the resolution in the actuators stroke is $0.05\,\mu$m with 3200 microsteps/turn. It is important to monitor the length of each leg continuously not only by counting the motor steps but also using an independent feedback system which involves a Hall-effect based rotary encoder (see also § 2.2). Magneto-mechanical limit switches are mounted at both ends of the actuators. In our design, all of the legs are identical except chirality. Each leg has a total stroke of 100 mm in our concept. The "home position" of the hexapod is defined as to be halfway between the fully retracted and fully extended states. In this home position, each leg has a length of 510 mm by considering the distances between the centers of the respective universal joints. Both the base and payload platforms are triangle-shaped structures with a side length of $\approx$ 700 mm. We use commercially available extruded aluminium profiles for the sides of the triangle. This design, with the actuator travel length of $\approx$ 100 mm allows $\pm 10^\circ$ of rotation range of the hexapod in any direction which grants more than an hour sidereal tracking and allows smooth operation even if one or two of the legs are stuck. The camera platform will hold approximately 50 kg of instruments with a base diameter of $\approx$ 60 cm. The hexapod skeleton (without electronics, cameras, etc.) weighs 40 kg. It is relatively cheap compared to other commercially available hexapods.

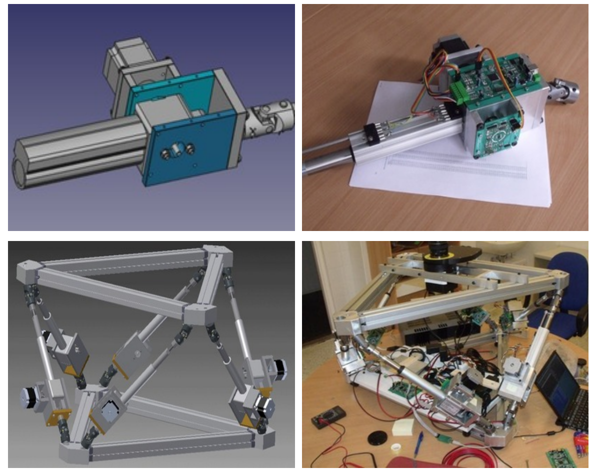

Fig. 1. *Upper left:* A CAD model of the hexapod leg with the motor and the universal joint. *Upper right:* the complete electronics mounted on the actuator. *Lower left:* a CAD view of he hexapod skeleton. *Lower right:* the complete hexapod in the lab, assembled with the electronics and a set of a single camera-filter-lens configuration.

Fig. 1 shows a CAD model compared to the completed leg and hexapod respectively.

2.2. *Electronics and firmware*

The control of the stepper motors is done by an AVR architecture microcontroller on each leg. We use a galvanically isolated RS485 interface to avoid ground loops and communication errors. The microcontroller counts the microsteps of the motors, but to achieve a complete stateless operation we designed a feedback system. The core of this is another AVR microcontroller that polls a magnetic rotary encoder and stores the shaft positions along with the rotation counts in a non-volatile ferroelectric RAM based storage. This Hall encoder has a resolution of 12 bit ($\approx 0.1^\circ$) so it is comparable to the number of the motor microsteps. The aimed accuracy and repeatability is about a micron in the actuator stroke. One of our future plans is to combine the motordriver and the rotary encoder in a single PCB (printed circuit board). All of the circuits have been designed in gEDA, an open source schematic and PCB designer program for GNU/Linux environments.

2.3. *Control subsystem and software*

RS485 interface is used for broadcast-type messaging for the ability of synchronized operations (e.g. start to retract/extend the legs at exactly the same time). The legs are connected with each other and the controller board by the RS485 bus while the bus controller is connected to a single-board computer (SBC). Individual IDs are written in the EEPROM

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of the driver microcontroller for each actuator that answers only if the controller sends a command with the correct communication protocol including the leg's matching ID. All of the legs take action to the broadcast commands (e.g., "start motion" is a broadcast message).

2.4. *Camera control and data acquisition*

We plan to use 19 wide-field cameras where the adjacend fields of $26 \times 26°$ slightly overlap and the system covers the sky above the 30° altitude. The cameras are equipped with 50×50 mm Sloan g'/r'/i' filters. During data acquisition, the filters are used in the following periodic sequence: g'/r'/i'/r'/... and so on. The lens have 85 mm focal length and $f/1.2$ focal ratio. Considering purely photon noise, this setup implies a photometric precision of $4-5$ mmags for r = 10 mag stars expecting with a sampling cadence of 3 minutes. The practical detection limit is about r = 16 mag, close to the saturation limit of LSST. We use exposures of 3 sidereal minutes and expect a duty cycle around 90%. The expositions are scheduled using Greenwich sidereal time for the comparison of images taken by different nights from the same area. The effective resolution is $22''$/pixel by employing KAF16803 4 k × 4 k detectors. The camera and the filter wheel are connected to a single-board computer via USB. The traffic of the whole device, including the camera, filter wheel, hexapod control as well as other housekeeping sensors (humidity, temperature, etc.) are tunneled via multiple TCP/IP channels. The data acquisition could therefore be controlled by any machine connected to the Internet.

3. SIDEREAL TRACKING

Sidereal tracking is not an obvious task for hexapods, although the device itself is capable of performing any kind of rotations. The proper linear combinations of leg extensions and retractions yield a rotation around the 3 axis (i.e. pure pitch, roll and yaw rotations). Assuming known parameters and dimensions of the hexapod (length of actuators, platform size, etc.) the stroke speeds of the actuators can be calculated and by setting these speeds we can achieve sidereal tracking. We used 3 sidereal minutes (roughly 179.5 seconds) of tracking time during the test series. Currently, the duty cycle is only 70% (instead of the planned 90%) because the data acquisition steps (hexapod repositioning, readout, etc.) are sequential. In the future, we will parallelize these subsequent steps.

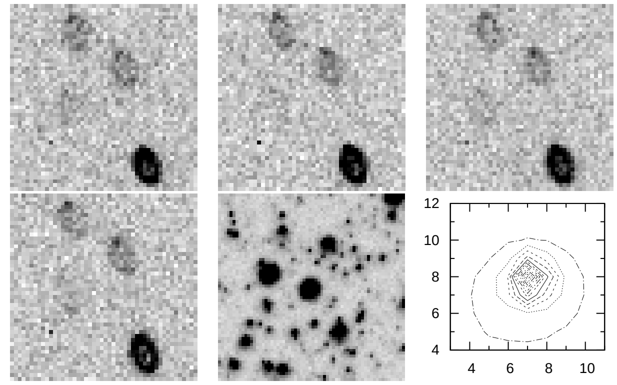

Fig. 2. *Upper and lower left:* Tracking using an $f = 800$ mm lens during a 3 min interval. *Lower center:* Image stamp of 64×64 pixels, taken with an $f = 85$ mm lens, exposure time: 130 seconds. *Lower right panel:* PSF of the stellar profile at the center of the previous image.

3.1. *Self-calibration*

In order to perform accurate sidereal tracking, a self-calibration procedure can be run. To get the numerical derivatives of the field centroid coordinates with respect to the pitch, roll and yaw rotations, we gathered 4 series of subsequent image pairs. This is done under the assumption that the device is exactly aligned to the compass points and to the horizon, and the numerical derivatives are exploited in order to compute the offsets from this perfect alignment. We used the tasks of the FITSH package (Pál 2012) for image analysis.

3.2. *Precision and repeatability*

The results of the above described procedure showed that the proper calibration of the hexapod mount gives an eligible sidereal tracking during the exposures. After the calibrations, for the first tests we used an $f = 85$ mm lens and the results were very promising. We have also done tests with an $f/8$, $f = 800$ mm catadioptric system to get detailed view of the precision of the sidereal tracking. These tests resulted in a tracking drift of $0.5''$/min, equivalent to 6×10^{-4} relative error (which is comparable to the prior assumptions for the accuracy of various dimensions of the hexapod assembly).

With the exposures scheduled by Greenwich sidereal time, we can compare the corresponding image center coordinates between distinct sidereal days. We can easily quantify this effect since the mount did many independent movement between two images taken with the same sidereal time on different nights. We found that the difference of the centroid coordinates is in the range of few arcseconds (some tenths of a pixel) with the $f = 85$ mm lens.

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4. RELATED PROJECTS

We also initiated smaller instrumentation development projects regarding to the hexapod itself. One of these is the involvement of microelectromechanical accelerometer systems (also known as MEMS accelerometers) in order to attain an independent and stateless mechanism for instrumentation control. The accelerometer is measuring the direction of gravity relatively to the MEMS chip: from such measurements we can calculate the orientation of the hexapod if all of the six legs are equipped with such a sensor.

These measurements characterized by the vector (x, y, z) where $-1 \leq x, y, z \leq 1$ if we assume that the detector itself is in rest. In other words, in these measurements we quantify static acceleration and the orientation of the chip is determined with respect to the local vertical direction. Thus, such sensors are able to yield an independent feedback about the status of the telescope mount. The accelerometer communicates via $\mathrm{I^2C}$ protocol which is mastered by a microcontroller (Fig. 3, upper left). This controller uses an RS485 bus to communicate with the frontend or another accelerometer units connected in a serial manner.

Without any kind of calibration, the accuracy is in the level of a few degrees, i.e. the systematic errors are few hundredths of the standard gravity. We currently perform more sophisticated tests to calibrate the instrument in order to yield sub-arcminute accuracy level. As a calibration procedure we take numerous measurements in positions that cover a sphere nearly uniformly. Ideally, each of the measured vectors (x, y, z) should be on a spherical surface, i.e. $x^2 + y^2 + z^2$ should be equal to unity. However, in reality, the lengths of these raw vectors differ from unity with a standard deviation of the aforementioned uncertainty of a few hundredths. By assuming a properly chosen set of $x' = x + C_x(x, y, z)$, $y' = y + C_y(x, y, z)$, $z' = z + C_z(x, y, z)$ correction functions, one could fit the $(x')^2 + (y')^2 + (z')^2 = 1$ surface. The resulted coefficients of $C_{x,y,z}$ can then be exploited in order to correct the raw values during *in situ* measurements. Our initial tests show that with such a procedure, it is easy to go below the arcminute level in the accuracy (i.e. the fraction of $\lesssim 10^{-4}$ of the standard gravity).

The proper sampling of the (x, y, z) vectors on a spherical surface is done by a mechanical device resembling to a differential (Fig. 3, lower right). With the proper combination of gear rotations, the whole sphere can be sampled with high density thus we can get a good fit and accurate correction values.

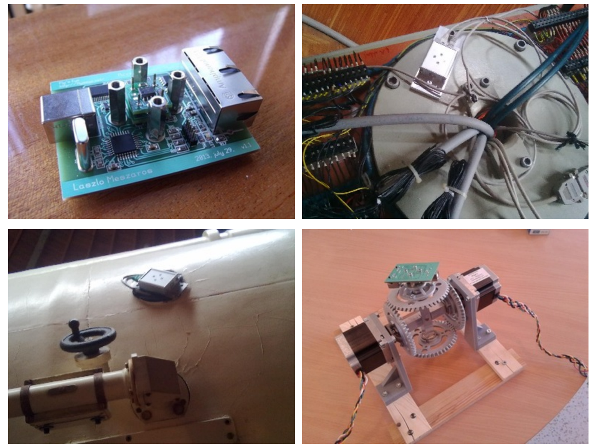

Fig. 3. *Upper left:* the motherboard PCB with the "multi-floor" $\mathrm{I^2C}$ bus. *Upper right and lower left:* an accelerometer unit mounted on the fork of the Piszkés-tető Observatory Schmidt telescope. *Lower right:* The differential mechanical device with the mounted accelerometer PCB..

5. SUMMARY

In this paper we showed the concept of the Fly's Eye Camera system with detailed description of the hexapod mount, electronics, camera system and control. By reason of redundancy there are several build-in feedback systems to ensure autonomous operation without (or with the least) human interaction. We found that this hexapod geometry with tracking algorithm and self-calibration is capable of very precise and accurate sidereal tracking. Our results proved that such a hexapod platform can be a suitable mount for optical imaging systems.

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