INSTRUMENTATION DEVELOPMENTS IN THE ASPECTS OF TIME-DOMAIN ALL-SKY SURVEYING AUTONOMOUS TELESCOPES

PhD thesis

Mészáros, László (MTA CSFK)
Supervisor: Pál, András, PhD (MTA CSFK)
Consultant: Vida, Krisztián, PhD (MTA CSFK)

Eötvös Loránd University
Doctoral School of Physics, Particle Physics and Astronomy program
Head of PhD School: Tél, Tamás, DSc
Particle physics and astronomy program
Head of program: Katz, Sándor, PhD

Konkoly Thege Miklós Astronomical Institute
Research Centre for Astronomy and Earth Sciences
Hungarian Academy of Sciences

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II
Preface

“Our science of today is the technology of tomorrow.”

Edward Teller

Our motivation to observe fainter or more distant astrophysical phenomena implies the need of the development of more advanced telescopes. With the technological improvements of the XXI\textsuperscript{th} century, the sensitivity of astronomical instrumentation could evolve. These improvements are not related to only the increased aperture sizes or enhanced surface qualities, but more accurate and precise telescope mounts or new types of mounts with different operation principles also appeared in parallel with the advancement of technology. The particular requirements and development strategies of future instruments are characterized primarily by their scientific purpose. One of the key scientific goals is to perform sky surveying. The main motivations for astronomical surveying include the production of catalogues, searching of spatial or temporal variations while there are no specific constraints on the input objects and the data acquisition is more-or-less homogeneous. Considering any kind of such scientific motivation, it should always be kept in mind that regardless of the observed wavelength domain, instrumentation design for a scientific goal always goes hand-in-hand with a trade-off between imaging resolution, observation cadence (i.e. how frequently can we observe the same field) and field-of-view (i.e. what is the area on the sky which is visible in an elementary data acquisition cycle). One of the survey types where this latter quantity – the size of the field-of-view – is maximized is called all-sky surveys. In the case of these surveys, the trade-off is reduced to be between observation cadence and imaging resolution. If our survey requires high imaging resolution – usually limited by the atmospheric seeing – then this trade-off would imply that even with complex and modern instrumentation background, the cadence will be comparatively long, in the order of weeks or months. Such surveys then miss all of the astrophysical phenomena having timescales shorter than a few days. In the case of high imaging cadence, the corresponding optical or imaging system needs to cover nearly the full sky simultaneously. This is attainable by moderate size optics, having only a few tens of centimeter in diameter or it can be even more compact, like a fish-eye lens.
For the first option the imaging system subsequently scans through the sky while the fish-eye lens is able to observe the whole sky simultaneously. An alternative is to build an instrument with several identical optical elements where a single unit has an intermediate size field-of-view while the combined area effectively cover the full visible sky. Such a setup is attained by the Fly’s Eye Camera System, which is one of the first ground-based instruments of its kind.

The aim of this work is to present the details of the Fly’s Eye device, an all-sky monitoring device that is capable of operating in a fully autonomous manner. This goal demanded the development of numerous kind of electronics, 4 mechanics and software algorithms which have been done within the confines of Konkoly Observatory of the Hungarian Academy of Sciences. In Chapter 1 a brief introduction is given about astronomical instrumentation in general and I also present both the concepts of the Fly’s Eye device and our intentions of developing such a unique telescope. While being a full-sky monitoring instrument, the Fly’s Eye Camera also needs to perform sidereal tracking in order to compensate for the apparent motion of the sky. This tracking is performed by a so-called hexapod mount. The technical details and the theory of the motion of this hexapod mechanics are described in Chapter 2. In order to implement the tracking of the apparent rotation of the sky accurately, a series of calibration procedures need to be performed. The mathematical description of these procedures can also be found in this chapter. The procedures related to the assembly of the payload platform – including the design of the individual camera units and the unique support structure –, the instrument enclosure and the power cabinet are detailed in Chapter 3. In parallel with the Fly’s Eye design, we investigated the applications of MEMS accelerometers in order to apply them in accurate telescope pointing systems. The system design, calibration scheme and results are summarized in Chapter 4. A glossary of the frequently used engineering terms used throughout this work can be found after the main chapters and the summary.
Chapter 1

Introduction to astronomical instrumentation

"Before anything else, preparation is the key to success."

Alexander Graham Bell

In 1609, Galileo Galilei was the first who looked through a refracting and magnifying tool (left panel in Figure 1.1\(^1\)) with the intention of getting better insight of the night sky. Hans Lippershey – a Dutch spectacle maker – was the one who invented the instrument used by Galileo, and proposed a patent of his invention: the telescope. Arranging various refracting elements and using it to observe celestial objects opened the possibility for investigating the Universe and discovering new astronomical phenomena. Since then, observational astronomy, instrumentation and tool-kits started to evolve – and even nowadays, astronomical instrumentation is a precise indicator of technological advances.

In terms of optical design, telescopes can be constructed by involving two schemes. The properties of refractors utilizing only lenses (i.e. refracting elements) has been described by Johannes Kepler. Soon, astronomers discovered that mirrors (reflective elements, instead of lenses) can also be used for collecting and focusing light. While many designs were proposed (e.g. by James Gregory), Sir Isaac Newton invented the first widely used optical arrangement in 1668, the so-called Newtonian telescope (right panel in Figure 1.1\(^2\)). Reflecting telescopes eliminate chromatic aberration, while using a concave parabolic mirror reduces the spherical aberration. Several designs and new technologies appeared with the passing of centuries: for instance, the invention of achromatic lenses in the middle of the

\(^1\)https://www.museogalileo.it/en/
\(^2\)https://pictures.royalsociety.org/image-rs-8462
Figure 1.1: Magnifying tools to gain better insight of the night sky: the telescope. 
*Left:* original refractor telescope made by Galileo Galilei. It can be found in Galileo Museum, Florence, Italy. *Right:* the second model of the Newtonian telescope built by Sir Isaac Newton in 1671 and now owned by the Royal Society of London.

XVIII\textsuperscript{th} century, the silver coated glass mirrors in the late XIX\textsuperscript{th} century or the combination of the two described telescope type yielding the catadioptric system invented in the 1820s by Augustin-Jean Fresnel – all of these were capable of perfecting the telescope and making even more compact light path configurations. In the recent few decades, technological revolution opened the era of the development of extremely large telescopes and deploying telescopes into space. Nonetheless, the fundamental principles of the telescopes have not changed.

1.1 Telescope supporting mounts

As telescopes spread widely in astronomical observatories, the need for a proper, sufficiently stable stand also arose. These structures required to be robust enough for holding the (sometimes heavy) weight of the particular instrument, while at the same time, it needed to be steerable for the proper pointing. Fixed support structures were used merely for the simplification of the mounts which were basically orientated towards the zenith and measured star positions. Single-axis mounts with one degree of freedom were also used in earlier times. These so-called transit mounts had a fixed azimuth direction and were able to rotate around a horizontal axis. Nevertheless, two-axis mounts are the most commonly used ones to support astronomical instrumentation since these are the most structurally simplistic designs which allow the observer to reach arbitrary points on the sky. In the early telescope designs, these two-axis mounts were *alt-azimuth* mechanics. Their dominance lasted until the motorization era when mechanical driving of the axes became possible. By using the so-called *equatorial mounts*, the tracking of celestial
objects became achievable by driving a single axis with constant angular speed. In the XXI\textsuperscript{th} century both the alt-azimuth and the equatorial mounts are widely employed. Due to the advancement in technology and computing, nowadays the largest telescopes exploit the alt-azimuth design almost exclusively where a proper pointing model and the synchronized operation of the drive systems of the two telescope axes make it possible to precisely track any position on the sky. Equatorial mounts are more convenient for \sim meter-sized telescopes. The aforementioned alt-azimuth and equatorial telescope mounts operates on the same principle and are referred to as sub-classes of \textit{serial robots}. This \textit{serial} property is due to the implementation of both types, i.e. the full driving system for the second axis\textsuperscript{3} is supported by and hence co-rotates with the first axis\textsuperscript{4}. With even more complex mechanical design, drive system and backend-level computing, it is possible to construct \textit{parallel robots} for supporting telescopes and allowing them to steer and track celestial objects. One of the most widely recognized parallel robot is the so-called \textit{hexapod} or \textit{Steward-platform} where the structure to be aligned (i.e. the telescope optics in our case) is supported by six legs where the length of the legs are adjustable in accordance with the intended movements. Although this class of parallel mechanics implies different treatment compared to serial robots, it is important to summarize the key concepts of both classes.

\subsection{1.1.1 Alt-azimuth mounts}

By using two rotating, perpendicular axes, a telescope can be pointed to anywhere on a spherical surface. The most straightforward is to move our telescope up- or downward (altitude) and to the left- or to the right-way (azimuth). Here, tracking is not a trivial task since it can only be achieved by simultaneously driving both axis with the appropriate (and slowly changing) speed. On the other hand, with computerized controlling and fine movement driving system, these issues can easily be handled. Further challenges are implied by the fact that such mounts follows only the apparent position of a celestial object but do not compensate for the rotation of the field-of-view. Namely, when neither of the axes are parallel with the rotation axis of the Earth, the observed field-of-view will also be rotating during the observation. This effect can be compensated for by an additional mechanical element. An another effect called a \textit{gimbal lock} has to be taken into account during tracking: The tracking speed increases with higher elevation and accelerates to infinity at altitude = 90\degree yielding a limitation for these mounts while tracking at high, 89\degree \lesssim h altitudes.

\textsuperscript{3}This second axis or second stage is referred as declination and altitude axis, for equatorial and alt-azimuth telescopes, respectively.

\textsuperscript{4}The first axis or stage is referred as hour angle and azimuth, for equatorial and alt-azimuth telescopes.
1.1.2 Equatorial mounts

For this type of mechanics one of the axis (the hour axis) is parallel with the rotation axis of the Earth (i.e. it points to the celestial pole) while the another one (the declination axis) is perpendicular to it. This setup is free from the field rotation effect but it requires accurate polar alignment to implement fine tracking. These systems are equipped with a mechanism called clock drive that revolves the right ascension axis once within almost exactly 23 hour, 56 minutes and 04 seconds, i.e. the length of one sidereal day. Thus, with this mount the tracking can be achieved by rotating a single axis. Construction uncertainties and non-zero tolerances in the manufacturing process yield various sources of misalignments in these mounts. For instance, the optical axis is not necessarily parallel to the telescope tube or the two main axes are not perfectly perpendicular, or the hour axis is not perfectly aligned to the celestial pole (see also earlier). In addition, there are even more complex phenomena which play important roles in such mechanisms – for instance, the telescope tube or the declination axis could bend because of their own weight, with the bend angle depending on the pointing itself. Most of these effects can be characterized by algorithms called pointing models and hence these can be calibrated to have an absolute pointing in the order of a second of arc – or even better. Within these equatorial class of mounts, there are many variants which are named after or referred to by the way the two axes are fixed with respect to each other or to the ground. In Hungary, many of these variants are represented, for instance:

- Cross-axis mount (e.g. supporting the 1 m Ritchey–Chrétien–Coudé telescope at Piszkéstető Observatory, left panel in Figure 1.2.);

- Open fork mount (e.g. mount for Schmidt telescope at Piszkéstető Observatory, middle panel in Figure 1.2.);

- German equatorial mount (e.g. mounting of the former 50cm Cassegrain telescope at Piszkéstető Observatory, right panel in Figure 1.2.).

1.2 Telescopes

The etymology of the word “telescope” is originated from the Ancient Greek: telescopos means “far-seeing”. As it has been summarized earlier, this can be achieved by a device that consists of light collecting elements which can be either lenses or mirrors. Those optical devices that are equipped with lenses are called refractors while those that use a mirror for focusing the light are reflecting telescopes or reflectors. Catadioptric telescopes consist of both mirrors and special lenses.
1.2. TELESCOPES

Figure 1.2: The largest telescopes in Hungary are located at Piszkéstető Observatory with various types of equatorial mounts. Recently, the 50 cm Cassegrain telescope has been dismounted and removed in order to be replaced by a new 80 cm telescope supported by an alt-azimuth mechanics lower right. This new robotic telescope intended to perform follow-up observation of high energy transient astronomical phenomena.

1.2.1 Refracting telescope design

In case of these telescopes, a set of lenses create the image of (more-or-less distant) objects in the focal plane. Several type of distortion effects need to be considered for these telescopes: spherical aberration, coma, astigmatism, chromatic aberration, field curvature, etc. These effects can be characterized and therefore minimized by applying a series of various glass types and shapes (such as biconvex, biconcave, plan-convex, plan-concave, convex-concave, concave-convex, where one or both of the lens surfaces can also be aspherical). Refractors are not common among large telescopes, since these would require not just only very long tubes but very large and well manufactured lenses to reach the same performance a reflecting telescope is
capable of. However, it is still popular among amateur astronomers since compact refractors or photographic lenses provide faster focal ratio and therefore objects with lower surface brightness can be imaged with them. Furthermore, due to precise glass manufacturing and surface finishing the commercially available lenses used by professional photographers are capable of very high quality imaging even for astronomical purposes.

1.2.2 Reflecting telescopes

In reflecting telescopes a curved mirror is used for light collection. Compared to the refractors, these devices can be more compact for a certain diameter and effective focal length – since it is possible to fold the optical path by introducing other reflecting elements in the telescope tube. Moreover, for refractors, the lens has to be perfect and homogeneous within the whole volume of the material while for mirrors, only the surface is needed to be circularly symmetric and perfectly polished which is achievable more easily. However, some of the above described aberration effects are also present in these systems – these aberrations are then compensated by varying the shape of the primary, secondary or further mirrors and/or additional optical elements (such as with smaller lens in the light path where the diameter of the incoming focused light beam is smaller). Without the sake of completeness, some of the most common designs are the following:

- Newtonian telescope – parabolic primary, flat secondary mirror;
- Gregorian telescope – parabolic primary, ellipsoid secondary mirror;
- Cassegrain telescope – parabolic primary, hyperbolic secondary mirror;
- Ritchey–Chrétien telescope – a variation of Cassegrain design with two hyperbolic mirrors.

1.2.3 Catadioptric systems

By placing a corrector lens with a specific surface in front of the curved mirror creates a combination of the aforementioned type systems: the catadioptric telescopes. Such hybrid optical systems minimize the previously mentioned aberrations with higher efficiency than the individual designs. The best-known member of these telescopes is the Schmidt telescope design where a special shaped aspheric lens – also known as the Schmidt corrector plate – provides correction for the spherical aberration of the spherical mirror. Schmidt–Cassegrain and Maksutov–Cassegrain designs are also well known in both amateur and professional astronomical applications. The Schmidt–Cassegrain telescope uses a similarly shaped corrector plate with a parabolic mirror while in a Maksutov–Cassegrain setup a convex-concave (negative meniscus) lens provides spherical correction.
Note that the above described optics are only telescopes that are designed for observations within the visible spectrum. However, the discovery of the other bands of the electromagnetic spectrum induced the appearance of telescopes that are capable of imaging in other particular wavelength passbands. Such observations also require different types of detectors.

1.3 Imaging methods and parameters

Until the middle of the XIX\textsuperscript{th} century, imaging of astronomical objects was as sophisticated as how the observer was good at drawing. The first major leap towards unbiased astronomical imaging was due to the invention of photography. For such purpose, a glass plate covered with photosensitive material (photographic plate) has been utilized. This imaging technique has then been replaced by photoelectric methods with the appearance of charge-coupled devices (commonly known as CCDs) and later on the complementary metal-oxide semiconductor (CMOS) based imaging integrated circuits\textsuperscript{5}. The fundamentals of a CCD are as follows. Let us assume a silicon substrate covered with silicon-dioxide that is illuminated by light, i.e. bombarded with photons. Due to the photoelectric effect, electrons are emitted within the silicon plate. By arranging a matrix of electrodes on the surface of the silicon-dioxide, and applying positive voltage on these electrodes, potential valleys can be created within the silicon material. In these valleys the emitted electrons are accumulated. By periodically changing the voltages, these “charge packs” can be shifted towards the adjacent electrodes. This procedure is called readout and implies other electronics integrated on the same semiconductor substrate, such as amplifiers and and control transistors. In the terminology of electronic imaging, the segments defined by this electrode array are called picture elements or \textit{pixels}.

The combination of the telescopes and the above mentioned CCD and/or CMOS technology is often referred to as \textit{optical imaging system}. The capabilities of these telescope-detector designs are characterized by various, sometimes non-independent quantities. These parameters can be related to the optical system, the detector or the timings used on these detectors – see also Table 1.1.

\textit{Étendue} is a very informative parameter that can be computed by multiplying the field-of-view by the effective light collecting area – and therefore, it is measured in \text{deg}^2\text{m}^2. In practice, it determines the amount of information coded into a particular image.

It can be seen on Figure 1.3 that Hubble Space Telescope has the largest resolution among all of the plotted telescopes, however, this resolution is only available

\textsuperscript{5}It should be noted that while for several decades, the leading instrument variants for attaining accurate astronomical photometry were based on photoelectron-multiplier tubes, these technologies were not capable of performing imaging, only counting photons in a pre-defined aperture.
1.4 THE FLY’S EYE CONCEPT AND ITS SCIENTIFIC GOALS

<table>
<thead>
<tr>
<th>Optical system</th>
<th>Detector</th>
<th>Combined parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>aperture size</td>
<td>detector resolution (pixel size)</td>
<td>imaging resolution</td>
</tr>
<tr>
<td>focal length</td>
<td>physical detector size</td>
<td>étendue</td>
</tr>
<tr>
<td>focal ratio</td>
<td>sampling cadence</td>
<td>field-of-view</td>
</tr>
</tbody>
</table>

Table 1.1: The main parameters describing an optical imaging system. The étendue is defined by the field-of-view multiplied by the effecting light collecting area and has a unit of $\text{deg}^2\text{m}^2$.

Figure 1.3: The effective resolution and optical étendue of some currently operating and proposed telescopes. The Large Synoptic Survey Telescope (LSST) is expected to have the largest étendue among both the available and proposed telescope designs. As it can be seen from the plot, the design of the Fly’s Eye camera system has an étendue that is comparable to e.g. the Kepler Space Telescope.

for a very small fraction of the sky. Kepler has a $\sim 2$ order of magnitude smaller resolution, while its étendue is $\sim 4$ order of magnitude higher due to the significantly larger field-of-view.

1.4 The Fly’s Eye concept and its scientific goals

While investigating the relations between resolution, cadence and coverage, a trade-off between these quantities is easily seen: an instrument with high cadence, high resolution and high simultaneous celestial coverage cannot be constructed. Our
group proposed a concept of developing an all-sky (above $\sim 30^\circ$ horizontal altitude) monitoring device with high étendue that is capable of performing autonomous observations with high cadence (in the order of minutes), however with a lower imaging resolution (see also Figure 1.4). Since there are no such instruments existed before, the Fly’s Eye device intend to fill this gap.

Scientific goals

The primary purpose of the Fly’s Eye device is to perform time-domain astronomy. Therefore, its scientific targets cover a wide range of astronomical phenomena: from small bodies in our Solar System to the brighter extragalactic events.

Meteor detections enable us to derive meteoroid paths and determine the orbit of the object. Characterizing the distribution of dust in the Solar System will help astronomers to fine-tune planet formation theories. Asteroids usually have an
irregular shape, varying albedo over their surface and rotate around an inclined rotation axis. These cause rotational modulation in their brightness. By providing continuous photometric data about these we will be able to supplement the existing databases and models. The Fly’s Eye device also has the capability of monitoring hazardous near-Earth objects (NEOs).

Various fields will be able to exploit the data of the Fly’s Eye instrument to investigate astrophysical phenomena in galactic scale. Studying the star formation is a popular field of astronomy. Young stellar objects often show quasi-periodic flux changes or transient processes. By investigating intensity variations on a shorter timescale, the Fly’s Eye can contribute to the understanding of the origin of these processes. Furthermore, other stars – including our Sun – show stellar activity due to changes in their magnetic field. The time-domain observations of active stars of different ages can help us to draw important conclusions about the astrophysical background of the stellar magnetic phenomena and its evolution. Moreover, calculating the radii and mass of eclipsing binary star systems from the photometric variation provides further details about stellar evolution. Discovering of transiting extra-solar planets became available only in the recent decades when astronomical instrumentation evolved to have the required sensitivity to detect $\sim 0.01\%$ dimming in intensity. In the extremely large field-of-view of the Fly’s Eye numerous “hot Jupiter” type extrasolar planets are waiting to be discovered and characterized. Observing of Cepheid variables (the “the standard candles” of the Universe) can contribute to the refinement of the galactic distance-scale.

The monitoring of nearby galaxies for bright supernovae and transient events can provide information about extra-galactic distances. In addition, we can recruit the Fly’s Eye instrument to contribute to the newest field in astronomy: to investigate the field from which a gravitational wave is detected and look for any kind of phenomena occurred at the time of detection alert or even prior to it.

**Motivation for our instrument design: the hexapod**

The most common types of mechanics that support professional astronomical telescopes are either equatorial or alt-azimuth mounts. However, both of these have its own drawbacks that needed to be considered in order to achieve proper sidereal tracking. In the case of alt-azimuth systems, an additional mechanical device – so-called field de-rotator – is needed to eliminate the field rotation since these mechanics follow the celestial position of a particular target in a way which is related to the observation location instead of the apparent motion of the sky. While in the case of equatorial mounts, the hour axis is parallel to the rotation axis of the Earth. Here, the uncertainties can be characterized by the offset from the ideal
1.4. THE FLY’S EYE CONCEPT

case (how precisely the hour axis of the telescope points to the celestial pole), hence the apparent field rotation is negligible in the most common applications.

By considering an estimation for the field rotation, one can see that it is proportional both to the field-of-view and the offset of the driven axis from the celestial pole. Namely, by tracing a certain field for a time of \( \Delta t \), the effective field rotation will be in the order of \( \Delta t \cdot \Omega \cdot \rho \cdot \Delta p \), where \( \Omega \) is the sidereal frequency \( (2\pi/1 \text{ day}) \), \( \rho \) is the size of the field-of-view (in radians) and \( \Delta p \) is the offset of the driven axis from the celestial pole (also in radians). In the case of an alt-azimuth mechanics, \( \Delta p \approx 90 - \phi \) (where \( \phi \) corresponds to the geographical latitude). Therefore, the field rotation will not be negligible even for shorter exposure times. In addition, this latter equation implies also that the speed of a field de-rotator has a dependency on the geographical latitude. In the case of an equatorial telescope, equipped with a common detector system, both \( \Delta p \) and \( \rho \) are small, hence the field rotation is negligible even for longer exposure times. For such mounts, however, a larger field-of-view could still have significant field rotation even for a small polar misalignment. In other words, in the case of an extremely wide-field instrument like the Fly’s Eye device, even an equatorial mechanics would be ineffective in terms of proper sidereal tracking due to the presence of non-negligible polar misalignment.

All in all, we can conclude that for such a extremely wide-field instrument, we need a mount which supports tracking corrections along all of the three so-called principal axes or principal rotation axes. These three axes are usually referred to as pitch, roll and yaw. This nomenclature of rotations (and angles corresponding to various rotation directions) is widely used in flight dynamics analysis and the attitude characterization of free-floating solid objects, such as spacecrafts or satellites. In the cases when these three axes are needed to be adjusted in a finite domain, one of the most suitable device is the aforementioned parallel robot, the Steward-platform or hexapod.

This alternative solution involves parallel robotics for developing the primary mount of an optical telescope system. In the middle of the XX\(^{th}\) century, D. Stewart invented a platform the motion of which is done by 6 identical struts. In the literature, these struts are also referred to as actuators, jacks or legs – note that the name hexapod also means "six legs". These legs are attached to a base and the top moving platform in a 3 − 3 mounting arrangement. These struts can either be pneumatic, hydraulic or electric. More recently piezo-based linear actuators are also available (with a characteristic size of a few centimeters). The positioning of the top platform – which is generally referred to as payload platform or simply payload – with respect to the base can be achieved by changing the length of these actuators. The legs are attached to the platforms with control points that are usually universal joints or ball joints – depending on the construction of the leg mechanics. All in all, this construction is a system with 6 degrees-of-freedom: translation movement in lateral, longitudinal and vertical directions and rotational movement of pitch, roll and yaw. Due to the possibility of complete range spatial motion, these robots are
1.4. THE FLY’S EYE CONCEPT

Figure 1.5: **Left:** The AMiBA is a $\sim 0.5$ m sized radio telescope located on Mauna Loa, Hawaii and performs cosmic microwave background observations in the 3 mm wavelength band. The carbon fiber reinforced plastic jack screws of the hexapod are worm gear driven via electro-motors. The jacks have a length of $\sim 2.8$ m in steady position while these can be extruded by 2 meters during operation. **Right:** The Hexapod Telescope has a 1.5 m aperture mirror and carries out spectroscopic observations with its spectrograph with a resolution of $R = 50,000$ (BESO). The instrument is located at Cerro Armazones Observatory, but it is currently in a decommissioned status. Note that its secondary mirror is also supported by a hexapod.

also widely used in complex mechanical systems like aircraft simulators. Of course, their applicability is exploited in another fields, such as production automation, machine tools, medical applications or astronomy. In the recent decades, these astronomical applications mainly mean applications for aligning secondary mirrors of large telescope. In a few cases, hexapods are used as a primary mount for pointing or tracking a telescope, but not for optical imaging telescopes.

Using a hexapod as a primary mount is a rather unique approach, only few telescopes are supported by such devices. The Array for Microwave Background Anisotropy (AMiBA) telescope is a radio telescope dedicated to observing the cosmic microwave background and its distortions (see Koch et al. 2009) while the Hexapod Telescope is a 1.5 m Ritchey-Chrétien optical telescope performing spectroscopic observations with a fiber-fed eschelle spectrograph (Chini 2000). These two telescopes are shown in Figure 1.5. As it can be seen the Fly’s Eye initiative is the first telescope on the Earth that exploits a hexapod for sidereal tracking in direct optical imaging. The another type of astronomical applications of hexapod robots is the support of the secondary mirror of large telescopes (having a diameter of a few meters). See, for instance Geijo et al. (2006) for such applications in the VISTA telescope or Schipani et al. (2008) for the VST telescope. The hexapod for supporting the secondary mirror of this telescope is also displayed in Figure 1.6.
1.4. THE FLY’S EYE CONCEPT

Figure 1.6: The hexapod based secondary mirror positioning subsystem of VST telescope (left) and the VST telescope itself right.

In Chapter 2, I describe the possibility of the utilization of a hexapod kinematics for astronomical purposes. From Section 2.2. to Section 2.5 the technical details of our hexapod design are presented – the geometry and the hardware structure itself, followed by the electronics and controlling system, respectively. The mathematical solution for the device motion is given in Section 2.6. Furthermore, Section 2.7 explains a set of required calibration procedures in order to perform precise tracking and the results of the preliminary test phases that confirm the capabilities of the device.

The final assembly of the Fly’s Eye is presented in Chapter 3. In this chapter I give a detailed specification of the framework payload platform (Section 3.1) and how the individual camera units are assembled and placed in their particular positions. In Section 3.2, I demonstrate how the designed enclosure is capable of protecting the Fly’s Eye instrument. Furthermore, in the same section the power supply cabinet for the camera system and the enclosure is presented in detail, including the controlling protocol. The complete system integration is described in Section 3.3 while the effective capabilities and scientific results are presented in Section 3.4.
Chapter 2

Hexapod mount for celestial tracking

“There’s a way to do it better – find it.”

Thomas Alva Edison

Hexapods are robust and versatile parallel robots, however, they rarely applied in astronomy due to the requirement for complex control. As it has been outlined earlier, one has to overcome various difficulties in order to achieve a sufficiently precise celestial tracking for an extremely wide-field imaging instrument. The alt-azimuth and equatorial mounts cannot be calibrated precisely enough for this application hence parallel robotics have been chosen as an alternative solution.

In this chapter, first I the describe the symmetries and limitations of such robots, following by a description of the assembly. In Section 2.2, I summarize the geometry and the basic parts of a hexapod. The concept of the payload is described in Section 2.3. It followed by the details of the driving mechanism, the controller electronics and software in Section 2.4. and Section 2.5, respectively. Section 2.6 explains the mathematical background of the hexapod motion and in Section 2.7, I outline the calibration procedures and demonstrate the capabilities of the design.

2.1 Symmetry, limitation and degrees-of-freedom

The applicability of the hexapod depends on the size of the displacement and attitude movement ranges and the weight capacity that it is capable of supporting. The total displacement and rotation of the payload platform relative to the base is determined by the maximum change in the length of the legs (also called as travel length or total stroke). The characteristic size of the platforms, the location of the control joints on the platforms and the weight capacity is a function of the applied material of the platforms and the chosen type of joints and actuators. Besides of these parameters, the accuracy and precision also have a dependency on the
type of the driving mechanism. As a guideline, we can say that the translation displacement of the payload platform is in the same range as the travel length of the legs, while the maximum rotation angle ($\Delta \rho$, in radians) can accurately be estimated with the ratio between the travel length, $\Delta L$ and the characteristic size of the platform, $S_p$:

$$\pm \Delta \rho \approx \frac{\Delta L}{S_p}.$$  \hfill (2.1)

Several types of symmetries can be considered for basically all hexapod types with the layout of Figure 2.1. The legs are identical in their type, driving mechanism and the full stroke. Furthermore, the arrangement of control points shows a three-fold dihedral symmetry, $D_3$, which results in a hexagon shape with two different alternating side lengths. By these two lengths, we can parametrize the payload and the base platforms. Another numerical parameter is the length of the legs that also defines the so-called home position: the shortest or the longest possible stroke of the actuator or the middle position (halfway between these lengths). Considering symmetries, a hexapod can be parameterized with a total of $1 + 2 \times 2 = 5$ geometric quantities: the length of the legs in their home position, and the sides of the hexagon-shaped control points on both the base and payload platforms.

We can specify the hexapod further by defining the type of the control points and the legs. In our case, the screw driven electromechanical actuator (leg) and the two universal joints on both ends are the control points. Now we shall investigate if a hexapod with the given parameters can be assembled and is able to perform the required spatial motion in the expected range. In a reference frame, any solid mechanical part has 6 degrees of freedom. Each movable part also has some internal degrees of freedom. Namely, the universal joint has two internal degrees of freedom (henceforth DoF), while a ball screw driven actuator has one. Multiplying all of these DoFs by the number of the parts results in a total of $2 \times 6 \times 8 + 6 \times 7 \times 6 = 144$ DoFs for a disassembled hexapod with a fixed base. As we start to assemble the components, the DoFs are reduced. With the assembly of two fitting parts (one assembly operation) the number of the DoFs is reduced by 6. Mounting the universal joints on both end of the legs is $2 \times 6 = 12$ operations and another $2 \times 6 = 12$ operation is the installation of the legs on the base and the payload platform on the legs, respectively. Hence we reduce the DoFs by $6 \times 2 \times 6 + 6 \times 2 \times 6 = 144$ which implies the fact that such hexapod can unequivocally be assembled. As a result, only the internal DoFs have relevance. Since the universal joints are constrained to the legs and the platforms, only the variability in the length of the legs determines the total DoFs of the hexapod.
2.2 Geometric layout

As Figure 2.1 shows, the base and the payload platform has a $D_3$ dihedral symmetry in a form of a hexagon shape with alternating shorter and longer sides. In the design, these side lengths have been defined as 97.41 mm and 742.59 mm, respectively. The platforms are built as follows: extruded aluminum profiles were used for the longer sides of the hexagon, while the two control points close to each other (i.e., two neighbouring universal joints) are connected by a milled aluminum block. Both the base and payload platforms have the same setup, hence, these are interchangeable. As mentioned above, the legs are ball-screw driven linear actuators that are connected by universal joints to the platforms. The assembled hexapod has a total weight of $\sim 40$ kg excluding electronics and cabling. The length of the legs – the distance between the center points of the universal joints – are set to 510.00 mm as a home position. For our chosen actuator, the maximal effective safe travel length is $\sim 100$ mm which results in a variability in the control point distances $l_i$ ($1 \leq l_i \leq 6$) of $560 \text{ mm} \lesssim l_i \lesssim 460 \text{ mm}$. The full rotation and displacement motion domains of our hexapod design – as defined by the described geometry – are summarized in Table 2.1.

The resolution and repeatability requirements of a hexapod is determined by its application, in our case, the tracking of the apparent rotation of the sky. Our
### 2.3. PAYLOAD PLATFORM

<table>
<thead>
<tr>
<th>Direction</th>
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<th>+ limit</th>
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<td>+9.5</td>
<td>deg</td>
</tr>
<tr>
<td>Pitch</td>
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<td>+9.3</td>
<td>deg</td>
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<tr>
<td>Yaw</td>
<td>$\rho$</td>
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<td>+9.2</td>
<td>deg</td>
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<td>+72</td>
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<td>-75</td>
<td>+75</td>
<td>mm</td>
</tr>
<tr>
<td>Up-down</td>
<td>$Z$</td>
<td>-78</td>
<td>+70</td>
<td>mm</td>
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**Table 2.1:** Motion domains of the Fly’s Eye hexapod in the various rotation and displacement directions. The direction domains are defined around the home position (where the length of the legs are 510 mm). The motion domain limits for the rotations and displacements are rounded to the nearest tenth of a degree or millimeter, respectively.

The goal is to reach a resolution of 0.1 pixel for the sidereal tracking which is equivalent to 2″ for our optical setup (see Section 3.1.2.3). If we consider the equivalence of $1'' \equiv \pi/648000$, the required precision is 10 microradians. If we take into account the characteristic size of the instrument, this is equivalent to an approximately 10μm precision in the leg strokes. Our observing scheme is to perform sidereal tracking during the exposures, then reset the position of the hexapod during during image readout and filter change, and before the next exposure. It can be seen that the required rotation domain (in radians) equals to the exposure time multiplied by Earth’s sidereal angular rotation rate. A time interval comparable to the intended exposure time results in a relatively small actuator travel length during tracking, compared to the size of the hexapod. Moreover, we are able to avoid backlash in the actuators since the small travel length allows us to perform sidereal tracking by solely pushing manner with each of the actuators. For this reason, the initialization of the hexapod includes an additional retraction in order to ensure the purely pushing motion during its routine sidereal tracking operation.

### 2.3 Payload platform

The concept of the Fly’s Eye is to run simultaneous observations with 19 cameras. These are mounted on the payload platform of the hexapod by a spherical rack structure. The main parts of the camera rack structure (including parts that fixes the frame to the platform) are built using extruded aluminum profiles (similar to some parts of the hexapod) while the connection elements are 3D printed. At first glance it was questionable whether such plastic elements would be capable of holding the weight of the frame and the 19 camera units and the auxiliary hardware. However, according to our experiences in 3D printing, we found, that these printed parts are sufficiently strong and are suitable for our purpose. The characteristic
size of this structure is in the range of a meter and equipped with all the cameras, its mass is $\sim 60$ kg. From these load characteristics, the principal moment of inertia and the average force affected on the actuators can be determined.

2.4 Hexapod driving hardware

The legs responsible for the hexapod motion are high-precision ball-screw driven linear actuators with universal joints mounted on both end (see Figure 2.2). The chosen off-the-self ball-screw actuator has a 4 mm pitch thread. Combining this with a 25 : 1 speed ratio worm-drive mechanism yields a 0.16 mm length change for every full turn of the worm-shaft. In order to improve the resolution, and thus the controllability, of the motion, the worm-shaft is coupled with a 1 Nm torque stepper motor with 200 full steps. Such setup results in 0.8 $\mu$m extrusion or retraction per motor step. Furthermore, the controller logic of the motors is a high precision H-bridge based interface that is capable of sine-cosine microstepping up to the resolution of 1:16. By enabling this microstepping feature, we got 0.05 $\mu$m resolution in the actuator controlling. Therefore, during sidereal tracking, the required $\approx 0.03$ mm/s leg stroke became manageable since it is equivalent to $\approx 0.2$ turn/sec or $\approx 600$ microsteps/sec stepping frequency.

The actuator has two input shafts. One is reserved for the aforementioned motor drive while on the other axis a diametrically magnetized cylinder magnet has been mounted in clutching part. The orientation of this magnet is measured by a full-turn Hall-effect based rotary encoder, that is applied to monitor the rotation of the axis. This sensor has a resolution of 12 bit, hence, 4096 positions can be differentiated within a single turn. This resolution is comparable to the 3200 microsteps/turn that the motor driver is capable of.

The actuator can also be featured with adjustable magnetic limit switches. An onboard microcontroller unit (MCU) responsible for the polling of the limit switches, measuring the power consumption of the stepper motor and controlling the motor controller, furthermore, retrieving the shaft position using the Hall-encoder (see Section 2.5). The MCU drives the system in a way that the legs can be driven separately and in a fully autonomous manner. The motion of the motors can be programmed in various ways such as driving with constant speed, speed up or ramp down with constant acceleration or change the acceleration with a constant jerk.

In the case of applying of the ball-screw driven actuator combined with two universal joints on both ends, an interesting side effect appears. Let us imagine that the hexapod is rotated around a pivot point defined by one of these universal joints. In this case, the actuator does not have to be driven, however, the applied rotation (via the alternation of the lengths of the 5 another legs appropriately) will intrinsically turn this ball-screw mechanism and therefore change its length. This
Figure 2.2: *Left panel:* a computer-aided design (CAD) view of the hexapod skeleton structure, showing the base and payload platforms and the six legs. Each leg consists of a high precision worm gear driven ball-screw linear actuator driven by a stepper motor and two universal joints. *Right panel:* the fully assembled hexapod in the laboratory, just prior delivery for first light tests. The hexapod can be seen with mounted electronics while additional control hardware and a single-board computer (SBC) is fixed to the base platform. The payload is a single imaging camera, filter wheel and lens. For simplicity, housekeeping and lens focusing are managed via spare Serial Peripheral Interface (SPI) and/or Inter-Integrated Circuit (I2C) connectors on the base board.

Side-effect is known as the *screw rotation error* and basically present at some level whenever the payload platform is moved by another actuator. While the motor rotation is detected by the above mentioned Hall-effect sensor, this indirect effect should be measured by another independent encoder mechanism the operation of which is based on an alternative principle. By mounting an accelerometer sensor (see Chapter 4) on the actuator structure (or equivalently, to the motor support casing or the driver board which is mounted on the actuator) the tilt changes of the leg can be detected, thus the magnitude of this effect can be quantified. Moreover, these acceleration detectors can function as an alternative and/or supportive feedback system. The pointing of a hexapod based telescope can be retrieved from the accelerometer output data, however, due to the high complexity of this problem it is yet to be investigated in more details.

### 2.5 Electronics and controlling

As mentioned above, each actuator is driven by an A4982 type high-precision microstepping motor driver. This is supervised by an ATmega328P 8-bit Alf and Vegard’s reduced instruction set computing architecture (AVR) microcontroller featured with 32 KBytes of in-system self-programmable flash program memory, 1 KBytes of electrically erasable programmable read-only memory (EEPROM) and 4 KBytes of internal static random-access memory (SRAM). Furthermore, the
2.5. ELECTRONICS AND CONTROLLING

Microcontroller memory is supplemented by I²C communication protocol based non-volatile ferroelectric random access memory (FRAM) with a size of 2 KBytes that can be rewritten at least \(10^{14}\) times. On the single two-sided motor-driver printed circuit board (PCB), several I²C-based sensors and auxiliary electronics are mounted such as current and temperature sensors and a digital-to-analog interface. This latter provides the reference voltage for the motor controller which regularizes the motor current. In addition, a bidirectional I²C voltage-level translator was required since the aforementioned accelerometer sensor operates on 3.3 V voltage level (see also Section 2.4 and for a detailed description see Chapter 4).

We use the universal asynchronous receiver-transmitter (UART) interface of the MCU in order to establish communication with the hexapod controller using a galvanically isolated RS485 bus. One of the advantages of using an RS485 bus is the multi-drop property: commands sent via this bus are read by all of the six hexapod legs simultaneously. Therefore, the motion of the legs can be controlled with the exact same timing. Figure 2.3 shows the block diagram of the hexapod subsystems. For debugging purposes, an USB interface has been added to the controller by combining the transmit lines of the RS485 bus receiver and this USB interface. Both interfaces can be used for debugging or controlling the individual legs, however, not simultaneously.

The working principles and basic properties of the rotary position detection involving Hall-effect based encoders used for position feedback was described in Section 2.4. The corresponding Hall-sensor is also hosted by this board and it is located in the geometric centre of the bottom layer. The PCB is mounted on the actuator in a way that the distance between the magnet and the sensor is roughly 1 – 2 mm. Through three holes on the board in circular pattern, the PCB
Figure 2.4: The printed circuit boards for the motor driver electronics of the 6 hexapod legs. The main electronic parts (MCU, motor controller logic, etc.) are located on the top of the board while the magnetic rotary encoder is located in the geometric centre of the bottom side. Note, that a thermometer is mounted in the geometric centre of the top side thus the temperature dependency of the encoder can be characterized. The encoder can be positioned right above the diametrically magnetised cylinder magnet (clutched to the rotating axis) using the three holes in circular pattern with 120° separation.

– and hence the Hall-sensor – can easily be positioned right above the magnet (see Figure 2.4). Furthermore, this board is also responsible for the supervision of the state of the limit switch and the monitoring of the power consumption with the capability of intervening if necessary.

The MCU of this hexapod motor driver electronics runs the embedded program (also called firmware) which is responsible for the motor control, communication, motion command decoding and the aggregation of the data provided by the sensors. Figure 2.5 shows the flowchart of this firmware with the main loops running on the MCU. Beside the main communication channels between peripherals, the RS485 bus system and the higher level control channels are indicated. All of the electronic boards of the hexapod and the Fly’s Eye device uses a half-duplex master-slave communication protocol implemented over multi-drop (such as the RS485 or, alternatively, the CAN) bus system. Since this multi-drop bus network topologically differ from the widely employed higher level fast communication solutions – which is based on point-to-point communication schemes, such as USB, Ethernet or Internet/TCP/IP – a translator is required to serialize the commands received
from a control computer. In our system design, this is implemented in the form of a multi-drop serial network access and control daemon (MDSNACD) which accesses the devices via TCP/IP-based protocol. In this system, where each of the motor drivers are connected to the same RS485 bus line, these drivers are identified by a unique address programmed into the first bytes of the EEPROM area of the microcontroller. For long-term maintainability, additional information, such as the version of the firmware is also included besides these unique identifiers (e.g., device code and node number).

During the hexapod motion control (for instance, sidereal tracking or setting the hexapod into its home position), a master device sends a packet that contains 8-bit bytes followed by a 9th control bit for more robust packet serialization. One command packet includes not only the address and the command, but also the required information for the slave device whether the master expects any answer or not. In general, each command request should be followed by an adequate answer, with the exception of broadcast commands were no reply is expected. The motion parameters of the legs (i.e., the coefficients of the polynomial functions characterizing the time dependence of the actuator strokes) can be uploaded independently for each of the 6 legs. Maximum 8 pre-programmed sequences can be uploaded in a queue and these sequences can be extended while the motors are running (to ensure a smooth motion). By sending a “START” broadcast message, all of the drivers can perform the pre-programmed motion simultaneously. This way a smooth, continuous and synchronized leg operation can be achieved. Within the MCU core, the primary peripherals are constantly running (polling and/or driving the RS485 bus, reading the magnetic encoder, motor step control, etc.) while the auxiliary electronics (such as the temperature sensor or the accelerometer) are awakened only by a request. Such an implementation results in an autonomous operation while polling of the individual legs is necessary to the determine their status.

2.6 Motion

The hexapod mount is intended to compensate the apparent rotation of the sky during exposures. Due to its geometry, the hexapod is able to rotate around any arbitrary axis within its allowed rotation domain. This allows a hexapod-based instrument to be independent from the geographical location. Furthermore, neither precise leveling nor polar alignment is required since the device can fine tune the tracking from the position drift of the observed sources.

With the geometry described in Section 2.2 the motion of a hexapod mechanics can be quantified by determining the attitude of the platform with respect to the base. Let us define $O$ as an orthogonal transformation matrix with the introduction
of the \( P \), \( \Pi \) and \( \Omega \) variables as the roll, pitch and yaw angles:

\[
\mathbf{O} = \exp \begin{pmatrix}
0 & -\Omega & \Pi \\
\Omega & 0 & -P \\
-\Pi & P & 0
\end{pmatrix},
\]
while $\Delta = (X, Y, Z)$ defines the offset vector between the centres of the two platforms. In the case of the home position of the design, the roll, pitch and yaw values will be $P = \Pi = \Omega = 0$, while the corresponding horizontal displacement vector components are $X = 0, Y = 0$ and the distance of the platform reference points is $Z = 348.35\, \text{mm}$. In order to apply the hexapod as a mount of an all-sky imaging instrument and determine the relative attitude of the payload platform, the $l_k$ (where $k = 1 \ldots 6$) length of the legs have to be computed as a function of the parameters introduced above, i.e. $l_k(P, \Pi, \Omega, X, Y, Z)$. By using simple vector arithmetic it results in the following formula

$$l_k = \|\Delta + \mathbf{O} \cdot \mathbf{j}_k^P - \mathbf{j}_k^B\|$$

(2.3)

where $\| \cdot \|$ denotes the Euclid norm (length) of the vectors, and $\mathbf{j}_k^P$ and $\mathbf{j}_k^B$ vectors are constants that define the distance of control point of the $k$th actuator from the payload and base platforms, respectively. Let us calculate the derivative matrix $\mathbf{L}$, which defines the changes in the length of the actuators by arbitrarily altering the orientation and/or displacement of the payload with respect to the base, or in other words, it determines the relative position of the payload in respect to the base when the actuators are controlled,

$$\mathbf{L} = \frac{\partial (l_1, l_2, l_3, l_4, l_5, l_6)}{\partial (P, \Pi, \Omega, X, Y, Z)}$$

(2.4)

The lack of parametric singularity can be checked by calculating the determinant of $\mathbf{L}$ that has to differ from zero for any allowed parameters of $(P, \Pi, \Omega, X, Y, Z)$ and/or $(l_1, l_2, l_3, l_4, l_5, l_6)$. With the previously quantified geometry of the Fly’s Eye hexapod (see Section 2.2), the following values can be derived for the $\mathbf{L}$ matrix:

$$\mathbf{L} \approx \begin{pmatrix}
+0.033 & +0.287 & +0.254 & -0.254 & -0.287 & -0.033 \\
-0.312 & +0.127 & +0.185 & +0.185 & +0.127 & -0.312 \\
-0.307 & +0.307 & -0.307 & +0.307 & -0.307 & +0.307 \\
+0.365 & -0.730 & +0.365 & +0.365 & -0.730 & +0.365 \\
-0.633 & 0 & +0.633 & -0.633 & 0 & +0.633 \\
+0.683 & +0.683 & +0.683 & +0.683 & +0.683 & +0.683
\end{pmatrix}.$$  

(2.5)

Here, the roll, pitch and yaw angles $(P, \Pi, \Omega)$ are measured in milliradians, while the distances are measured in millimeters. It can be seen from the values of the last line of the matrix (i.e. which determines the motion in $Z$ direction), that altering the position of the payload platform by 1 mm requires $\approx 0.683 \, \text{mm}$ stroke in each of the actuators. The 4th and 5th lines – which are the representatives of the $X$ and $Y$ directional motions of the payload – do not have exactly the same structure due to the fact that the right angle between $X$ and $Y$ directions is not related to $D_3$ (i.e. the 120°) symmetry.
As mentioned above, the hexapod does not suffer from any parametric singularity if the determinant of $L$ differs from zero. In order to prove this let us calculate the $L^T L$ matrix where $L^T$ denotes the transpose of the matrix $L$. The resulting matrix will be

$$L^T L \approx \begin{pmatrix}
+0.295 & 0 & 0 & 0 & +0.279 & 0 \\
0 & +0.295 & 0 & -0.279 & 0 & 0 \\
0 & 0 & +0.565 & 0 & 0 & 0 \\
0 & -0.279 & 0 & +1.600 & 0 & 0 \\
+0.279 & 0 & 0 & 0 & +1.600 & 0 \\
0 & 0 & 0 & 0 & 0 & +2.799
\end{pmatrix}, \quad (2.6)$$

which clearly shows that the $\det(L)$ unambiguously differs from zero – therefore, our hexapod design does not suffer from parametric singularity and can be operated smoothly, including the position when the hexapod is looking towards the zenith. If the corresponding calculation is repeated for an alt-azimuth mechanics with two driven axes, we would get a $2 \times 2$ matrix with zero determinant, showing that an alt-azimuth mechanics cannot be used for tracking in that position.

The inverse problem (i.e., the determination of the attitude of the payload platform with respect to the base from the known length of the legs) can be solved iteratively with the Newton–Raphson algorithm and the derivatives given by $L$. Since $L$ has only small variations in the $460–560$ mm travel length, the algorithm converges quickly. Namely, by defining $L_0$ as the derivative matrix in the $l_i = 510$ mm home position, then the root mean square of the matrix elements of $L^T L - L_0^T L_0$ is going to be around 0.07. This value is less than an order of magnitude of the elements of the $L^T L$ matrix, which implies a very fast convergence for the Newton–Raphson method.

### 2.7 Sidereal tracking

As it was mentioned earlier, hexapods are capable of performing any arbitrary rotations within the domain of the given geometry, hence can be installed at any location of Earth as telescope mounts. Furthermore, no precise leveling or polar alignment is required, since these otherwise subtle corrections can also be performed by the hexapod itself.

If we assume that our device is installed on either of the poles, the tracking only requires rotation around the vertical axis, i.e. purely yaw rotation ($P = \Pi = 0$ and $d\Omega/dt = 2\Pi/P_{\text{sidereal}}$). On the other hand, if we install it on the equator, then $dP/dt$ equals to $2\Pi/P_{\text{sidereal}}$, while $\Omega$ and $\Pi$ is zero. If the device is installed at any other location, this sidereal tracking will be a combination of the aforementioned two rotations, i.e. a combination of roll and yaw rotations where the respective amplitudes of these rotations are proportional of the cosine and sine of the latitude.
A not perfectly aligned hexapod base will result in a minor angular speed of the
pitch axis.

In the initial test series of our hexapod, the device was aligned with a smart-
phone, equipped with digital bubble leveler, compass and MEMS magnetometer.
With these tools, a better than one degree precision can be achieved for the align-
ment, and this way, a sub-arcsecond precise sidereal tracking can be reached. More-
over, Equations (2.2) and (2.3) are applicable not only during tracking but also in
the full domain of the hexapod motion. If the misalignment is equal to, or greater
than several degrees we can apply an algorithm described in the following sub-
sections to determine the parameters that are needed for the computation of the
transformation matrix.

2.7.1 Self-calibrating procedure

For this calibration procedure we used the sky as the reference frame. Let us denote
the geographical latitude of a hypothetical Fly’s Eye device with \( \varphi_0 \). By assuming
that the hexapod is aligned accurately, the linearly approximated speed of the leg
strokes will be:

\[
\frac{dl_k}{dt} = n_{\text{sidereal}} (\cos \varphi_0 \frac{\partial l_k}{\partial P} + \sin \varphi_0 \frac{\partial l_k}{\partial \Omega}),
\]

where \( n_{\text{sidereal}} = 2\pi / P_{\text{sidereal}} \) is the sidereal angular frequency of Earth. The partial
derivatives \( \frac{\partial l_k}{\partial P} \) and \( \frac{\partial l_k}{\partial \Omega} \) can be computed by plugging the values of Equa-
tion (2.5) into Equation (2.4). Of course, the accurate alignment has some minor
uncertainties, which yields a deflection in the sidereal tracking, namely a position
drift in the field-of-view centroid and the field rotation. In order to quantify the
ambiguity, a series of images were acquired and the plate solutions for each image
were determined. The series should contain at least two images, however, the more
images we acquire, the more accurate our computations will be. The drift and
the field rotation can be quantified in the units of radians per second. From the
plate solutions of the subsequent images, the apparent offset and the difference in
the field orientation have to be converted into radians and divided by the image
cadence in order to obtain the drift and field rotation rates. Since numerous images
are available, linear least squares regression is applied in order to determine these
parameters. Let us denote the angular speed by \( \omega_1 \), the drift part by \( \omega_2 \) and the
field rotation by \( \omega_3 \) for the field. The time separation of the subsequent images is
\( \Delta T \). The angular speeds for each image pairs are

\[
\begin{align*}
\omega_1 &= \frac{S \Delta x}{\Delta T}, \\
\omega_2 &= \frac{S \Delta y}{\Delta T}, \\
\omega_3 &= \frac{\Delta \rho}{\Delta T},
\end{align*}
\]
where $S$ ([arcsec/pixel]) is the plate scale and $(\Delta x, \Delta y)$ is the offset of the centre of the image, while $\Delta \rho$ is the difference between the field orientations. The linear part of the differential plate transformation can be written as

$$
\begin{pmatrix}
  x' \\
  y'
\end{pmatrix} = \begin{pmatrix}
  \Delta x \\
  \Delta y
\end{pmatrix} + \begin{pmatrix}
  \cos \Delta \rho & -\sin \Delta \rho \\
  \sin \Delta \rho & \cos \Delta \rho
\end{pmatrix} \cdot \begin{pmatrix}
  x - x_c \\
  y - y_c
\end{pmatrix} 
$$

(2.11)

Here $(x_c, y_c)$ are the coordinates of the centre of the image in the pixel coordinate system (near to the half of the image pixel size). For an adequate hexapod alignment and tracking, the offset values of $\Delta x$, $\Delta y$ and $\Delta \rho$ should be in the range of pixels or tens of a pixel.

Next we add the $A_1$, $A_2$ and $A_3$ perturbation offset parameters to Equation (2.7)

$$
\frac{d\ell^{(A)}}{dt} = n_{\text{sideral}} \left[ (\cos \varphi_0 + A_1) \frac{\partial \ell_k}{\partial F} + \sin \varphi_0 + A_2 \right] \frac{\partial \ell_k}{\partial \Omega} + A_3 \frac{\partial \ell_k}{\partial \Pi} 
$$

(2.12)

By running the same procedure, it is straightforward to retrieve the corresponding $\omega_m^{(A)}$ ($m = 1, 2, 3$) angular speeds. Both the drift and field rotation can be removed, if we determine the adequate values of $A_1$, $A_2$ and $A_3$ parameters that satisfy the

$$
\omega + \sum_{k=1}^{3} A_k \frac{\partial \omega^{(A)}}{\partial A_k} = 0 
$$

(2.13)

equation. The partial derivative $\partial \omega^{(A)}/\partial A_k$ can be calculated from the test images, and can be approximated as

$$
\frac{\partial \omega^{(A)}}{\partial A_k} \approx \frac{\omega^{(A_k)} - \omega_m}{A_k}.
$$

(2.14)

The $\omega_m^{(A_k)}$ drift and field rotation angular rates are now derived from the case where the hexapod motion was perturbed, and $A_1$ is non-zero, while the other two $A_k$ ($k \neq 1$) values are zero. In total, four set of images should be acquired in order to determine the $\omega_m$, $\omega_m^{(A_1)}$, $\omega_m^{(A_2)}$ and $\omega_m^{(A_3)}$ angular velocity values.

The greatest advantage of the procedure described above is that we do not need to have any initial knowledge about the attitude of the hexapod. Furthermore, the algorithm will compensate for the screw rotation error, and can be accommodated to the conditions where one, or even three of the hexapod legs are out of order (due to some electronic or mechanical malfunction). Mathematically, it corresponds to the fact that linear combination of the $L$ matrix components have a rank of at least 3 – otherwise Equation (2.13 will be singular.

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2.7.2 Absolute calibration

From the self-calibration images, we can extract further information. Namely, the absolute position of the Fly’s Eye unit can be given with respect to the celestial reference frame by determining the apparent field coordinates of the cameras with the following procedure. First, the astrometric solution of the stellar field in J2000 system is derived from the coordinates of the visible objects. These coordinates have to be corrected for the precession, nutation, aberration and refraction by utilizing the standard procedures (Meeus 1998; Wallace 2008). Finally the resulting equatorial coordinates are collated with the local geographical latitude and sidereal time. With a similar procedure, the field rotation with respect to the J2000 system has to be transformed to the field rotation with respect to the apparent north direction.

For these celestial coordinate or field rotation conversion procedures, the singularity in the parameterization of the celestial coordinate systems has to be considered. Let the matrix $A(\alpha, \delta, \rho)$ be

$$
A(\alpha, \delta, \rho) = 
\begin{pmatrix}
\cos \alpha & -\sin \alpha & 0 \\
\sin \alpha & \cos \alpha & 0 \\
0 & 0 & 1
\end{pmatrix} \cdot 
\begin{pmatrix}
\cos \delta & 0 & -\sin \delta \\
0 & 1 & 0 \\
\sin \delta & 0 & \cos \delta
\end{pmatrix} \cdot 
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \rho & -\sin \rho \\
0 & \sin \rho & \cos \rho
\end{pmatrix},
$$

(2.15)

where $\alpha$ is the right ascension, $\delta$ is the declination and $\rho$ denotes the field rotation angle. Furthermore, $\vartheta$ denotes the local sidereal time and $\phi_0$ is the local geographical latitude. It can be shown that

$$
O = A(\alpha, \delta, \rho)^T A(\vartheta, \phi_0, 0)
$$

(2.16)

is close to unity and the vector invariant of its logarithm determines the required roll, pitch and yaw offset values that has to be passed to the hexapod control system. The vector invariant can be computed with the following equations:

$$
x = O_{32} - O_{23},
$$

(2.17)

$$
y = O_{13} - O_{31},
$$

(2.18)

$$
z = O_{21} - O_{12},
$$

(2.19)

$$
r = \sqrt{x^2 + y^2 + z^2}, \text{ and}
$$

(2.20)

$$
t = \text{Tr}(O) = O_{11} + O_{22} + O_{33}.
$$

(2.21)

Then the components of the logarithm of $O$ are

$$
\begin{pmatrix}
P \\
\Pi \\
\Omega
\end{pmatrix} = \frac{\text{arg}(t - 1, r)}{r} 
\begin{pmatrix}
x \\
y \\
z
\end{pmatrix}.
$$

(2.22)
Mészáros, L.  

2.7. SIDEREAL TRACKING

Figure 2.6: 

Left panel: a small stamp showing a region of $64 \times 64$ pixels, i.e., approximately $23' \times 23'$ area of the sky. Image has been acquired during an exposure of 130 seconds, using an $f/1.8$, $f = 85\text{ mm}$ lens and the hexapod for sidereal tracking.  

Right panel: the point-spread function of the stellar profiles are shown on the stamp of the left panel. The PSF is clearly symmetric at its core, the wings are due to the aberration of the lens. Note that if the sidereal tracking by the hexapod would completely be turned off, the lengths of the stellar trails during this 130 seconds long exposure would be $\sim 61$ pixels long, i.e., comparable to the size of the stamp itself.

or zero, in the case $x = y = z = 0$.

2.7.3 Testing the hardware and the algorithms

For testing the hexapod and the described algorithms, we acquired a series of images with a single camera unit mounted on the geometric center of the payload platform in a way that it observes the zenithal area. The camera unit has a resolution of $4k \times 4k$ and a pixel size of $9\mu m \times 9\mu m$ and equipped with an $f/1.8$, $f = 85\text{ mm}$ lens. A filter wheel was also mounted without filters to ensure the proper back focus distance. This setup was almost completely equivalent to the final optical assembly, the only difference is that $f/1.2$ lens are used instead of $f/1.8$.

As it has been mentioned in Section 2.7.1 we have taken four image sets for the approximation of Equation (2.14). Each set contains four individual frames, with an integration time of 20 s per frame. The acquisition of the series took 10 minutes in total since the duty cycle was not ideal (the readout of the images and the hexapod re-positioning procedure were not running in parallel). From the image sets, the $\omega_m$ field drift and the $\omega_m^{(A_k)}$ field rotation parameters can be determined. To retrieve the astrometric solution, we used the FITSH software package (see Pál 2012). Once the coefficients $A_k$ were known, the leg stroke speeds have been re-programmed. With the updated sidereal tracking speed, we acquired images with
an originally proposed exposure time. An image stamp and the respective point-spread function (PSF) of the central object in Figure 2.6 demonstrates that both the hexapod and the algorithm works decently. Thus, we can conclude that the hexapod design is capable of operating as a mount for an all-sky imaging system like the Fly’s Eye instrument.

The fineness of the tracking has been investigated by replacing the $f/1.8, f = 85\, \text{mm}$ lens with an $f/8, f = 800\, \text{mm}$ catadioptric lens by Samyang. The modified optical setup yields a resolution of $2.3''$ per pixel, i.e., the accuracy is increased by an order of magnitude compared to the preliminary test. Note that a reduced field-of-view is inherent in the increased focal length. With the calibrated hexapod, a $\sim 3\, \text{minutes}$ long observation sequence was run with 30 seconds of integration time for the subsequent frames. The higher resolution images showed, that the RMS deviation is in the range of 0.3 pixels, i.e., $0.7''$.

In order to investigate further the hexapod capabilities, a very sensitive and very high resolution tiltmeter (HRTM, manufactured by Lippmann Geophysikalische Messgeräte) was mounted in the centre of the payload platform. These sensors are utilized in astrogeodetic measurements (see Hirt & Seeber 2008) for determining the direction of the local gravity with respect to the vertical direction yielded by the celestial reference frame. Such instruments are capable of measuring the tilt angles (pitch and roll) with a precision of $0.01 - 0.02''/\sqrt{\text{Hz}}$. By mounting a device of this precision on the hexapod, it can be shown that its repeatability is in the range of $0.1''$. Furthermore, the hexapod has an ambient temperature dependency in the order of $\sim 1''/^{\circ}\text{C}$. It has a significant impact on the system precision, since inhomogeneous temperature in the mechanical structure may cause unpredictable thermal expansion. In order to monitor the temperature fluctuations, we mounted I$^2$C thermometers on the each motor driver electronics and on several other point within the Fly’s Eye payload (for instance, on the power distribution board of camera units and in the embedded computer).

I conclude that the Fly’s Eye hexapod design is capable of performing sidereal tracking with sub-arcsecond level precision even in long term operations. In order to keep the precision on this level, a re-calibrate procedure can be performed whenever it is required. While hexapods primarily were not meant to be telescope mounts it has been demonstrated that the $\sim 2''$ RMS residual is comparable to the pointing precision of a meter-sized telescope.
Chapter 3

The Fly’s Eye camera system

“Quality means doing it right when no one is looking.”

Henry Ford

As it was shown in the previous chapter, the hexapod mount has several advantages:

- No polar alignment is needed, and the field-rotation compensation is also part of the tracking motion sequence.

- By analyzing a series of subsequent images, one can implement a procedure which provides the self-calibrating capability of the hexapod.

- Sidereal tracking is still manageable with a hexapod, even if three of the legs are out of order. In other words, the hexapod is intrinsically tolerant to electrical and/or mechanical malfunctions.

- The hexapod has the ability of compensating for the long-term motion of the celestial pole (precession, nutation), the 435-day period free oscillation of the polar motion, called the Chandler-wobble (Chandler 1891), and the short-term irregularities of the rotation of Earth

  1

- Unlike equatorial mounts, the hexapod design is independent from geographical locations, and unlike alt-azimuth mounts, the hexapod does not have a gimbal lock, while tracking close to the zenith.

- The tracking accuracy of the hexapod is more than an order of magnitude higher than the resolution of the proposed optical setup.

  1https://www.iers.org/IERS/EN/Science/EarthRotation/EarthRotation.html
For any autonomously or remotely operated telescope the most important requirement is to possess real time information about the state of the system. For this purpose, various feedback systems are available to ensure smooth and fail-safe operation.

In this chapter, I describe the payload of the hexapod (which is the mosaic system of 19 individual Fly’s Eye camera units and its support structure), the power supply and protection of the system, the system integration and the first results related to the instrument performance.

3.1 Payload platform

3.1.1 Camera support structure

As it was shown in Section 2.3 the payload of the hexapod is a spherical rack structure which accommodates the wide-field camera units in a fashion that it can observe roughly the half of the visible sky. This spherical frame has a honeycomb-like structure and interchangeable camera units (called camera nodes or nodes) are installed in the hexagonal slots of this structure. In the following, I introduce the basic mechanical structures which are the fundamental components of the Fly’s Eye camera assembly. I detail the camera nodes in the subsequent section.

The main mechanical constraint of a camera node is that a proper assembly needs at least three separate connection points. Using three connection points significantly reduces any kind of (otherwise) elastic deformations of the support structure, while two or a single connection points would still allow a camera node either to bend or twist due to torque. While one hexagonal slot has six adjacent sides, only three of these has to bear these three connection points, so the topology of the camera node arrangement would naturally look similarly to the left panel of Figure 3.1. However, the cameras used in our design have a boxy shape, therefore we need to apply a slightly different way of mounting. For this purpose, two types of connecting elements have been designed. These can be mounted on the camera body in that fashion that forms a T-shape. The topology of these arrangement can be seen in the right panel of Figure 3.1.

In practice, the sides of the hexagonal structure are made of so-called T-slot profiles. These profiles are made of extruded aluminium, and there is a versatile range of selection from these profiles available in the market. Basically, a T-slot profile is an aluminium profile with a cross section of an X-alike shape and (usually) four T-slots on each sides, see Figure 3.2. These profiles can easily be cut to their intended length after manufacturing and the central hole also adds additional flexibility by, for instance, making it to be threaded and fixed to adjacent parts. The applied cross section size of these profiles depend on the load, in our case we
3.1. PAYLOAD PLATFORM

Figure 3.1: This sketch illustrates the topology of the camera fixation. The green hexagons represent the supporting frame, while the red lines are the mounting accessories. The blue circles and squares symbolize the camera housings. The intrinsic symmetry and topology of this arrangement can well be seen in the left panel where we assume that the cameras have a cylindrical shape. However, our camera housing has a rectangular shape, thus the final mounting solution is similar to the drawing shown in the right panel.

used 30 × 30 mm profiles with 8 mm T-slots. One of the typical connection elements to the T-slots are also called hammer nuts.

Using T-slots on the profiles (which form the frame of this hexagonal support structure) allows us to yaw the camera nodes independently from each other (see Figure 3.3). This yawing both simplifies the assembly–disassembly process and allows us to fine-tune the orientation of the field-of-view of a given camera with respect to other cameras. As we will see later on, improper alignments of these cameras can result in a sub-optimal mosaic field (see Figure 3.19 in Section 3.3).

The shape of each slot also shows a $D_3$ symmetry, however, only a few of the slots are exactly alike since the regular hexagonal topology is distorted by the curvature of the sphere. The difficulty in the design is due to the constraint that 3 sides of the hexagonal partitions have to be co-planar in order to mount the camera units in the rack slots (see Figure 3.4). Since each slot is constrained by this co-planarity, it can be seen that the connection element or “corner element” has a highly convoluted shape because at these connection points 3 differently angled profiles meet (see Figure 3.4). The manufacturing of these elements would be a challenge even for a 5-axis Computer Numerical Control (CNC) milling machine. Instead, the production of such parts is fairly simple with a 3D printer. The geometry for the 19 camera nodes and the corresponding segments of the honeycomb framework are summarized in Table 3.1, while the Figure 3.6 shows the actual topology. In total,
72 pieces of aluminum profiles (see upper panels of Figure 3.5) and 54 of these 3D printed corner elements were needed.

While the hexagonal racks are oriented in a way that the surface normal of the adjacent segments have a separation of 24 degrees, the azimuthal distance can differ for the outermost segments due to the surface curvature. This yields a higher overlapping area with the field-of-view of their neighboring units for the segments pointing to lower horizontal altitudes. An additional degree-of-freedom, namely the rotation around the optical axis in implied by the design (the mounting screws are gliding in the groove of the profile) which is required since the field-of-view of the optical setup is square shaped and needed to be aligned properly.

Note that the centre of the 1200 mm sized spherical surface defines a natural pivot point around which the hexapod need to be rotated. Using this pivot as the origin of the rotation implies the fact that during sidereal tracking the distance between the inner side of the enclosure and the dew shields of the lenses does not change.
### 3.1. PAYLOAD PLATFORM

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Table 3.1: The first column contains the segment identifier (an integer between 1 and 19), the next three columns contain the azimuth, elevation and roll angle of the segments, while the last two columns show the corresponding (rounded) hour angle and declination values for the geographical latitude of the current Fly’s Eye installation (which is $\varphi \approx 47.8^\circ$). Note that the fifth column shows negative hour angle, i.e. the angle which should be added to the sidereal time to get the right ascension of the FoV centroid. This sign difference is due to the chirality differences between the instrument coordinate system and the celestial coordinate system. The former one is right-handed while the reference system defined by the traditional hour angle - declination angles is left-handed.
3.1. PAYLOAD PLATFORM

Figure 3.3: A single camera node as it is mounted in its slot of the supporting structure. The orientation of the field-of-view can be adjusted by the sliding of the mounting screws (fixed with hammer nuts) in the T-slot. A yaw adjustment with approximately $\pm 10^\circ$ limitation is available for each particular camera nodes (see the blue and green positions). Note that in this perspective, the central circle is in fact the housing of the mechanical shutter while the boxy camera housing is located below.

3.1.2 Individual camera unit

An individual camera unit (Figure 3.7) consists of a camera, a filter wheel, a lens, a single board computer and a supervisor electronics. These subsystems are assembled together in the fashion that a unit is interchangeable – so if a serious problem occurs, it can be easily replaced by an identical one only by disconnecting the power and Ethernet cables an releasing the three mounting screws (see below).

3.1.2.1 Camera

The detector itself is an air-cooled 4k $\times$ 4k, 16 megapixel Finger Lakes Instrumentation (FLI) MicroLine camera. This camera is built around the detector KAF-16803 which has a pixel size of $9\mu m \times 9\mu m$. On the front and back sides of the camera body, a “T-shape” and a straight aluminum parts (see Figure 3.7) have been
3.1. PAYLOAD PLATFORM

Figure 3.4: A camera node is fixed into its position by 3 screws with hammer nuts. This requires the hexagon structure to have 3 co-planar sides. This constrain exist for all the adjacent slots, as it is displayed here. The red-green-blue colored planes are the co-planar faces of the supporting T-slot profiles, corresponding to these three particular camera nodes. It can be seen that these twisted profiles can only be connected by a very convoluted element.

mounted by which it can be easily installed into its position in the rack frame. At the three end – which forms an equilateral triangle – of these parts oblong-shaped holes have been milled for the mounting screw-hammer nut pairs. Since these nuts are capable of sliding in the profile groove, this setup allows the ability to align the camera unit around its $Z$ axis. Hence, we can adjust the orientation of the field-of-view. I note here that this adjustment has a limitation of a few degrees, however, it is sufficient in all cases: as it is shown in Section 3.3 for the final combined field-of-view of the device (see also Figure 3.22).

3.1.2.2 Filter wheel and data acquisition scheme

Besides simply measuring the flux variations of a celestial object, we can obtain much more astrophysical information (e.g. temperature) by using different filters. We use Sloan $u'/g'/r'/i'/z'$ filter to acquire images in well-defined standard band-passes. The data acquisition scheme is as follows. Since the sensor of the camera has its quantum efficiency peak in the middle of the $r'$ band, every 2nd image is taken.
3.1. PAYLOAD PLATFORM

Figure 3.5: Design and construction details of the Fly’s Eye camera support structure. Upper left: the CAD model of the relative alignments of the $30 \times 30 \text{mm}$ extruded aluminium profiles with the $8 \text{mm}$ slots and without the corner elements. Upper right: a photo from the workshop after cutting and lathing the profiles. Due to symmetries only 8 different lengths are needed. The lower left panel shows the fully assembled support structure as mounted on the payload platform of the hexapod. The 3D-printed corner elements can be clearly seen here. The lower right photograph shows a close-up view of a few of these corner elements and a 3D-printed part which connects the support frame to the hexapod payload platform.
3.1. PAYLOAD PLATFORM

Figure 3.6: The topology of the hexagonal camera segments with the identifiers of the installed cameras, respectively (left). A theoretical allocation of the field-of-views for the corresponding topology projected to an all-sky image (right).

Figure 3.7: A completely assembled camera node (left) which requires a 12 V power supply and internet connection for primary communication. All of the other sub-unit connections are located within this module, therefore the camera units are easily interchangeable. For redundant accessibility, an RS485 line connects the subsequent camera nodes in a serial manner and provides a backup line (e.g. for resetting) if the primary TCP/IP based uplink or the embedded control computer would not respond. The lens heating ring (right) is mounted on the middle of the lens body, right below the rubber ring of manual focusing. Its 12 V operating voltage is provided by the auxiliary electronics, including the capability of remote control. In contrary to the other electronics, the heating ring is connected to the “normally open” relay channel of the auxiliary electronics: the default state of the heater is the off state and can be turned on demand.
with this filter. For the subsequent images there is a trade-off between the sampling cadence and the astrophysical impact of the particular filter. Namely, every 6th is $g'$ or $i'$ and every 12th is $u'$ or $z'$ resulting in a $u' - r' - r' - g' - r' - i' - r' - z' - r' - etc.$ sequence. Figure 3.8 illustrates the described data acquisition sequence.

In order to obtain multi-color observations a FLI/CFW-4-5 type 5 position filter wheel have been mounted on the camera that can host 50mm $\times$ 50mm $\times$ 3mm sized filters.

During the test phase these devices showed unstable operation due to improper slot positioning or even jamming of the wheel in some rare cases. The cause of this can be that limited spacing is available between the surface of the filter wheel plate and the connector pins of lens, therefore, friction can be caused by either production uncertainties or thermal expansion. Moreover, these situations were worsened by the lack of feedback, that kept the nature of the error unknown. The factory electronics was only equipped with a magnetic Hall-sensor that can be employed as a feedback although its purpose was only the detection of the home position. The solution was the re-designing of both the electronics and the wheel plate. Some of the original interfaces, e.g. the motor controller integrated circuit (IC) were kept. The MCU has been replaced by an ATmega328. The replacing of the MCU simplifies the software development since it is widely used in previous projects by our group. Beside the Hall-sensor and the counting of the motorsteps, the electronics was upgraded with another independent feedback system. If geometry of the chain drive is known, one can monitor the chain motion via two independent opto interrupter (more specific transmissive photo-interrupters) that are separated by $1/4$ phase of the chain-link holes effectively turning the chain into incremental encoder. By comparing the output of the three feedback systems, we are able to determine the actual state of the wheel. Moreover, in case of a fault, the appropriate intervention can be performed. After replacing the wheel plates for the 19 units,
I have found for that some of these had a looser chain tension which produced a resonant effect during motion. For this purpose, I designed a small 3D printed gear, mounted on a 4mm sized deep groove ball bearings. The motor mounting screw (which located closely to the path of the running chain) can serve as an axis for the bearing thus having a chain tension unit.

The housing also has been modified in order to install a set of 0.5 mm optical fibers by which a pixel-flat field calibration procedure can be carried out (see left panel in Figure 3.9). By directing the light of the test-LED of the upgraded controller board onto the sensor as homogeneously as possible, the relative sensitivity of the adjacent pixels can be measured. The most appropriate methodology is that if the light is spread into 4 fiber channels directed to enter perpendicularly to the edge of the sensor with a few millimeter offset from the corners (see right panel in Figure 3.9). Initial images (see e.g. Figure 3.10) and the subsequent processing have already shown that this type of calibration efficiently works in practice.

### 3.1.2.3 Lenses

We use commercially available Canon lenses that have a focal length of $f = 85$ mm and $f/1.2$ fast focal ratio. The optical setup yields a $26^\circ \times 26^\circ$ field-of-view and $20''$ per pixel effective resolution. Thus, the fully assembled Fly’s Eye device will cover 10,000 $deg^2$ area of the sky of which $\sim 20 - 25\%$ are covered by overlapped fields along the sides of the individual images. Moreover, $\sim 5\%$ is doubly overlapped (in the corners). With this setup, the whole sky above $30^\circ$ horizontal altitude can be observed simultaneously.

Note, that the chosen Canon EF85 1/1.2L II USM lenses are designed to be used with 35mm full frame format sensors, while our detectors have a net size of $36.9 \times 36.9$ mm. Since the crop factor (Figure 3.11) is $< 1$, the equivalent FoV projected to a $4096 \times 4096$ pixel sized sensor can be approximated with an octagonal
shape by neglecting the $512 \times 512$ pixels of right angle triangles in the corners (see also Figure 3.6).

For such large field-of-views, the radial optical distortion has to be taken into account. The nature of this distortion does not only manifest in the decreasing profile quality of the objects, but in a shift in the position of the stars with respect to the celestial reference frame. The magnitude of this shift increases with the distance from the image centre (see Figure 3.13). Throughout this work, I used Brown–Conrady model to compensate for this type of distortion.

Since the expected right ascension and declination coordinates are known for the image centre (see Table 3.1), the list of stars for the corresponding field can be retrieved from USNO-B (Monet et al. 2003) or GAIA-DR2 catalogues (Moitinho et al. 2017). In these procedures, these catalogues are usually referred as input catalogues. On the obtained frames, a star detection algorithm was run and the pixel coordinates returned by this algorithm were cross-matched with one of the aforementioned input catalogues. The inverse transformation between pixel
Figure 3.11: In digital photography, crop factor is ratio between a reference sensor size and the applied sensor size. The reference is the 35 mm film format on which 24 mm × 36 mm frames can be acquired (green transparent rectangle). The diagonal of this rectangle is equals to the diameter of the field-of-view (blue transparent circle) for which the optics are optimized. If we superimpose the applied sensor size of 36.9 mm × 36.9 mm (red transparent square), we can see that the cross-section of the field-of-view and the sensor forms a nearly octagonal shape (red octagon). The four triangular corner areas should then been removed from further processing due to the low imaging quality.

coordinates and the catalogue coordinates was then applied on the frame centre pixel, \((x, y) = (2048, 2048)\), giving the accurate right ascension and declination coordinates of the image centre. These right ascension and declination coordinates, corresponding to either the field centroid or to the individual sources (stars, etc.) are also referred as world coordinate system coordinates or WCS coordinates\(^2\) when discussing data processing steps related to FITS images. For fine tuning, another catalogue query has been run with the resulted accurate centroid coordinates in order to provide an adequate overlapping between the field of the obtained frame and the catalogue. In this iterative process, we cross-match again the respective fields, this time having a proper matching even in the corners. Then, we apply the

\(^2\)https://archive.stsci.edu/fits/users_guide/node50.html
Brown–Conrady model on the refined input catalogue object coordinates in order to determine the magnitude of the optical distortion,

\[ x_d \approx x_u (1 + k_1 r^2 + k_2 r^4 + \ldots); \]
\[ y_d \approx y_u (1 + k_1 r^2 + k_2 r^4 + \ldots), \]

where \( x_u \) and \( y_u \) are the projected WCS coordinates, \( k_1 \) and \( k_2 \) are the distortion coefficients and \( r^2 = x_u^2 + y_u^2 \). In order to perform this WCS projection, one can use many types of radial functions. One of the most widely used is the so-called tangential projection, where the distance from the field center is proportional to the tangent of the angle of incidence. This projection is also called as the rectilinear projection since great circles on the sky are projected to straight lines.

Matching the distorted coordinates \( x_d \) and \( y_d \) again with the list of detected stars in the image, the distortion can be quantified (see Figure 3.12). The values of \( k_1 \) and \( k_2 \) can be determined iteratively by repeating the process a few times by changing the values of the coefficients. Furthermore, if we plot the projected but not distorted WCS distances as a function of distance from the centroid pixel-coordinates, the slope of the fitted line will be the focal length in pixel dimension. For this algorithm, I applied various tasks of the FITSH software package (Pál 2012).

We found that \( k_1 = -0.0763 \) and \( k_2 = -0.241 \) yields a good astrometric accuracy in the corners. Accurate astrometry is highly important, since the images are merged by their overlapping sides and corners, hence the determination of the photometric magnitudes could result fake values or even fails. Essentially, the image quality improves along the image edges if we exclude the outermost part of the lens from the imaging, i.e. by decreasing the diameter of the diaphragm. The value of the f-number is unknown since the motion of the diaphragm is done electrically in an incremental stepping manner, but this procedure can be repeated subsequently in a precise manner. This diameter of the entrance pupil is found to be optimal around \( \sim 61 \text{ mm} \) which corresponds to an f-number of \( \sim f/1.4 \).

The chosen lens type is a member of the Canon "L" series which were designed to be more durable against environmental effects, such as fine dust or humidity (these are equipped with water-resistant sealings) and can tolerate lower ambient temperatures. Despite using these robust lens, it turned out that in winter conditions may cause faults in electrical focusing and/or setting the diaphragm. To overcome these issues, I designed a lens heater ring capable of emitting 6W in total at 12V operating voltage. The basis of this lens heater is a series of resistors connected in a parallel manner, covered with heat-shrink tube, that is surrounded with a thin heat reflecting foil and packed in a 3D printed ring which can be mounted on the lens. In the final assembly, the lenses are equipped with their dew shield.

Operating the instrument on a longer term revealed that even the several applied protecting layers cannot keep the lenses sufficiently clean from e.g. dust, or large
Figure 3.12: Three representative stamps from one single image. The green circles show the resulted pixel coordinates of the stars from the input catalogue after applying the inverse transformation in the undistorted case, while the red ones indicate the results after utilizing the inverse transformation where the distortion coefficients were set. It can be seen that in the centre of the image (left panel), the two methods are yielded identically good astrometric accuracy: the red circles are plotted first and totally overlapped by the green ones. With the increasing radial distance from the centre (middle panel), differences are appearing between the two results and in the corners (right) the distorting effect became significantly larger – in the range of a few pixels. The lower intensity in the last panel is due to vignetting of the lens.

amount of insect and spider remains). In the future, the maintenance of the Fly’s Eye telescope will have to include frequent and regular lens cleaning procedures.

3.1.2.4 Controller electronics and supervisor computer

On each node, two types of electronics have been mounted. The ALIX.3d2 model from PCEngines is a single board computer (SBC) that controls the data acquisition procedure including the image handling and the filter changing. The primary communication and data uplink is done via Ethernet. The ALIX.3d2 features several communication interfaces. Two 2.0 USB standard ports are available where the camera and the filter wheel are connected, I²C for the housekeeping sensors and backup memory, SPI for the lens and an RS232 interface for communication with the supporting electronics.

The main duty of the auxiliary electronics is to distribute the power to the camera, filter wheel, SBC and lens heating with the ability of remote controlling each channel by the switching of mechanical relays (see Figure 3.14). As a feedback, the power consumption of each power output line can be monitored via embedded Hall-effect based linear current sensors. Furthermore, it can provide housekeeping measurements about the camera unit itself. The supervisor electronics is accessible via the aforementioned RS232 communication protocol from the SBC and via a
galvanically isolated external RS485 bus line into which all of the camera nodes are connected. A high-speed logical AND gate provides the multiplexing for the receive channels of these communication lines. The RS232 is the primary line of communication during routine operation, while the RS485 is reserved for backup.

3.2 Protection and power supplying

3.2.1 Enclosure

In order to protect from environmental effects, a unique dome-like structure was constructed around the Fly’s Eye telescope. 50 × 50 mm Bosch–Rexroth extruded aluminum profiles were used for the framework of the enclosure. The doors were
Figure 3.14: Block diagram of the camera node electronics subsystems, focusing on the external buses and power distribution. Thick arrows show the power lines (12V) while thinner, bidirectional arrows show the data flow and the respective bus protocol. The yellow boxes represent the parts related to the optics where the propagation of the incoming light is symbolized by the blue arrows. The node itself is represented by the dashed box.

built using the 30 × 30 mm version of the same profile. The structure is mounted on a concrete block by two profiles tightened with M16 threaded shafts from the sides. The frame is covered by aluminum plates with white painting for heat absorption and to minimize the cool down time of the enclosure.

HARL-3624 type outdoor linear actuators have been chosen to implement the opening and closing procedure. These actuators are originally designed for satellite antenna positioning, however, due to their characteristics (maximum load capacity of over 200 kg and travel length of 24” ≃ 61 cm), these actuators are perfect candidates for driving the doors. In addition, these mechanics are equipped with several feedback devices such as adjustable limit switches and built-in magnetic sensors (reed-sensors). The controller electronics is capable of counting the provided 48 pulse/inch resolution signal of the reed sensor. Thus, the position of the door can be determined with millimeter level accuracy. The travel speed depends on the load weight, and has a maximum of 5 mm/sec with maximum load. In our application, the time required for opening/closing is roughly 1 minute.

Within the enclosure, the attributes of the environment can be controlled in various manners. Temperature adjustment is done by a heating cable. The operating principle is the same as the one described in Section 3.1.2.3 for the custom
designed lens heating. In this case, a commercially available professional-grade heating cable has been chosen (see magenta cable in the left panel in Figure 3.16). It operates with mains AC and the power output is $\sim 200$ W on a length of $\sim 10$ m. This power is enough to increase the temperature well above the dew-point of the closed enclosure. Although, during the cooling of the 19 cameras, the Peltier elements also produce heat, their continuous operation would dramatically decrease the lifetime of the cameras. In order to constantly preserve the heat excess inside during shutdown, the inner surface of the enclosure is fully covered with 50 mm thick expanded polyethylene foam (“polifoam”) layer that provides efficient thermal insulation. Further isolation can be done by properly sealing the enclosure in its closed state. P-shaped rubber profiles are mounted along all the connecting edges both between the two doors and the base and the doors. Furthermore, during opening, an L-shaped wooden part installed on the inner edge of one of the doors (see right panel in Figure 3.15) protects the instrument from the snow accumulated on the top of the dome. Moreover, as a first line of defense, an aluminum plate with a rubber stripe seals the gap in order to prevent drifting snowflakes to find a way in (see left panel in Figure 3.15). The absolute humidity can be controlled by two standard 80 mm fans: one is venting the air inward while the other controls the outflow (right panel in Figure 3.16). Note that both the in- and outflow venting holes are covered with dust filters. Custom-designed environmental sensors are continuously monitoring and logging the interior temperature, humidity and atmospheric pressure data of the Fly’s Eye enclosure (see the device in the center of left panel in Figure 3.16). By installing a series of such electronics in a serial fashion, we are able to monitor the spatial fluctuation of the temperature. Thus, the above described heating cable can be operated autonomously based on the data provided by these sensors.

Redundant monitoring of the state of the enclosure doors is essential for the Fly’s Eye device to be able to operate in an autonomous manner safely. The aforementioned built-in reed sensors in the actuators send a signal after each motor turn. By counting these ticks, we can determine the actual position of the doors with an effective resolution close to 1 mm. As a secondary and tertiary feedback, the state of the limit switches and the current consumption of the motors are also polled continuously.

A surveillance camera pointed towards the direction of the Fly’s Eye was mounted on the dome building of the new 80 cm telescope. The camera is accessible via Ethernet (right panel in Figure 3.17). On its images, the date and the Universal Time is also indicated in order to confirm its validity. Finally, an accelerometer device is mounted on the inner side of both doors (see left panel in Figure 3.17). These combined subsystems provide sufficient and reliable information about the attitude of the doors. Moreover, two out of the four described feedback systems has the accuracy on $\sim 1$ mm hence the size of the remaining gap (if any) can be quantified.
3.2. PROTECTION AND POWER SUPPLYING

Figure 3.15: *Left:* An overlapping aluminum plate is mounted on one of the doors, to cover the gap between the doors. The rubber stripe was added later as a sealing. *Right:* During the commissioning of the enclosure, we tested how the snow accumulation can be handled by the various protective layers. After a snowstorm, the internal regions was completely dry and during the opening, the accumulated snow on the top of doors slipped safely downwards while wooden part can prevent the snow from accidentally falling in. With the aluminum cover it forms a “U”-shape structure in which the edge of other door fits perfectly.

If a particular feedback system is unavailable or if contradictory data are provided by the different methods, the supervisor system or person has to be notified if any intervention is required. Obviously, the safest emergency shutdown protocol would be the termination of the observation and closing the enclosure. However, the loss of one of the subsystems does not necessarily mean that the observation cycle cannot be continued.

3.2.2 Power cabinet

The power supply cabinet is deployed right next to the Fly’s Eye enclosure (see Figure 3.18). The main reason of the separated power cabinet is to avoid mains electricity entering the enclosure. The only exception regarding this is the heating cable which inevitably requires mains. The system is supplied by three-phase, 400 V alternating current mains with each phase supposed to be loaded equally. The phases are first connected to a residual-current device with a limitation of 30 mA which followed by 16 A circuit breakers. Unfortunately, at Piszkéstető Observatory, short-term (in the range of few second or millisecond) blackouts are regular. Therefore, a timing relay was added for each phase line that are connected to a solid state relay via a wired **AND** manner. The setup keeps the system unpow-ered to avoid spike-like pulses, and only recovers if all the phases are stabilized for
a given period of time. In addition, the presence of the high voltage is indicated by a LED signal lamp unit. A power socket is mounted for on-site works.

The primary energy-related products (ErPs) for the phases are the 19 power supplies which regulate the 12 V DC power level for the camera units. For the hexapod, we used its auxiliary electronics, while for the door moving actuators, a separate power supply was used. The output voltage for these devices is $\sim 13.8$ V instead of exact 12 V, since these have a valve-regulated lead-acid (VLRA) battery connecting option which requires a slightly higher voltage level. Three of such uninterruptible power supplies (UPS) has been used. As mentioned above, such anomalies are common at Piszkéstető Observatory, thus the UPS is required to ensure that the hexapod is able to return to its home position and the enclosure can be closed during a blackout. The capacity of the applied 7 Ah VLRA batteries are oversized in order to be capable of performing numerous (opening-)closing cycles and $\sim 2 - 3$ hours continuous operation with all the attached electronics.

Besides the regulation of the power for the Fly’s Eye device, the cabinet implies several other duties. Via two redundant multi-mode optical fibres (one is installed as a spare) and a media converter switch, the gigabit Ethernet uplink can be distributed into 8 channels in total, 6 of which is currently occupied. One of these is connected to the communication master device that supervises the RS485 line. The
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Figure 3.17: Left: Two accelerometers are mounted on the inner surface of the enclosure. The RJ45 couplers are mounted in the rotating axis of the doors yielding a constant cable length during the opening/closing phases. This is the same RS485 bus to which the environmental sensor devices and the hexapod itself are connected. Right: An image of the surveillance camera, showing the Fly’s Eye enclosure in a partially opened state. From the date and UT time, we are able to determine the validity of the images taken by this camera. The camera is mounted on the nearest building and it is sensitive enough to properly see the enclosure even during the night. The inlet shows this surveillance camera mounted on the building.

connected subsystems (the accelerometer based door supervising unit, the environmental sensors of the dome and the cabinet, the actuator controller electronics) can be controlled and monitored via TCP/IP. The actuator controller is featured with push-buttons by which the opening/closing procedure of the individual doors can be manually controlled on site.

The operating voltage of the actuator is 36 V. Therefore, an additional booster electronics were required in order to provide this voltage level.

The described low consumption electronics – including the media converter, busmaster, actuator controller electronics, environmental sensors, etc. – are connected to UPS of the hexapod hence these can also function during a blackout. All of the devices installed in the cabinet (excluding the VLBA batteries) have a standard 35 mm DIN-rail compatible case or can be mounted by a clip.

3.3 Project timeline and system integration

The first test runs were carried out with a single camera pointing at the zenith. The primary purpose of these observations was to demonstrate the feasibility of the Fly’s Eye concept, and in particular, the utilization of the hexapod as a telescope mount. Furthermore, investigating the performance of the optical setup. In progression, the
camera support framework has been designed parallel with the enclosure concept and its controlling subsystems. The construction of the enclosure was the second milestone that followed a few months of testing period during which the resistance to snowstorms has also been checked. After upgrading the enclosure with additional protective elements, the Fly’s Eye system was successfully installed with the first 7 cameras in March, 2016. The rest of the camera units were installed a few months later (see Figure 3.20). Ever since, the instrument has been upgraded, improved and maintained several times. And due to the redundant methodology, the Fly’s Eye was able to run continuous observations in a semi-autonomous fashion. In this semi-autonomous operation series, the instrument has been started manually after dusk while data acquisition and all of the shutdown procedures (due to twilight, clouds, weather conditions, network failures, etc.) are preformed in a fully autonomous manner.

Figure 3.21 shows the field-of-view of the respective cameras while Figure 3.22 is an ordinary mosaic image composed by all the 19 cameras. It covers an area of $\approx 10,000\text{deg}^2$. Furthermore, a zoomed image can be seen in Figure 3.23 with the Big Dipper of Ursa Major.
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Figure 3.19: A mosaic test image with 7 cameras. As it is seen the topmost field is slightly rotated; this is due to the improper alignment of the camera unit in its slot. This camera unit had then been needed to be rearranged by releasing the mounting screws and rotating the node while the sides of the adjacent field-of-views are became adjusted to provide sufficient overlaps. By having new images been acquired, the accuracy of the adjustment was confirmed.

3.3.1 Mode of operation

As it has been mentioned in Sections 2.5, 3.1.2.4 and 3.2.1, environmental data are gathered at various points of the instrument – including camera nodes, enclosure control and environmental sensors in the dome. These so-called housekeeping data are logged for monitoring instrument health, ensuring protection, and utilized for the investigation of photometric trends. These data can be shared via Message Queuing Telemetry Transport (MQTT) protocol. Using the MQTT protocol, the separated subsystems are able to subscribe for a particular topic of their interest and retrieve the message released by one of the distributors, so-called brokers. All of the messages are timestamped, and retained flag attributes are attached when published. For newly subscribed clients messages with set retained flag help to get
Figure 3.20: An aerial image of the fully assembled Fly’s Eye device. The cabinet containing the power supply units and backup batteries can be seen in the lower right corner.
the a status update immediately after they subscribe to a topic while for publishing clients it eliminates the wait for sending the next update. In other words, a retained message is the last known good value. This way each client can retrieve the most up-to-date status of the particular topic. In larger scales, the Fly’s Eye itself can be considered as a client. Via TCP/IP, it shares information of its overall status – including housekeeping data, enclosure status, error signals, etc. – while it is signed up for messages published by external devices such as the all-sky camera images or meteorological information – and further topics related to weather- and sky condition. Based on the received messages, it can be decided whether the system should start observations. These data are also timestamped, this way we are able to monitor downlink conditions and verify their validity. The times provided by individual onboard clocks of the several applied embedded computers are also published, so a client – subscribed for this topic – can compute the time-differences between the local and remote clocks and then share the results. In a similar fashion, additional timekeeping information can be handled, such as \( \text{DUT1} = \text{UT1} - \text{UTC} \) or the schedule of the leap second insertion.

Based on the above described MQTT publish/subscribe messaging protocol, the Fly’s Eye device performs routine observation as follows:

- The main embedded computer obtains the related instrument-status, housekeeping, environmental and timekeeping data from the internal end external devices via MQTT;
Figure 3.22: The combined field-of-view with all the cameras. All of the visible constellations are indicated. There are brightness differences between the adjacent images due to the difference between sensitivity and bias level of the sensors (the images are left uncalibrated for clarity). In the bottom corner of the mosaic image, Jupiter can be seen in the constellation Virgo. \textit{Inset:} An all-sky image taken at Piszkéstető. The blue octagons are the predicted field of views.
Figure 3.23: *Upper:* A zoomed part of the mosaic image where the brightest stars of the Big Dipper asterism can be seen. *Lower:* A more zoomed-in part of the image. The inlet image of Whirlpool Galaxy is a result of a combination of a series of images with a gross exposure time of 1 hour.
It analyzes these information weather the conditions are suitable for observation:

- the hexapod is working properly (no any error messages received from the legs), all the camera nodes are online and the cameras are cooled down, the filter wheels are not stuck, etc.;
- in the image of the all-sky camera, the stars can be detected with a good photometric quality (i.e., the sky is suitable of observation);
- all the environmental effects (windspeed, humidity, precipitation) are below of safety limits;
- the timekeeping data are valid.

If everything is set, a door-opening command is published and executed.

During opening/closing, initial calibration steps are performed with the hexapod (as described in Section 2.2), the cameras are cooled and dark and pixel-flat images are obtained.

After both of the doors opened successfully, their state will be updated and shared thus, the data acquisition subsystem can start to coordinate the tracking with the hexapod, setting the filters, focusing the lenses and acquiring the images.

While the doors are open, the main computer continuously sends keep-alive signals. If this is not received by the enclosure control subsystem, the Fly’s Eye is sent back to its steady state and the doors are closed automatically.

A “close” command is sent, if the weather- or sky conditions are no longer suitable for continuing the observations. Note, that during the night, several opening-closing procedures can be performed due to the sudden changes of the weather. In order to avoid rapid and non-stop opening–closing procedures, a hysteresis has been defined for the proper circumstances.

The timekeeping information are also continuously polled and the main controller computer is alerted whenever the “open” state of any of the doors times out. Updated environmental, housekeeping, timing and status data are sent in every minute and an MQTT message specified as “timed-out” if its age exceeds 70 seconds.

### 3.3.2 Storage capabilities

The fully assembled Fly’s Eye instrument with 19 cameras produces roughly 70–100 GB data per a single night. By assuming constantly good sky conditions
3.3. PROJECT TIMELINE AND SYSTEM INTEGRATION

throughout one year, this produces 30–40 TBs of data including calibration images.

A high capacity dedicated storage was assembled (see Figure 3.24) solely for the Fly’s Eye data. In the design, $10 \times 8\,\text{TB}$, $3.5''\,\text{hard disk drives}$ are combined with Redundant Array of Independent Disks (RAID) technology, namely, with a RAID6 array. With this setup, the net space available is 64 Tb, since two of the disk are reserved as parity.

A docker electronics has been designed with the purpose of remotely switching both the 5 V DC and the 12 V DC power supply of the individual disks. The power supply is a commercially available Mean Well SP-150-12 with an output current of 12.5 A at 12 V DC while the 5 V needed by the disks is regulated on the docker board separately. During startup, a sequential delay has been added in order to a) avoid inrush current performed by the numerous disks in the first few seconds b) provide enough time for the host computer to recognise the booted disks. A 5 s delay is suitable for these effects to settle. On each docker electronics, a current sensor monitors the consumption. An example plot of the power consumption as a function of time during startup can be seen in Figure 3.25.

Figure 3.24: The assembled storage rack unit in its test phase. The magenta wires are SATA cables which have been replaced by new, adequate length ones in the final design. Three standard 80 mm fans provide air cooling.
Figure 3.25: The power consumption for a hard disk drive node as a function of time during startup. It can be seen that during boot, all of the disks at once could not be supplied, since in the first 10 seconds of initialization the power draw is $\times 2.5$ higher than the normal usage. A sequential startup with a delay of 5 seconds yields a distributable energy draw for the power supply.

The supervision of the hard disk drives is done by a PCEngines/APU1d SBC platform. Since these boards feature only two SATA ports (of which one is needed to be soldered manually), additional controller boards are required for the several SATA inputs. We used ST521PMINT type SATA multiplexer controller cards, as these are capable of performing 6 Gbps data transfer rate at maximum.

The whole storage system is packed in a 3U high electronic enclosure having the width according to the 19 inch rack standards.

### 3.4 Photometric precision and system performance

The 150 sec exposure time combined with the $\sim 6$ seconds of readout time corresponds to a duty cycle efficiency of $\sim 96\%$, just considering the CCD data acquisition. In addition, the hexapod also requires $8 - 9$ seconds to reset, but it can be performed in parallel with the readout. In addition, the $1 - 2$ seconds long filter changing can also be performed in parallel both with the readout and the hexapod resetting. Therefore, we can conclude that the gross duty cycle is also around $\sim 95\%$ for the Fly’s Eye device. After reading out the CCD frame on each camera
node, the single-board computers upload the images to an intermediate storage, where this higher level computer is responsible for the post-exposition processes.

The optical setup (Section 3.1.2.3) combined with our detector yields a theoretical photometric precision of $\sim 4 - 5$ mmags per cadence. This value is determined for an averagely bright $\sim 10^m$ star in $r'$ band, where the quantum efficiency of the sensor is the highest. Although the atmospheric quality at the installation site is low – the typical seeing value at Piszkéstető Observatory is between $1 - 4$ on the Pickering scale – the images will not be seeing limited since this scale of a few arcseconds is much less than the pixel scale and the optical PSF size. The faintest visible objects on a single exposure of 150 sec has a brightness of $\sim 15^m$ (also in $r'$ band). With such capabilities, the Fly’s Eye camera system provides time series photometric data for numerous variable astrophysical phenomena.

Fainter stars can be detected by stacking up several images: if 25 consecutive images (equivalent to roughly 1 hour of exposition time) are stacked into one frame, astrometry and photometry can be done for even $\sim 17^m$ stars (see Figure 3.26). Note, that these limitations are in the range where the Large Synoptic Survey Telescope (LSST Ivezic et al. 2008) has its saturation limit. This way our measurements can complement the database of LSST or other surveying telescopes e.g. Panoramic Survey Telescope And Rapid Response System Pan-STARRS, (Pan-STARRS Kaiser et al. 2002). The saturation limit for the Fly’s Eye instrument is in the range of $\sim 9^m$ hence it covers at least $6^m$ magnitude orders. The concept of a “Mosaic Array of Numerous Ultrasmall Lens” (MANUL) instrument has been presented by our group that is capable of performing optical photometry measurements for stars visible to the naked eye, i.e. brighter than $\sim 6 - 7^m$ in $V$-band. With such an imaging device we would be able to extend the covered range with $\sim 5^m$. The characteristic size of this proposed observatory is in the range of a few tens of centimeters hence it would be easy to equip the Fly’s Eye with it by mounting it somewhere on the payload of the hexapod. In addition, by deploying 8 – 9 Fly’s Eye unit would provide a comparable étendue (see Chapter 1) that of LSST.
Figure 3.26: A stacked image combined from 25 individual frames, equivalent with a single image taken with an exposure time of 1 hour. The green markings indicate the magnitude values of the identified stars. It can be seen that the faintest sources have a brightness of $17^m$ or below, slightly depending on the actual colour of the star.
Chapter 4

Telescope positioning with MEMS Accelerometer

“The scientific man does not aim at an immediate result. He does not expect that his advanced ideas will be readily taken up. His work is like that of the planter - for the future. His duty is to lay the foundation for those who are to come, and point the way.”

Nikola Tesla

4.1 Introduction

As it has been outlined in Chapter 2 and Chapter 3, redundancy has high priority in a remotely or autonomously operating astronomical instrument. Information regarding to the status of the system can be retrieved via various type of independent mechanical, optical, magnetic or electronic limit switches in conjunction with linear or rotary encoders. Due to the remote and autonomous operation, the system is vulnerable to mains electricity and/or communication failures that may cause the total loss of the attitude of the telescope. Even when control is restored, one cannot be certain that e.g. a single encoder provides reliable information on the actual state of the instrument, since manual positioning of the mount can disorientate the encoder. If we intend our system to be as fail-safe as possible we need to find alternative solutions that are reliable enough in the aforementioned cases, i.e. someone manually moves the telescope during power loss.
Figure 4.1: Left: Operating principle of a capacitive accelerometer. Due to inertia, for an applied acceleration the mass will respond with a displacement in conjunction with the attached plate. This induces a change in distance between this and the fixed outer plates. In the presence of electric potential difference the plates form a capacitor and its capacitance depends on the distance of the conducting plates. Thus, we can measure the change of capacitance in order to obtain the distance between the plates.

We can use techniques that are capable of measuring the magnitude of the accelerating force effecting on a particular device. These sensors, the so-called accelerometers, are able to determine dynamic (impacts, shocks and vibrations) or static (inclination) accelerations. Due to recent developments, their usability covers many applications such as free fall detection, shock and vibration monitoring of laptops or tilt/orientation measurement of smartphones (e.g. for leveling applications). In these cases, the package sizes are limited, hence the name: MicroElectroMechanical Systems (MEMS). The fundamentals of this technology have been laid in the ‘80s (Angell et al. 1983), and it became common and commercially available in the last decade with the advancement of portable devices (such as tablets, smartphones and cameras). The components of MEMS have a typical size of $1 - 100 \mu m$ (see Figure 4.2), although some devices arranged in arrays that can have an area of $\sim 1000 \text{mm}^2$ (Gabriel et al. 1988). The integrated circuit package dimension is typically a few mm$^3$ in volume.

The operation principle of MEMS accelerometers are based on either the variation of capacitive or piezoelectric effect (Lee et al. 2005, Chollet & Liu 2013). Figure 4.1 illustrates the capacitive method. Inside the sensor, there are fix and movable microscopical electrode plates. The movable plate is connected to an inertial mass. By accelerating the sensor, the distance between the plates will change. This will cause measurable capacitance variations and hence the magnitude of the acceleration can be calculated.

In the case of the piezoelectric accelerometers, the inertial mass is mounted on a piezoelectric material. Due to mechanical stress, a measurable electrical potential appears on the material. With this method, the sensors can measure static or dynamic accelerations along with the direction of the acceleration in 3 dimensions,
if 3 sensors are placed perpendicular to each other. For our purposes, a 3-axis accelerometer was sufficient. In the static case, the sensor measures the orientation of the gravitational field with respect to its orientation, thus the pitch, roll and yaw angles of the device can be derived with an accuracy and precision depending on the actual manufacturer and chip type. Note, that geodesic and gravitational verticals differ due to local anomalies (see Hirt 2006; Hirt & Seeber 2008), however, these effects have 2 orders of magnitude smaller impacts on the output data of the accelerometer channels than our intended accuracy. The cheapest (∼1$) version of such sensors has an accuracy of a few degrees, thus they can be used as a suitable backup limit switch. With proper calibration, the accuracy of these sensors can be increased to the range of sub-arcminutes which would be precise enough for creating a pointing model of a telescope.

The capabilities of such sensors can be exploited in numerous ways in astronomical instrument development. Even a single channel accelerometer can be applied as a limit switch by properly mounting it on a telescope (i.e. parallel to the optical axis of the telescope enabling it to detect tube movements) in order to prevent the telescope to go below the horizon (Maureira 2014). For an equatorial mount that is located on a temperate geographical latitude, the horizontal limiting of the mount requires evaluation of trigonometric equations. For such telescope mounts, MEMS accelerometers could provide an alternative, location-independent technique to handle mount motion limitations. Various telescope systems with frequent repositioning – including fast response devices (Fors et al. 2013) and survey telescopes (Burd et al. 2005) – require more robust and redundant feedback systems in order to perform accurately. Although several pointing models are applicable for these systems, these sensors could provide an alternative method to retrieve the orienta-
tion of a telescope. Since the azimuth axis is vertical, these sensors are not capable of assisting any alt-azimuth telescope mount. Due to their operation principles, these are sensitive only to the static acceleration of the gravitational force which implies that these will be invariant for any kind of rotation around the vertical axis, i.e., they cannot determine the azimuth angle. All in all, such sensors provide a way of adding another line of defense for failsafe operation of an autonomous astronomical instrument, and a useful tool for other possible applications (e.g. see Sections 2.4 and 3.2.1).

In this chapter I present how the aforementioned embedded MEMS accelerometers can be used for telescope positioning with an accuracy of $\lesssim 1'$ level. I also describe the methodology of retrieving the pointing model from the raw accelerometer data. In Section 4.2, I introduce our design concept including the electronics and firmware and the higher level frontend software and data acquisition scheme. In order to achieve the mentioned accuracy, a series of calibration procedures needs to be performed for the chosen accelerometer device. Section 4.3.1. outlines the calibration of the device itself while Section 4.4. describes the experiment and analytical solution by which we managed to retrieve the pointing model.

4.2 Accelerometer design

It is inevitable in any autonomous or remote controlled telescope to possess the real time state of the system in order to provide safe operation (Section 4.1). Therefore, the instruments need to be equipped with several different type of independent feedback systems. One could be a microelectromechanical (MEMS) accelerometer, that uses the static gravitational acceleration to measure the reference direction. In this reference frame, the axis of the telescope mount is angled with respect to the vertical direction. During the rotation of the telescope axis, the orientation of the attached accelerometer will also change. It can be seen that the sensors are invariant for any rotations which axis is parallel to the direction of gravity – for the same reason this feedback system is not directly applicable for alt-azimuth mounts, a bevel gear transmission is needed. By such transmission, the rotation around the vertical axis can be converted to a rotation around an inclined or horizontal axis. This way we get a telescope position and independent feedback system. This also works as an absolute encoder, since it will know the orientation if someone manually positions the telescope after a blackout. The chosen accelerometer device is a cheap MEMS sensor that has an out-of-factory accuracy of $1^\circ$. A calibration procedure has been developed in order to achieve the $1'$ level. For this purpose, two type of calibration devices were built using 3D printing. In order to use the sensor for accurate telescope positioning, a higher level electronics and bus system is required around the accelerometer chips.
4.2. ACCELEROMETER DESIGN

For developing the data acquisition algorithm we have to consider the high data rate provided by these sensors, that is in the range of kilosamples per second and the output values are undersampled. These properties imply that the output can be characterized by Gaussian white noise with a nearly unity standard deviation.

4.2.1 Sensor and hardware

We chose the capacitive three-axis 10bit resolution sensor MMA8453Q manufactured by Freescale Semiconductor, Inc. The sensor is available in a $3 \times 3 \times 1$ mm quad flat no-leads (QFN) package and has the selectable 2 g, 4 g and 8 g scales which provide various static or dynamic application possibilities. The communication is done via I2C protocol. Out of its 16 pins only the I2C pins were used while the other auxiliary bi-state output pins (e.g. landscape/portrait detection, free-fall detection, etc.) were not utilized in our design.

The device itself is mounted on a $12 \times 12$ mm PCB with bypass capacitors and address selector resistors. This small circuit board is connected to the I2C line in a way that four pillars function as the data (SDA), clock (SCL) signal and +3.3V power (VDD) and ground (GND) lines. Several type of daughterboards have been designed with different sensors (such as thermometers, gyroscopes, humidity sensors, barometers, etc.) that can also be connected on this bus resulting in devices of various functionalities. These boards has the same arrangement for connection, hence these can be stacked on each other separated with spacers.

Since these digital electronics has minor, but relevant thermal dependencies, it is important to measure the temperature of the close environment of the accelerometer. For this purpose, two high precision I2C based LM92 thermometers were placed below and above the accelerometer. In fact, the temperature sensor beneath the accelerometer is located on the motherboard. This multi-layer daughterboard is illustrated in Figure 4.3 where sensor system is placed in the geometric center of the main board with a tenth of a millimeter precision. The core of the higher level electronics, which drives the I2C communication, is an Atmega 8-bit AVR microcontroller unit (MCU) (see Figure 4.4) featuring 8 kilobytes of in-system flash program and 1 kilobytes of static RAM and EEPROM memory in total. The applied MCU has a single universal asynchronous receiver and transmitter (UART) interface to which the transmitter side of both the USB and RS485/422 level shifter interfaces are connected through a wired AND logic, while the receiver is connected directly to both. The USB-to-serial UART interface chip provides the +3.3V (regulated from the +5V line voltage) power supply for the microcontroller and for the devices connected to the I2C bus. The maximum power that can be drawn from this pin is 50 mA, which is well within the total consumption of the MCU and the I2C devices. The USB is dedicated mainly for testing and debugging purposes. Due to the dual interface, the main communication protocol is available in either half-duplex (RS485) or full-duplex (RS422) modes. The two RS485 drivers are
Figure 4.3: The accelerometer main electronics with the multi-layer sensor boards are mounted at the center of the main board. The left-side socket is an USB-B (“device side”) while the right one is a dual RJ45/8p8c connector. The MCU is located at the lower-left corner, next to the USB socket and the quartz crystal. The four spacer nuts around the sensors keep the main board fix within its enclosure.

connected to a dual socket RJ45/8p8c connector. Since the units are bus powered, one can build a multi-drop network system of several accelerometer units in a serial manner by using standard Ethernet cable and RJ45 plugs.

4.2.2 Firmware and data acquisition

In order to provide safe and reliable data stream between the accelerometer units and a higher level host computer (e.g. PC or a single board computer) we use the same 9-bit package-based master–slave communication protocol as described in Section 2.5. For the USB controller this can be done by setting the parity bits to emulate the control bit. Each accelerometer is identified by a unique address. A message package includes not only the address and the command but also the required information for the slave device whether the master expects any answer or not. The broadcast commands need to be replied.
4.3 Calibration procedures

As it was mentioned above, our choice of a cheap accelerometer comes with $\sim 1^\circ$ accuracy. While this value makes it suitable for a backup limit switch (to avoid the telescope to look close to or below the horizon), further refinements are required if we want to build a more precise telescope feedback system for an autonomous telescope. The chip selection was based on two main factors: the ease of integration and the featuring 3 axes within the same chip package. In order to reach the aimed (sub-)arcminute accuracy level, one has to perform some kind of calibration on the accelerometer outputs. The calibration implies two steps. First we made an
4.3. CALIBRATION PROCEDURES

absolute measurement of the errors related to the sensor itself, that arise due to defects in manufacturing, e.g. the axes are not perfectly perpendicular to each other. In the second step, the accurate mapping between the sensor output data and the telescope orientation was determined.

4.3.1 Spherical calibration

The accelerometer senses all the static and dynamic accelerations that effected by an external force. In our case we intended to measure the acceleration of the local static gravitational force \( g \). Other phenomena have only minor effects, although they need to be taken into consideration. Such is the acceleration of the centrifugal force due to the sidereal rotation of the Earth. Its contribution to the acceleration \( g \) can be estimated by \( L \Omega^2 \), where \( L \) is the meter range instrument size and \( \Omega \) is the angular velocity \( \sim 7 \times 10^{-5} \text{rad/s} \). This is equivalent to \( 10^{10} \) times smaller acceleration compared to the standard gravity, thus, it is negligible.

For a measurement request, the sensor provides 10 bit raw data for each axis which are the vector components \((x, y, z)\) of the accelerating force. For all individual measurement it should be true that

\[
x^2 + y^2 + z^2 = g_0^2.
\]

Since the sensor data is dimensionless by scaling the output values as \( g_0 = 1 \), the equation will become simply

\[
x^2 + y^2 + z^2 = 1.
\]

The length of the measured raw vector differs from unity due to the presence of random and systematic errors with a standard deviation of a few hundredths of the uncertainty level. To determine the characteristic value of the root mean square (RMS), a spherical surface was uniformly measured and the scatter of \( r = \sqrt{x^2 + y^2 + z^2} \) was calculated. The accelerometer we used has an RMS error in \( r - 1 \) of \( \approx 0.021 \). If we add a \( \sigma \) Gaussian white noise to the output of an ideal accelerometer we get the same \( \sigma \) as the standard deviation in \( r \). In order to get the smallest RMS error in \( r - 1 \) we apply an affine transformation on \((x, y, z) \Rightarrow (x', y', z')\)

\[
\begin{pmatrix}
x' \\
y' \\
z'
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
x \\
y \\
z
\end{pmatrix}
+ \begin{pmatrix}
A_{xx} & A_{xy} & A_{xz} \\
A_{xy} & A_{yy} & A_{yz} \\
A_{xz} & A_{yz} & A_{zz}
\end{pmatrix}
\begin{pmatrix}
\Delta x \\
\Delta y \\
\Delta z
\end{pmatrix},
\]

where \( A_{ij} \) components of the symmetric matrix and the \((\Delta x, \Delta y, \Delta z)\) offset vector are the 9 unknown. Since the transformation is linear in its parameters, Equa-
tion (4.3) can be written as

\[
x' = x + \sum_i p_i^x f_i^x(r),
\]

\[
y' = y + \sum_j p_j^y f_j^y(r),
\]

\[
z' = z + \sum_k p_k^z f_k^z(r),
\]

(4.4) \hspace{2cm} (4.5) \hspace{2cm} (4.6)

where \( r = (x, y, z) \) is the output vector of the accelerometer, \((p_i^x, p_j^y, p_k^z)\) quantities are the components of the parameter vector. To get a series of \((x_l, y_l, z_l)\) vector, we sampled a sphere in \( N \) points \((1 \leq l \leq N)\). The constraint that \((x'_l, y'_l, z'_l)\) has an unit length can then be reordered to have the form of

\[
\sum_i 2x_l p_i^x f_i^x(r_l) + \sum_j 2y_l p_j^y f_j^y(r_l) + \sum_k 2z_l p_k^z f_k^z(r_l) = 1 - \left( x_l^2 + y_l^2 + t_l^2 \right) - \left[ \sum_i x_l p_i^x f_i^x(r_l) \right]^2 - \left[ \sum_j y_l p_j^y f_j^y(r_l) \right]^2 - \left[ \sum_k z_l p_k^z f_k^z(r_l) \right]^2.
\]

(4.7)

Taking into consideration that the values of \(1 - (x_l^2 + y_l^2 + t_l^2)\) is in the range of \(\sigma\), and the \(\left[ \sum_i(\ldots) \right]^2\) have a magnitude of \(\sigma^2\) thus these latter terms are negligible in the first iteration. The remaining equation can be simplified to an iterative linear least squares problem for the values of \((p_i^x, p_j^y, p_k^z)\). The solution is straightforward because more sampled \(N\) points have been attained than number of \(P\) parameters. In the next iteration, the squared terms can be applied. The optimization of the method is repeat until convergence. Although the solution is straightforward, there are some open questions that need to be answered.

- How to sample homogeneously a sphere in \(N\) points? It requires some mechanism that rotates precisely with a given resolution. Once set to a measurement point it waits until the system settles in a steady state and then a measurement could be performed.

- What is the most suitable \((f_i^x, f_j^y, f_k^z)\) regression function set that results in unity \((x')^2 + (y')^2 + (z')^2\) values?

- In those cases when one of the vector components of \(r\) (for instance, \(x\)) is close to 0, a large value of the respective parameter vector component \((p_i^x)\) just slightly perturbs the value of \((x')^2\). Thus, such cases have only little effect on the total least square problem. This may cause problems if the base function has small absolute values.

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• How does the calibration result (i.e. the components of the \((p_x^i, p_y^j, p_z^k)\) parameter vector) depend on the external environmental effects?

After answering these questions we have an efficient way to get the best fit values for the 9 unknowns and thus we are able to minimize the standard deviation of \((x')^2 + (y')^2 + (z')^2\) thus achieving the aimed sub-arcminute accuracy for our accelerometer.

4.3.1.1 Calibration device

In order to answer the first question, a calibration device was designed, that is able to rotate the sensor so that the output vector moves on a spherical surface and samples it at a given rate (Figure 4.5). Although the accelerometer has three axes, the output of the sensor is invariant to the rotation around the vertical direction (parallel to \(g\)). Thus the device requires two independent mechanisms with one rotating degree of freedom for each. The solution for this problem is a parallel robot, similar to a differential. Four backlash-free bevel gears are connected in a way as differentials, and the two opposite side gears are driven by separate stepper motors. A hollowed cross connects the gears by bearings hence it is able to move freely. Through the hollow the cables can run thus avoiding twisted wires. The motion of the other two gears is determined by the relative rotating speed and direction of the driven gears and also serves as the platform for the accelerometer to be calibrated. In addition I was able to run the spherical mapping measurement for two sensors since there are two platforms available. The gears and other parts of the device were 3D-printed. The driven gears are connected to the motor with timing belts. On the side of the gear, the belt is connected to a 3D-printed pulley. The motor driving electronics are accessible via RS485 communication protocol and connected to the same bus as the accelerometers. This electronics is a modified version of the one I used to drive the Fly’s Eye hexapod legs. With this device, the sphere can be sampled with high density. Measuring a position takes a few seconds, after which the sensors settle in another few seconds. In total, the whole calibration procedure takes a few hours, and it can run automatically.

4.3.1.2 Parameter fitting

First, the \((f_x^i, f_y^j, f_z^k)\) function set implied by the affine transformation of Equation (4.3) is evaluated. This transformation needs \(P = 9\) parameters. Furthermore, we sampled through the spherical surface homogeneously in 10,000 individual data
points for the least square fitting. The fit resulted in the values of

\[
\begin{align*}
\Delta x &= +0.020483 \pm 0.000018, \\
\Delta y &= -0.018311 \pm 0.000018, \\
\Delta z &= -0.000423 \pm 0.000018, \\
A_{xx} &= +0.006452 \pm 0.000026, \\
A_{yy} &= -0.003808 \pm 0.000026, \\
A_{zz} &= -0.006783 \pm 0.000025, \\
A_{yz} &= +0.001530 \pm 0.000020, \\
A_{xz} &= -0.000247 \pm 0.000020, \\
A_{xy} &= -0.000603 \pm 0.000020
\end{align*}
\]

the residual of \( \sqrt{(x')^2 + (y')^2 + (z')^2} - 1 \) decreased to 0.0021 (see Figure 4.6) which is equivalent to \( 0.12^\circ = 7.3' \) angular accuracy. This is 10 times smaller than the RMS of the raw measurement (see Section 4.3.1), however, still \( \sim 10 \) times larger than the \( 2 \times 10^{-4} \) white noise contribution to the components of the acceleration output channels. In other words, an affine transformation does not eliminate all of
the systematic errors. Since the values of the coefficients $A_{xy}$, $A_{xz}$ and $A_{yz}$ are not equal to zero within the reported uncertainties, it means that the sensor axes are not perfectly perpendicular. After the affine transformation, another transformation of $(x', y', z') \rightarrow (x'', y'', z'')$ has been applied in order to eliminate the remaining systematic errors. Since the affine transformation removed the cross-talk of the channels, the transformation can be separated to functions of the component: $x' \rightarrow x'', y' \rightarrow y'', z' \rightarrow z''$. We search these functions with linear interpolation in the interval of $[-1, 1]$ with a uniform spacing of $\Delta = 1/M$. Including the two end points we have $2M + 1$ interpolation control point and hence $3 \times (2M + 1)$ unknowns for
4.3. CALIBRATION PROCEDURES

the three axis. The transformation then takes the following form:

\[
\begin{align*}
x'' &= x' + C^{(x)}_{L(x')} \left[ R(x') - \frac{x'}{\Delta} \right] + C^{(x)}_{R(x')} \left[ \frac{x'}{\Delta} - L(x') \right], \\
y'' &= y' + C^{(y)}_{L(y')} \left[ R(y') - \frac{y'}{\Delta} \right] + C^{(y)}_{R(y')} \left[ \frac{y'}{\Delta} - L(y') \right], \\
z'' &= z' + C^{(z)}_{L(z')} \left[ R(z') - \frac{z'}{\Delta} \right] + C^{(z)}_{R(z')} \left[ \frac{z'}{\Delta} - L(z') \right],
\end{align*}
\]

where

\[
\begin{align*}
R(t) &= \frac{t}{\Delta}, \\
L(t) &= L(t) + 1
\end{align*}
\]

are integers and the magnitudes of the \( C_m \) interpolation coefficients \((-M \leq m \leq M)\) is in the same range as the residual of the affine transformation, namely \(|C_m| \lesssim (1.5 \ldots 2.5) \times 0.0021\). Since the transformation equations above are special cases of the Equations (4.4), (4.5) and (4.6), we can use Equation (4.7) in a similar least squares fashion to determine the \( C_m \) coefficients.

The number of points needed for the interpolation depends on the nature of the residual structure. For our specific accelerometer sensor, \( M = 100 \) intervals were needed in order to get a reliable interpolation procedure. As mentioned earlier, the interpolation function becomes “unstable” for small \((\lesssim D_0 = 0.05)\) \(|x|, |y|, |z|\) values since the square of these parameters just slightly increase the value of \(x^2 + y^2 + z^2\). To get a reliable fit in the complete \((x, y, z) \in [-1, 1]\) domain, additional constraints have to be added by designing a complementary calibration procedure.

4.3.2 Planar calibration

The “chaotic” gaps (see upper panel in Figure 4.9) where \(|x|, |y|, |z| \lesssim D_0 = 0.05\), cannot be neglected since the total area of the calibration surface of \(3D_0 \approx 15\%\) is influenced by this effect. For its elimination another calibration device and procedure has been developed.

4.3.2.1 Calibration device

Another device was designed, capable of sampling the gaps that were excluded from the previous calibration phase (Figure 4.7). The main difference between the two devices is that this supplementary unit has only one horizontally rotating shaft. The accelerometer can be mounted on the shaft with a specific attitude. The accelerometer was rotated around the horizontal axis in small steps, and
as in the previous calibration procedure, a readout has been performed after the sensor settled. This way the output of the accelerometer samples along a circle that is deflected equally from all of the three axes, namely its normal vector is \((\pm 1/\sqrt{3}, \pm 1/\sqrt{3}, \pm 1/\sqrt{3})\). In those cases when the value of one of the channels is close to zero, the other will have the value of \(\approx \pm 1/\sqrt{2}\), since the intersection of a sphere and a plane always results a circle. Taking into consideration that there are four possible circles to measure, and eight possible configurations, this implies that several accelerometer units can be calibrated simultaneously. The similarity in the two calibration device is that the rotating axes are hollowed to avoid twisting wires. Further similitude is the driving mechanism with a stepper motor–timing belt–pulley combination and the communication interface configuration.

During the calibration, a very stable pedestal is needed since the angle between the vertical and the rotating axis must not alter. Therefore, the device is mounted on an aluminum stand which is equipped with rubber footing pads to reduce the effect of any vibration. The other part of the device is manufactured by using 3D printing just like the previous calibration device.
4.3.2.2 Parameter fitting

With the device described above we sampled through a circle which will be a nearly great circle, since the accelerometer is mounted on the polyhedral structure with fix angle respect to the rotating shaft. This great circle is intersecting the calibration sphere with a plane. The parametric equation of this plane can be written as:

\[ n_x x + n_y y + n_z z = C. \]  \hspace{1cm} (4.13)

\( n_x, n_y, n_z \) parameters are components of the planes normal vector and \( C \) is constant.

Let us add a constraint by defining the length of the normal vector to be unity:

\[ n_x^2 + n_y^2 + n_z^2 = 1. \]  \hspace{1cm} (4.14)

If this equation is satisfied, \( C \) will be the cosine of the angle between the vertical direction and the axis of the shaft. As mentioned earlier, the intersected great circle has roughly equal normal vector components:

\[ |n_x|, |n_y|, |n_z| \approx 1/\sqrt{3}, \]  \hspace{1cm} (4.15)

thus the radius of this circle will be \( \sqrt{1 - C^2} \).

Summarizing the calibration procedure first on the measured points, where \( D_0/\Delta < |m| \): we used the affine transformation and the interpolation procedure we described in Section 4.3.1 resulting the red circles in Figure 4.8. For these data points, we evaluate Equation (4.13). With the least square method and the constraints defined in this section, we defined the exact value of \( n_x, n_y, n_z \) and \( C \).

The residual of this fit determines the stability of the angle between the vertical and shaft axis. Finally we fit the \( C_{|m| \leq D_0/\Delta} \) with linear least squares method by minimizing the merit function

\[ \chi^2 = \sum_{|x| \leq D_0} [(n_xx' + n_yy' + n_zz') - C]^2 + \]

\[ + \sum_{|y| \leq D_0} [(n_xx' + n_yy' + n_zz') - C]^2 + \]

\[ + \sum_{|z| \leq D_0} [(n_xx' + n_yy' + n_zz') - C]^2. \]

It has been shown that with this method, the “chaotic” gap – where \( |x|, |y| \) and \( |z| \) has a smaller value than a given \( D_0 \) – can be filled (see Figure 4.9).

After the application of the spherical and planar calibration procedures, we get a decrease of the level of \( 2.3 \ldots 2.6 \times 10^{-4} \) in the residual from the unit sphere. It is equivalent to \( 0.013 - 0.015^2 \approx 0.8 - 0.9' \approx 48 - 54'' \) RMS. The order of magnitude
corresponding to this residual level is the same as the white noise contribution in the output data, which means that after the proper calibration, the accelerometer sensor will have an accuracy comparable to the random noise (at the timescale of the elementary readout cycle).

4.3.3 External factors

As all electronic elements, the accelerometer can also be sensitive to environment effects. Changes in the ambient temperature, the electromagnetic interference (EMI), the small fluctuation in the power supply and variation in the gravity at different locations may cause significant impact on the output data of the sensor. These factors have to be taken into account during the calibrations and the applications of the sensor.
Figure 4.9: A typical reconstructed interpolation function for the $x$-channel of one of our accelerometer units. The upper panel shows the “naive” fit where only the spherical constraints were involved in the reconstruction of the interpolation coefficients. It can be seen that for small $|x|$ values, the fit diverges and the results become unreliable. The middle panel shows the results of the same fit while the values for $|x| \leq D_0 = 0.05$ were forcibly set to zero. The lower panel shows a completely reconstructed interpolation function where spherical constraints were exploited for the two domains of $x < -D_0$ and $D_0 < x$ while planar constraints were used for the domain $|x| \leq D_0$. 
4.3.3.1 Ambient temperature

The variation of the ambient temperature has an influence on all integrated electronics that having semiconductors. Within the MEMS accelerometer, the temperature dependencies of the capacitive moving parts have an additional contribution to this effect (see Dai et al. 2008). To determine the changes in the output of the accelerometer due to temperature variations, two high accuracy thermometers were placed ≈ 5 mm below, and above the accelerometer sensor. This configuration provides reliable information about the ambient temperature around the accelerometer. We can also measure the temperature gradient between the temperature sensors to find out the effect on the sensor, if any.

We measured an ambient temperature of $22.86 \pm 0.16^\circ C$ and the gradient was $-0.11 \pm 0.02^\circ C$ (with respect to the thermometer below the accelerometer) during ≈ 4 hours of calibration procedure. This was in a settled, but not actively controlled environment. The results, presented in Section 4.3.1 and in Section 4.3.2 has been carried out under such circumstances. In order to characterize temperature dependency, the calibration procedure of Section 4.3.1 has been repeated for $N = 1000$ points at $8.88 \pm 0.14^\circ C$. We found that the $\Delta T = -13.98^\circ$ difference is significant enough to demonstrate the temperature dependency of the sensor. In the colder environment, the residual from the unit sphere goes up to ≈ $0.0019$, which indicates that temperature variations have an impact ≈ $1.3 \times 10^{-4}/^\circ C$ on the measured output values of the accelerometer channels. Applying the affine transformation on this data series, we get an RMS of 0.00021, which is in the range of the residual after the planar constraint calibration procedure of the warmer data set.

Now, first let us take a full fitting procedure at a certain $T_0$ ambient temperature. By using the resulting fitting parameters, we run spherical calibration procedures on a different ambient temperature $T_c$. Then on these output data we apply only the affine fitting in order to retrieve the coefficients denoted by $\Delta \hat{x}, \Delta \hat{y}, \Delta \hat{z}, \Delta \hat{A}_{xx}, \Delta \hat{A}_{yy}$, etc. respectively.

Then we apply Equations (4.3), (4.8), (4.9) and (4.10) with the coefficients corresponding to $T_0$ on the raw output data at some $T$ temperature. Next, we use Equation (4.3) with $k\Delta \hat{x}, k\Delta \hat{y}, k\Delta \hat{z}, k\Delta \hat{A}_{xx}, k\Delta \hat{A}_{yy}$, etc. coefficients, where $\Delta \hat{x}, \Delta \hat{y} \ldots$ were obtained at $T_c$ and

$$k = \frac{T - T_0}{T_c - T_0}. \quad (4.17)$$

This linear temperature dependence can be more accurately characterized by taking further measurements on alternate temperatures and/or by increasing the difference between $T_0$ and $T_c$. However, such a linear approximation can be feasible on even larger temperature ranges (see e.g. Dai et al. 2008).
4.3.3.2 Electronic dependencies

The operation of an analog circuit (including MEMS accelerometers) depends on the applied voltage levels. Since this dependency exists and the USB standard 5.00 V ± 0.25 V bus power line has relatively large variations, the power source needs to be stabilized. An onboard linear regulator was added, that provides a stable and accurate voltage level of +3.3 V supply. These linear regulators are capable of reducing the variations in the power line.

There are other undesirable effects that have to be taken into account. Due to the long cable length and the surrounding electronic devices, a high-frequency noise component can appear on the bus lines. Bypass capacitors can remove this effect both from the +5 V side and from the regulated side. In addition, the electronics is protected from voltage spikes induced by lightning, or other transient voltage events by an uni-directional transient-voltage suppression diode. These semiconductor components are capable of surviving 600 W peak power for a period of 10 µs (i.e. 10/1000 µs waveform, where 10 µs is the peak pulse duration and 1000 µs is defined as the point where the peak current decays to 50%). The operation is based on the shunting of the excess current in the case of the induced voltage exceeds the breakdown voltage. This voltage level is typically +10 – 40% of the operating voltage (depending on the actual type and the manufacturer).

4.3.3.3 Local gravity

The strength of the Earth’s normal gravity has dependency on the geographical latitude and the altitude – where the indirect effect of the centrifugal force is also included. This effect is the highest at the equator, and decreases towards the poles. This means that the measured gravitational acceleration is lower, as we are getting closer to the equator. The equation that describes this dependency is the International Gravity Formula, also known as Somigliana formula (see Somigliana 1930) is:

\[ \gamma = \gamma_e \frac{1 + k \sin^2 \phi}{\sqrt{1 - e^2 \sin^2 \phi}}, \]  

(4.18)

where

\begin{align*}
  k & : \text{constant}, \quad k = \frac{b \gamma_p - a \gamma_e}{a \gamma_e} \quad 0.001931851353, \\
  \gamma_e & : \text{normal gravity on the equator} \quad 9.7803267715 \text{ m/s}^2, \\
  \gamma_p & : \text{normal gravity on the poles} \quad 9.8321863685 \text{ m/s}^2, \\
  a & : \text{equatorial radius} \quad 6378137 \text{ m}, \\
  b & : \text{polar radius} \quad 6356752.3141 \text{ m}, \\
  e^2 & : \text{eccentricity of the spheroid} \quad e^2 = \frac{a^2 - b^2}{a^2} \quad 0.0066943800229, \\
  \phi & : \text{geodetic latitude}
\end{align*}
The values in the third column are based on the Geodetic Reference System – 1980 (GRS80) of the International Gravimetric Bureau.\(^1\)

The changes in the altitude has also an influence on the output of the accelerometer. The altitude dependency can be characterized as

\[
\frac{\Delta g_0}{g_0} = -\frac{2\Delta h}{R_0},
\]

where \(\Delta h\) is altitude change, and \(R_0\) is the mean radius of the Earth. Now, let us evaluate a change of 100 km northward and \(+100\) m in location and altitude, respectively. From Equations (4.18) and (4.19), we can calculate that the latitudinal displacement results in \(\approx +5 \times 10^{-5}\) increase, while the altitude variation decreases the gravitational strength by \(\approx +5 \times 10^{-5}\). By calculating the RMS residual from the reference ellipsoid results \(\sigma(\Delta g_0/g_0) \approx 2 \times 10^{-5}\) which means that the magnitude of these effects are smaller, than the residual of the calibration procedure, however, these are in the same order of magnitude. Such effects must be taken into consideration in the case of the relocation of a calibrated device.

### 4.4 Pointing model

Our goal was to use the accelerometer as a position feedback system on astronomical telescopes. In the design we exploited the fact, that the relative orientation of the accelerometer can be measured in the static gravitational field. However, the output data is invariant for any rotations around vertical axis, and does not sense displacements. After all the calibrations and external factors have been taken into account, we still have to determine how to transform the measurements into equatorial coordinates. For this purpose, two accelerometer units were mounted on the 60 cm Schmidt telescope of Konkoly Observatory, located at the Piszkéstető Mountain station. Figure 4.10 shows the experiment block diagram while Figure 4.11 illustrates the installed unit on the telescope.

The movement of both axes were detected by mounting one accelerometer on the fork of the mechanics, while another one was attached to the telescope tube itself. This setup has the following constraints:

- The unit located on the fork (unit #1) is mounted in a way that the \(z+\) direction is approximately parallel with the hour axis thus pointing northward with similar accuracy as the mechanics has;

- The \(z+\) direction of the accelerometer moving with the tube (unit #2) is roughly perpendicular to the optical axis.

\(^1\)http://bgi.obs-mip.fr/en
Figure 4.10: Block diagram of the complete subsystem with two accelerometers. In our test environment, the first one (#1) is mounted on the hour axis while the second one (#2) is mounted on the telescope tube (see also Figure 4.11).

Figure 4.11: **Left**: one of the enclosed accelerometers as it is mounted on the center of the fork of the hour axis mechanism of the Schmidt telescope. In this close-up view, only one of the RJ45/8p8c plugs is connected. **Right**: the accelerometer mounted on the telescope tube. The attitude is rather arbitrary, the only constraint is that the optical axis of the telescope lies in the accelerometer reference plane.

In order to avoid unwanted cabling outside the mechanics, the cables were running within the hollow fork arm parallel with other telescope cables. The units are connected to the same RS485 bus and accessible from a host computer via an USB-RS485 converter. The bus termination resistors are placed after the #2 unit in order to protect the data lines from distortions caused by the reflecting signals at the end of the line. If an ideal sensor would be placed horizontally, the measured output vector would be \( \mathbf{a} = (x, y, z) = (0, 0, g_0) \), where \( g_0 \) is the value of the local gravitational strength. Let us now change the orientation of the accelerometer.
After applying the \( \mathbf{R} \) active rotational transformation, the measured vector will be

\[
a = -\mathbf{g} \cdot \mathbf{R},
\]

(4.20)

were \( \mathbf{g} = (0, 0, -g_0) \) is the gravitational acceleration vector in the static (external) reference frame defined by the \( x_0, y_0 \) and \( z_0 \) axes (see Figure 4.12). If the coordinate system of the accelerometer sensor is denoted to be \((x, y, z)\), the transformation between the two systems will be

\[
\begin{align*}
x &= \mathbf{R} \cdot x_0, \\
y &= \mathbf{R} \cdot y_0, \\
z &= \mathbf{R} \cdot z_0.
\end{align*}
\]

Here, we made the assumption that the calibration procedures described in Section 4.3.1 and Section 4.3.2 were already performed in advance and the accelerometer is ideally accurate within the RMS of the calibration. For an ideal sensor, \( g_0 \) has the value of 1, thus the measured output vector \( a = (a_1, a_2, a_3) = (x'', y'', z'') \) will be \( a = (R_{31}, R_{32}, R_{33}) \) where the \( R_{3j} \) are elements of the matrix \( \mathbf{R} \). It can also be written in the form of

\[
a = \mathbf{R}^T \cdot (-\mathbf{g}),
\]

(4.21)
where $R^T$ is simply the transpose of the matrix $R$. This matrix can be determined if the geographical latitude and the attitude of telescope axes are given.

### 4.4.1 Isotropic pointing model

We search for the $R$ transformation, that results in the equatorial coordinates (i.e., the direction where the telescope points) from the calibrated raw measurements of the accelerometer that is fixed to the telescope. First, the calculations for the #2 unit (the unit mounted on the tube) has been carried out, since this unit has a more important role. The calculation of the unit #1 is much simpler. In order to determine the transformation, first we have to consider, how this transformation is built up, i.e., how the accelerometer was mounted with respect to the direction of the local gravity. To compute this transformation, the following elementary transformations have to be composed in the specified order: $A$ determines the attitude how the accelerometer unit has been mounted on the tube, $P_\delta$ and $P_\tau$ stands for the rotation of the declination axis and hour axis and finally, $G$ quantifies how the hour axis of the telescope have been placed on the ground. Hence, we can write

$$R = G \cdot (P_t \cdot P_d) \cdot A. \tag{4.22}$$

The transformation $A$ transformation will be computed in Section (4.4.2). If $\tau$ and $\delta$ indicate the hour angle and declination positions, respectively, and $\varphi$ marks the geographical longitude, then the $G$, $P_\tau$ and $P_\delta$ matrices can be written as

$$G = \begin{pmatrix} \sin \varphi & 0 & -\cos \varphi \\ 0 & 1 & 0 \\ \cos \varphi & 0 & \sin \varphi \end{pmatrix}, \tag{4.23}$$

$$P_t = \begin{pmatrix} \cos \tau & \sin \tau & 0 \\ -\sin \tau & \cos \tau & 0 \\ 0 & 0 & 1 \end{pmatrix}, P_d = \begin{pmatrix} \cos \delta & 0 & -\sin \delta \\ 0 & 1 & 0 \\ \sin \delta & 0 & \cos \delta \end{pmatrix}. \tag{4.24}$$

Let us now combine $P_\tau$, $P_\delta$ into the matrix $P := P_\tau \cdot P_\delta$. Here we assume an improper alignment of the telescope hence several type of aberrations arise, such as polar alignment, encoder zero point offsets, cross axis deflections or optical axis misalignment. Applying these effects on the $P$ transformation

$$P = H \cdot P_t \cdot X \cdot P_d \cdot T, \tag{4.25}$$

In ideal case, the $H$, $X$ and $T$ would be unity matrices. Let us assume that these misalignments are small relative to the $\sigma_p$ pointing residual. It implies that the second-order terms are negligible and the $\text{SO}(3)$ transformation can be expanded
in exponential form:

\[
H \approx \begin{pmatrix} 1 & -c & b \\ c & 1 & -a \\ -b & a & 1 \end{pmatrix}, \quad X \approx \begin{pmatrix} 1 & -f & e \\ f & 1 & -d \\ -e & d & 1 \end{pmatrix}, \quad T \approx \begin{pmatrix} 1 & -i & h \\ i & 1 & -g \\ -h & g & 1 \end{pmatrix}.
\]

(4.26)

The residual of the accelerometer serves as a limit to the pointing residual, namely one can assume that

\[
a^2 + b^2 + c^2 \lesssim \sigma_p^2, \quad (4.27)
\]

\[
d^2 + e^2 + f^2 \lesssim \sigma_p^2, \quad (4.28)
\]

\[
g^2 + h^2 + i^2 \lesssim \sigma_p^2. \quad (4.29)
\]

Let us introduce \(c' := c + f\) and \(e' := e + h\) from which the first-order series expansion depends on. The first-order expansion of the matrix \(P\) will then be

\[
P \approx \begin{pmatrix} c\tau c\delta & s\tau & -c\tau s\delta \\ -s\tau c\delta & c\tau & s\tau s\delta \\ s\delta & 0 & c\delta \end{pmatrix} + a \begin{pmatrix} 0 & 0 & 0 \\ -s\delta & 0 & -c\delta \\ -s\tau c\delta & c\tau & s\tau s\delta \end{pmatrix} +
\]

\[
+ b \begin{pmatrix} s\delta & 0 & c\delta \\ 0 & 0 & 0 \\ -c\tau c\delta & -s\tau & c\tau c\delta \end{pmatrix} + c' \begin{pmatrix} s\tau c\delta & -c\tau & -s\tau s\delta \\ c\tau c\delta & s\tau & -c\tau s\delta \\ 0 & 0 & 0 \end{pmatrix} +
\]

\[
+ d \begin{pmatrix} s\tau c\delta & -s\tau & -c\tau c\delta \\ -c\tau c\delta & -s\tau & s\tau c\delta \\ 0 & 0 & 0 \end{pmatrix} + c' \begin{pmatrix} s\tau & -c\tau c\delta & 0 \\ -s\tau c\delta & s\tau & -c\tau c\delta \\ -c\delta & 0 & s\delta \end{pmatrix} +
\]

\[
+ g \begin{pmatrix} 0 & -c\tau s\delta & -s\tau \\ 0 & s\tau s\delta & -c\tau \\ 0 & c\delta & 0 \end{pmatrix} + i \begin{pmatrix} s\tau & -c\tau c\delta & 0 \\ c\tau & s\tau c\delta & 0 \\ 0 & 0 & -s\delta \end{pmatrix},
\]

where \(s\) and \(c\) is the sine and cosine of the subscripted parameter \(\tau\) and \(\delta\), written as \(c\tau = \cos \tau\), \(s\tau = \sin \tau\), \(c\delta = \cos \delta\) and \(s\delta = \sin \delta\). The correction for how the accelerometer is mounted on the tube is involved in \(T\) via the parameters \(c'\), \(g\) and \(i\) since in the final form of transformation \(P\), only the product \(T \cdot A\) appears.

### 4.4.2 Attitude correction

As mentioned above, the matrix \(A\) matrix, that defines the orientation of accelerometer unit on the telescope is yet to be calculated. The sensor has been mounted on the tube in a random attitude due to the lack of space where the unit could be mounted. This attitude can be easily computed by combining a series of
rotations. It is found for the transformation is

\[
A = \begin{pmatrix}
  +0.6307 & -0.7759 & -0.0135 \\
  -0.3365 & -0.2577 & -0.9057 \\
  +0.6993 & +0.5758 & -0.4237
\end{pmatrix}
\] (4.31)

To compare the expected and the measured accelerometer output values, first Equation (4.30) has to be multiplied with \(-g \cdot G\) from the left and by \(A\) from the right. In order to simplify the computations, we use the \(A^T\) transpose matrix to multiply the accelerometer outputs. Thus the equation will be

\[
-g \cdot G \cdot (P) = a \cdot A^T.
\] (4.32)

A series of measurements were then taken with the accelerometer in different telescope positions (corresponding to different \(a_k\) values) and paired with the corresponding \(\tau_k\) and \(\delta_k\) values in order to minimize the merit function

\[
\chi^2 = \sum_k ( -g \cdot G \cdot P_k - a_k \cdot A^T )
\] (4.33)

to find the best-fit values of the \(a, b, c', d,\) etc. parameters of the pointing model. Assuming that the local gravity can be taken as unity, i.e., \(g = (0, 0, 1)\) we can write

\[
-g \cdot G = \begin{pmatrix}
  \cos \varphi \\
  0 \\
  \sin \varphi
\end{pmatrix}
\] (4.34)

Combining Equation (4.30) with Equations (4.34) and (4.32), we get

\[
-g \cdot G \cdot P = \begin{pmatrix}
  c_\varphi c_\tau c_\delta + s_\varphi s_\delta \\
  c_\varphi s_\tau \\
  -c_\varphi c_\tau s_\delta + s_\varphi c_\delta
\end{pmatrix} + a \begin{pmatrix}
  -s_\varphi s_\tau c_\delta \\
  s_\varphi c_\tau \\
  s_\varphi s_\tau s_\delta
\end{pmatrix} + b \begin{pmatrix}
  c_\varphi s_\delta - s_\varphi c_\tau c_\delta \\
  -s_\varphi s_\tau \\
  c_\varphi c_\delta + s_\varphi c_\tau s_\delta
\end{pmatrix} + c' \begin{pmatrix}
  c_\varphi s_\tau c_\delta \\
  c_\varphi c_\tau c_\delta \\
  0
\end{pmatrix} + d \begin{pmatrix}
  -c_\varphi s_\tau s_\delta \\\n  s_\varphi c_\tau c_\delta + s_\varphi c_\delta \\
  c_\varphi c_\tau s_\delta + s_\varphi c_\delta
\end{pmatrix} + e' \begin{pmatrix}
  c_\varphi c_\tau s_\delta - s_\varphi c_\delta \\
  0 \\
  c_\varphi c_\tau c_\delta + s_\varphi s_\delta
\end{pmatrix} + g \begin{pmatrix}
  0 \\
  -c_\varphi c_\tau s_\delta + s_\varphi c_\delta \\
  -c_\varphi s_\tau
\end{pmatrix} + i \begin{pmatrix}
  c_\varphi s_\tau \\
  -c_\varphi c_\tau c_\delta - s_\varphi s_\delta \\
  0
\end{pmatrix},
\] (4.35)

where \(c_\varphi\) and \(s_\varphi\) denote \(c_\varphi = \cos \varphi\) and \(s_\varphi = \sin \varphi\), respectively. Considering that the accelerometer output is invariant for the rotations around the vertical
axis, it can be shown that the vectors with the $a$, $b$ and $c'$ coefficients have linear dependency of $\varphi$, $\tau$ and $\delta$. This invariance is not obvious, since several subsequent transformations have to be applied to determine the final vector $a$. In order to simplify the final calculations, the terms with the parameter $c'$ were neglected.

In order to determine the real-life accuracy of the accelerometers, we acquired images in 23 different positions with the Schmidt telescope at Piszkéstető Observatory. This way we collected enough data to determine the pointing of the accelerometer. The $\tau$ hour angle and the $\delta$ declination values used for the computation can be gathered from either of the rotary encoders of the telescope, or the astrometric solution. First, we performed basic data reduction on the images by using the FITSH program package (Pál 2012). The astrometric solution is also provided by this package (using the USNO-B catalog, Monet et al. 2003), but as a sanity check, the online version of the Astrometry.net project (Lang et al. 2010) was also queried. The given central J2000 coordinates were converted to first equatorial system (by taking into account all the distorting effects that arises from the movement and nature of the Earth) for the epoch of image acquisition by using the algorithms of Meeus (Meeus 1998). The \texttt{lfit} (Pál 2012) module of FITSH was applied to perform linear regression via the algorithms of Press et al. (2002). The resulting values for the pointing model parameters are

\[
\begin{align*}
    a &= -0.00091 \pm 0.00017, \\
    b &= +0.00019 \pm 0.00010, \\
    d &= -0.00011 \pm 0.00021, \\
    e' &= +0.00975 \pm 0.00011, \\
    g &= +0.00082 \pm 0.00013, \\
    i &= -0.00070 \pm 0.00025.
\end{align*}
\]

That means that the fitting residual is 0.00025, which is equivalent to 0.0143° = 0.86′ = 52″ of accuracy. We can conclude, that after the described calibration procedures, the accelerometer is capable of operating with sub-arcminute level accuracy. Hence, we can safely and reliably apply the units as a part of a real telescope control and/or feedback system. Note, that the time span between the technical realization of the calibration procedures and the attitude fitting is approximately two months. Furthermore, there are other distorting effects, that are not quantified during the whole work flow – such as the mechanical vibration of the telescope, or the two-sample variance (frequency stability) in output values of the sensor. We can estimate the long-term variance of the systematic errors by repeating the attitude calibration in a longer period of time.
4.4.3 Extraction

Until this point we considered the accelerometer unit only as a feedback system of a telescope control system (TCS). Now, let us designate the accelerometer as the primary absolute pointing encoder. In order to implement this, only the \( \tau \) and \( \delta \) coordinates need to be extracted from the accelerometer output. Figure 4.13 shows the contour lines of an equatorial telescope located on the \( \varphi = 47.5^\circ \) geographical latitude. Here, the orientation of the accelerometer unit relative to the telescope tube and the fork mechanics is the same as I described in Section 4.4.2. In the plot, we can see that two similar accelerometer outputs are feasible in different telescope positions. Since this is a simple bimodal ambiguity, it can be easily resolved, if the value of the hour angle is known. For this purpose, an accelerometer unit is mounted on the tube and another on the telescope fork. As mentioned in Section 4.4, the value of \( \tau \) can be easily determined from the output of the auxiliary sensor. Note, that a rough approximation is enough from this unit to clarify the problem. In practice, the method is the following. Equation (4.32) has to be inverted by substituting the expression of Equation (4.35) where the latter one is a function of \( \tau \) and \( \delta \). Due to the first-order expansion, this can be performed in an iterative manner. The equation

\[
\begin{pmatrix}
\cos \varphi \cos \tau \cos \delta + \sin \varphi \sin \delta \\
\cos \varphi \sin \tau \\
- \cos \varphi \cos \tau \sin \delta + \sin \varphi \cos \delta
\end{pmatrix} =
\begin{pmatrix}
a_x \\
a_y \\
a_z
\end{pmatrix}
\]  

(4.36)
has to be solved for the $\tau$ and $\delta$, where $(a_x, a_y, a_z)$ are the components of the $a \cdot A^T$ product. This solution is substituted to the first-order terms and subtracted from the components $(a_x, a_y, a_z)$. We repeat the iteration until the solution converges.

The solutions for $\tau$ and $\delta$ are

$$
\tau = 90^\circ \pm \arccos \left( \frac{a_y}{\cos \varphi} \right),
$$

$$
\delta = \arg(d_x, d_y),
$$

where

$$
d_x = a_x \cos \varphi \cos \tau + a_z \sin \varphi,
$$

$$
d_y = a_x \sin \varphi - a_z \cos \varphi \cos \tau.
$$

The auxiliary sensor provides the information about the hour axis, hence the bi-modality can be resolved easily. Once $\tau$ is known, the value for $\delta$ will be unambiguous.

Another information is hidden in the covered area in Figure 4.13. Due to the limits of the local horizon, and the finite angle between the horizon and the polar axis of the telescope, only a stripe is covered instead of half of the sphere. The area of this partial stripe relative to the total surface is $\cos(\varphi/2)$. From this, we can see, that if the telescope is located northward or southward (from the equator), the area of the stripe will decrease. From the perspective of the accelerometer close to the poles the equatorial mounts act similarly as alt-azimuthal mounts. As mentioned in Section 4.2, the accelerometer is unable to determine azimuth angle of such mechanics.

If the sensor is used as a horizontal limit switch, the relation between the $h$ horizontal altitude and the accelerometer output can be characterized by

$$
\sin h = a_x.
$$

Note, that the centrifugal force caused by the slewing speed has also a distorting effect, and has to be take into account by quantifying. A standard slewing speed of $\sim 2^\circ/s$ produces a centrifugal acceleration of $10^{-5} \, g$, which equivalent to a few arcminutes if we convert it into attitude. However, the significance of this centrifugal acceleration depends both on the sensor’s distance from the axis and the speed of the slewing.

In this chapter I summarized the conditions how to use a MEMS accelerometer based electronics as an accurate telescope control and/or feedback system. I demonstrated, that with a cheap off-the-self sensor a sub-arcminute accuracy can be achieved. I also introduced the necessary calibration procedure how to attain
this accuracy level and what other kind of effects are needed to be considered during either the calibration procedures or the routine operations.
Ongoing developments and future plans

“All we have to decide is what to do with the time that is given us.”

Gandalf the Grey
– J.R.R Tolkien,
The Lord of the Rings
–The Fellowship of the Ring

Modular electronics with various functionalities

As it can be seen in the previous chapters, during the development of the Fly’s Eye instrument, versatile assortments of electronic, electro-mechanical and opto-electronic devices were designed for various purposes – including motor drivers, encoders, encoder controllers, actuator controllers, power switching controllers and communication interfaces. In these boards some of the electronic elements and their functionality are identical. The core is based on the same embedded microcontroller unit, and each use the same communication interfaces – only the driven peripherals differ. On the other hand, modularity is a key aspect, that is considered in the designs of our group (e.g. the individual camera units in Section 3.1.2 have the ability of easily replacing by unplugging two cables and releasing three mounting screws). For this reason a set of modular electronics were designed with the concept of a motherboard, that is the capable of adopting various type of smaller, functionality-dependent daughterboards. In the following, I will give a summary of these modular electronics.

Motherboard

The core of the motherboard is an 8-bit AVR microcontroller architecture that is well-tested in various implementations in previous projects (including the Fly’s
Eye design and the accelerometer board, see earlier). The main duty of this MCU is to supervise communication, to perform the interface-specific computations and to handle the data provided by another subsystem(s). For communication, both RS485 and CAN interfaces were integrated with both using the same input lines. Depending on the host system, only one protocol can be used at a time. For cyclic logging purposes the in-built memory is supported by an external non-volatile ferroelectric RAM (NVFRAM). These units are bus-powered, hence numerous different units can be connected in a serial fashion. Depending on the adopting system, the bus line voltage can have a value from a wide choice of standardized levels, such as 5 V, 12 V or 24 V. In the core module, a high efficiency step-down regulator provides 5 V (unless the bus itself provides this voltage) and a low-drop linear regulator supplies the 3.3 V operating voltage of the MCU and its primary interfaces. The daughterboards can be attached via $4 \times 6$ header pins arranged in a rectangular pattern. There are reserved pins for power lines and for communication (including RX/TX lines of the UART interface or SDA/SCL of I2C), while the remaining ones are connected to the GPIO pins of the MCU or directly to the output terminal blocks. The PCB shape is standardized in order to fit in the aforementioned enclosure (Figure 4.14).

Daughterboards

Various types of daughterboards (e.g. Figure 4.15) have been designed by considering the aforementioned pin-out (12 communication, 4 power and 8 output lines). Here, a short, yet not fully complete list is given for the already designed, manu-
factured, assembled and tested modules. The design of further daughterboards is in progress.

- **Stepper motor logic** – By a differential TTL interface, this module is capable of controlling terminal stages of stepper motors via setting the enable, direction and pulse pins.

- **Digital rotary encoder transceiver** – On the same board, the differential TTL interface is also able to handle the signals provided by SSI-based interfaces or incremental encoders.

- **Analog rotary encoder receiver** – This board can receive 1 volv-peak-to-peak (1VPP) output of 2-phase analog encoders.

- **Wi-Fi module** – With this module, the CAN/RS485 communication packets can be serialized or monitored via Wi-Fi. Furthermore, by employing a Wi-Fi access point, this unit is also capable of acting as a communication master device for the given protocol.

- **Communication multiplexer module** – RS485 packets can be converted to CAN-based protocol and vice versa. This module is found to be useful for connecting the more robust CAN bus interface with legacy electronics supporting purely RS485.

- **Current measuring unit** – Power consumption imply useful feedback about the operation of a device. With this board the current flow can be measured for 4 independent and galvanically isolated channels.

- **Relay switching module** – Shutting down or resetting an electronics is essential for a remotely operated systems. By 6 channels of galvanically isolated open-collector outputs, switching of 6 electro-mechanical relays can be managed.

- **Generic bi-state input module** – Detecting the state of various bi-state devices (e.g. limit switches, push buttons) can be implemented with this module in a galvanically isolated fashion.

**Applications**

From the described functionalities we can see that with these modular electronics, various type of automatization features can be implemented for new telescope designs, retrofitted meter-class telescopes and dome control subsystems – including motor and encoder control, communication channels, feedback systems. As their first implementation, for the renovation and automatization of the 24-inch
Figure 4.15: Upper left & middle: The core the motor driver module is a four channel differential TTL interface. The signal directions can be selected during the assembly phase by using solder bridge switches. Upper right: With six open-collector channels we can control a set of external relays in order to remotely switch on or off various devices (e.g. single board computers, cameras, etc.). We added extra protecting diodes on each side of each channel against power surge. Lower left: The GPIO channels of the microcontroller can also be configured as inputs, therefore, states of switches and similar mechanisms can be monitored. However, it is important to apply galvanic isolation in order to protect the MCU. Lower middle: A simple RS485-CAN converter daughterboard. Lower right: The Wi-Fi module built around a Zentri AMW006 transceiver device. The special antenna connectors required to slightly increase the board size and the number of the applicable output LEDs are reduced due to the placement of the connectors. I designed the three LEDs in a way that these indicate the Wi-Fi online, Wi-Fi link activity and CAN bus activity states of the module.

telescope at Konkoly Observatory, Budapest, several such units were used for axis motor driving, encoder controlling and for communication establishment. These electronics can also be used to drive and supervise the motors of the right ascension and declination axes of the Schmidt telescope at Piszkéstető. The controlling desk of this telescope will also be modernized in a much simpler an clearer fashion by involving these modular units. In addition, by applying these electronics, the dome of the new 80 cm telescope can be operated fully automated.
Summary

“...wonderful things that I was amazed...out of nothing I have created a strange new universe”

János Bolyai

In my thesis, I present the details of the development of an all-sky survey instrument with the intention of performing time-domain astronomical observations. With the Fly’s Eye camera system, we will be able to perform high cadence sampling of various astronomical phenomena in the \( \sim 9 - 15 \) magnitude range with an effective resolution of \( 20''/\text{pixel} \) above \( \sim 30^\circ \) horizontal altitude. The scientific goals of the Fly’s Eye camera system cover numerous astronomical phenomena: tracking meteors and near-Earth objects, determining the rotation and shape of asteroids, observing stellar activity, eclipsing binary stars, transiting extrasolar planets and detecting transient events with their pre-phase. The Fly’s Eye design has the advantage that if we stack \( \sim 25 \) consecutive images into one frame, the limiting magnitude will increase to \( 17 - 18 \), but this is accompanied by the decreased imaging cadence of \( \sim 1 \) hour for such faint sources.

The purpose of a telescope mount is to follow the apparent rotation of the sky. For this purpose, instead of an equatorial mount as a primary support, a hexapod was used for this project. This parallel robot is able to arbitrarily move its payload platform with respect to the base. Our design is capable of performing celestial tracking with sub-arcsecond level precision. In order to reach this level of precision, the device has to be calibrated. This procedure is based on the investigation of the position drift of the observed celestial objects. The hexapod device has numerous advantages, including fault-tolerant operation, geographical location independency and self-calibration capability.

In the second part, I describe the integration of the complete system including the assembly of the camera support structure and the individual imaging units. In order to provide environmental protection, a specified dome-like enclosure was designed. Within this dome, the ambient temperature and relative humidity can be controlled and the enclosure is equipped with several redundant feedback systems.
The Fly’s Eye device and its subsystems require numerous power supplies of which are mounted in a cabinet, that is located right next to the enclosure. Some of the subsystems require a UPC in order to terminate the observation and close the dome in case of a blackout. The fully assembled Fly’s Eye instrument is currently capable of performing observations in a half-autonomous way.

For an autonomously operating telescope, the most important is to attain reliable and valid information about the actual state of the system. I investigated the possibility of using MEMS accelerometers for this purpose as an independent and redundant feedback system. I demonstrated that with a proper calibration, these sensors are capable of providing a pointing model with a sub-arcminute level accuracy.
Összefoglaló

Értekezésemben bemutatom a Légyszem kamerarendszert, mely egy nagy időfelbontású, teljes-égbolt felmérő eszköz. Ez a műszer alkalmas a 30° horizontális magasság feletti teljes látható égbolt ~9–15m magnitúdó fényességű csillagászati jelenségeinek a megfigyelésére, ~20 ívmásodperces szögfelbontással. A Légyszem kamerarendszer ~3 perces időfelbontású megfigyeléseket végez, mellyel számos tudományterületnek biztosít részletes idősort: meteorok és Földközeli objektumok követése, kisbolygók alakjának és forgási tulajdonságainak meghatározása, aktív csillagok vizsgálata, fedési kettőscsillagok és exobolygók megfigyelése, tranziens jelenségek észlelése. Jegyezzük meg, hogy ~1 órányi felvétel összeátlagolásával (ami ~1 órás időfelbontást eredményez) a határőr fényesség elérheti a 17–18 magnitúdót is.

Csillagászati megfigyeléseknél szükséges az ég látszó elfordulásának követése, mely a különböző mechanikák feladata. Ebben az esetben ekvatoriális szerelés helyett egy hexapodot alkalmazunk. Ennek a párhuzamos robottípusnak a teherhordó felülete bármilyen pozíciót fel tud venni az alapjához képest. A tervezett hexapod szerelés ívmásodperccel alatt pontosságú követést képes biztosítani. Ehhez azonban az eszköz kalibrálása szükséges, mely azon alapszik, hogy meghatározzuk egy a látszó objektumok helyzetének elmozdulását a soron következő felvételeken. A hexapod számos előnytel bír, melyek között a hibátűrő működés, figyelőlés a földrajzi elhelyezkedéstől valamint önkalibrációs tulajdonság is szerepel.

Ezt követően szemléltetem az eszköz végleges összeállítását, beleértve a kameragéptyű és az egyedi tartószerkezet tervezésének részleteit, az optikai torzítás kiküszöböléséhez fejlesztett algoritmust, a pixel-szintű világoskép-kalibrációs eljárás részleteit. A Légyszem eszköz védelme egy egyedi kupola-szerű burkolat megepítése révén valósult meg. Ezen belül a hőmérséklet és az abszolút páratartalom is szabályozható. A burkolat számos visszajelző rendszerrel lett felszerelve. A működéshez szükséges villamos energiát tápegységek sora biztosítja, melyek a Légyszem rendszeréhez közel, el egy elosztószekrényben találhatóak. Egyes alrendszerek energiáját szünetmentes tápegységek biztosítják, hogy az eszköz alapálalapotába való visszatérése, illetve a burkolat záródása biztosított legyen áramszünet
esetén is. Jelenleg a Légyszem kamerarendszer fél-autonóm módon végez megfigyeléseket.

Autonóm működő vagy távolról irányítható csillagászati távcsöveknél elsődleges követelmény a rendszer állapotának valós idejű ismerete. Vázolom egy gyorsulásérzékelőn alapuló újfajta pozíciókódadó alkalmazásának lehetőségeit. Leírom, hogy milyen kalibrációs eljárások révén készíthetünk egy független távcsővezérlő rendszert, mely képes ívperc alatti pontossággal megmondani a távcső irányultságát.
Glossary

- **Printed circuit board (PCB)** electrically connects electronic components using conductive tracks and mechanically support by a non-conductive substrate. The substrate is cooper laminated and the physiognomy of particular circuit is retrieved by chemical etching.

- **Integrated circuit (IC)** is a complete electronic circuit packed of small silicon semiconductor material.

- **Microcontroller unit (MCU)** is a type of embedded small computer on a single integrated circuit. It contains a central processing unit along with memory and several types of programmable input-output peripherals and communication interfaces.

- The **firmware** is a specific type of computer program which run on embedded systems, mainly on microcontrollers or in some cases, single-board computers. Firmware codes typically smaller, highly optimized – mainly written in C with some inline assembly language parts – and has several real-time functionality compared to programs or codes run on desktop or server computers.

- **General-purpose input-output (GPIO)** is an unspecified digital signal pin of a microcontroller or an electronic device. The purpose and the behavior is defined and programmed by the designer.

- **Non-volatile ferroelectric RAM (NVFRAM, FRAM)** has the same functionality as the widely used non-volatile flash memory, but with the advantage of enduring at around $\sim 10^{14}$ write cycles. This endurance makes FRAMs to be employed as conventional memory but without the risk that data are lost because of a power outage or any external effect.

- **Electrically erasable programmable read-only memory (EEPROM)** is a type of non-volatile memory which can store a relatively small amount of data, but the individual bytes can be erased and reprogrammed electrically.

- **Reed-sensor** is a type of magnetic sensor whose operation is based on a reed switch. Two overlapping ferromagnetic blades are sealed in a hermetically
sealed enclosure, separated by a distance of a few microns. Normally the blades do not touch. When an external magnetic field is applied, the two blades are attracted thus closing the switch.

- **Hall-encoder** or Hall-effect sensor is based on the phenomenon that if electric current flows in a conductor or semiconductor and a magnetic field is applied perpendicular to the current than a voltage difference appears in the conductor transverse to the flowing current.

- **Transmissive photo-interrupter** is a photo sensor that consist of an optical receiving (photo-transistor) and a transmitting (infrared light emitting diode) element which are packed in a single U-shape housing. An object, crossing the gap will interrupt the infrared beam thus switching the phototransistor off.

- **Relay** is an electrically operated switching device that typically uses an electromagnet for switching.

- **Inter-integrated circuit (I²C)** is a synchronous, multi-drop, packet switched serial bus. It is used for short distance communication between a microcontroller unit and lower-speed peripherals. Short distance usually imply that these I²C capable devices are assembled on the same printed circuit board, but in a few cases, a board-to-board arrangement is also feasible. The typical data rate between I²C devices is comparatively small, in the order of 100-400Kbps. I²C is widely used in the robust integration of various types of sensors.

- **RS232** is a serial point-to-point communication standard. It can be used over shorter distances since it is signaling is prone to distort due to electric noise.

- **RS485** is a serial multi-point communication standard. It can be used over long distances since it is inviolable in electrically noisy environments.

- **RS422** is a serial multi-point communication standard which also allows full-duplex communication. Basically, it is implemented as two parallel RS485 lines, and hence, it can also be used over long distances since it also provides more reliable operation in noisy environments.

- **Serial peripheral interface (SPI)** is a full-duplex, single-master, multi-slave, synchronous, serial communication interface. Unlike I²C, SPI allows only a point-to-point communication, however, the data rate is much higher: it is in the order of 10Mbps – 100Mbps for most of the SPI-capable integrated circuits.
• **Universal asynchronous receiver-transmitter (UART)** is an interface device for asynchronous serial communication where the data format and transmission speeds can be configured. A master device transmits the data by bites in sequence while the UART interface of the slave client assembles the original data from the received bits.

• **Controller area network (CAN)** is a message based protocol that allows individual devices to communicate with each other without involving a host computer. The most prominent application is in vehicles where several tens or nearly a hundred subsystems may involved in routine operations.

• **Universal serial bus (USB)** is a fully plug-and-play standard that specifies the cabling, connector, power and protocol by which numerous type of peripherals can be connected to any computer.

• **Message queuing telemetry transport (MQTT)** is a publish-subscribe based messaging protocol implemented over the Internet protocol suite (TCP/IP). Clients can publish messages or can be subscribed to pre-defined topics which are handled by a message broker. The simplicity of this MQTT protocol allows us to use it even on systems with limited resources, such as microcontrollers or single-board computers.

• **A Single-board computer (SCB)** is a full value embedded computer with limited peripheral and computing capabilities compared to normal – such as desktop and server – computers. Despite the limited resources, several communication interfaces, such as USB, serial and Ethernet ports are available – nevertheless, typically a monitor or keyboard cannot be connected. One prominent feature of a single-board computers is the lack of moving parts which allows operations in more harsh environments and hence the failure rate is significantly less. Several single-board computer manufacturers integrate peripherals like I²C or SPI, available typically for microcontrollers.

• **Computer numerical control (CNC)** is a machining tool (such as a milling machine or a lathe) that uses microcontrollers or computers to control the production. Such tools are capable of following pre-programmed instruction sequences without human interventions.

• **Computer-aided design (CAD)** helps engineers to create models and to optimize designs. 3D modelling also helps in the visualisation of a complex design thus quality and productivity can be increased. The software often capable of exporting readable format for CNC machines.

• **Bevel gear** is a set of gear where the axes are inclined (typically 90°) and the gears has a conical shape.
• **Differential** is a mechanical device that is capable of transmitting torque to the simultaneously driven shafts that have different rotational speeds.
Thesis points

1. I designed the controller electronics of the first telescope with a hexapod mechanics in Hungary, and I participated in the assembling, testing and installation of the system. In astronomical instrumentation such a unique robot has never been utilized before as a primary mount for a direct imaging optical telescope. I show that the designed hexapod is capable of sidereal tracking with more than an order of magnitude finer accuracy than the resolution of the proposed optical setup.

2. During the design of the actuator motion controller electronics I implemented several feedback systems, since redundant operation has high impact in autonomous telescopes. By the various independent devices and algorithms I managed to determine the actual state of the hexapod legs. First, the electronics count the microsteps of the stepper motor. Furthermore, I have clutched a diametrically magnetized cylinder magnet to the driven axis of the actuator of which rotation is monitored by a Hall-effect based magnetic rotary encoder. In addition, the linear actuators are equipped with magnetic limit switches. The controller electronics continuously polling the state of the limit switch and the power consumption of the motor. These mechanically independent subsystems provide redundant monitoring of the state of the hexapod legs. The system can be supplemented by installing an accelerometer device on the controller board yielding an additional independent method for monitoring the behavior of the individual actuators.

3. I designed several components of the camera unit, and I participated in the designing and assembling of the payload platform. The camera units can be easily mounted on the unique frame structure with the feature of adjusting the particular field-of-views with ±10° limitation. Due to the extremely large field-of-view, the standard flat-field calibration procedures cannot be performed, therefore, I developed an alternative method. According to this, light is directed – as homogeneous as possible – to the sensor with optic fibres and the relative sensitivity of the pixels can be measured. I also designed several electronical and mechanical parts of the protective enclosure for the Fly’s Eye device, and I supervised the assembly of the system. Redundancy
is essential in this aspect as well (measuring the current flow of the actuators, adjustable limit switches, reed-sensor, accelerometer units, surveillance camera via Ethernet, ...).

4. The importance of an automatized data reduction pipeline cannot be neglected for an instrument producing \(\sim 70 − 100\) GB data in subsequent nights. Such amount of data is cannot be processed by human effort, therefore, I developed an algorithm by which the determination of the astrometric solution can be automatized. For cameras with large field-of-view, the radial optical distortion has significant impact on the imaging quality. My algorithm is capable of compensating this effect with the implementation of the Brown–Conrady model.

5. I designed and assembled a MEMS accelerometer based absolute encoder module that is capable of providing independent feedback from the spatial orientation of a biaxial mechanics. I developed the data acquisition firmware of the device. Statistical calculations and time-stamping are done onboard and the data are forwarded to a higher level frontend software.

6. I prove that this MEMS accelerometer based absolute encoder is capable of providing sub-arcminute accurate telescope positioning. However, a series of calibration procedures are needed to be performed in order to achieve this goal. First, I participated in the correction of the errors related to the sensor itself (e.g., uncertainties in the perpendicularity of the axes). Then, the relative orientation of the device to the telescope is needed to be determined. I have been involved in the derivation of the pointing model of the Schmidt telescope of Konkoly Observatory at Piszkéstető.
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- **Pál, A.; Mészáros, L.:** Concepts of the mosaic array of numerous ultra-small lens (MANUL) design", Ground-based and Airborne Instrumentation for Astronomy VI, 9908, pp. 990859- (2016)


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I. A doktori értekezés adatai

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3. A doktori értekezés szerzőjeként hozzájárulok a doktori értekezés és a tézisek szövegének plágiumkereső adatbázisba helyezéséhez és plágiumellenőrző vizsgálatok lefuttatásához.

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