The Fiber Multi-Object Spectrograph (FMOS) Project: the Anglo-Australian Observatory role

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ABSTRACT

The Fiber Multi-Object Spectrograph (FMOS) project is an Australia-Japan-UK collaboration to design and build a novel 400 fiber positioner feeding two near infrared spectrographs from the prime focus of the Subaru telescope. The project comprises several parts. Those under design and construction at the Anglo-Australian Observatory (AAO) are the piezoelectric actuator driven fiber positioner (Echidna), a wide field (30 arcmin) corrector and a focal plane imager (FPI) used for controlling the positioner and for field acquisition. This paper presents an overview of the AAO share of the FMOS project. It describes the technical infrastructure required to extend the single Echidna "spine" design to a fully functioning multi-fiber instrument, capable of complete field reconfiguration in less than ten minutes. The modular Echidna system is introduced, wherein the field of view is populated by 12 identical rectangular modules, each positioning 40 science fibers and 2 guide fiber bundles. This arrangement allows maintenance by exchanging modules and minimizes the difficulties of construction. The associated electronics hardware, in itself a significant challenge, includes a 23 layer PCB board, able to supply current to each piezoelectric element in the module. The FPI is a dual purpose imaging system translating in two coordinates and is located beneath the assembled modules. The FPI measures the spine positions as well as acquiring sky images for instrument calibration and for field acquisition. An overview of the software is included.

Keywords: astronomical instrumentation, fibers, piezo, fiber positioner, Subaru telescope, spectroscopy

1. GENERAL FEATURES

The Fiber Multi-Object Spectrograph (FMOS) for the prime focus of the Subaru telescope on Mauna Kea will provide the first wide field multi-object near-infrared spectroscopic capability on an 8-m telescope[1]. The effort to design and build the FMOS instrument is shared amongst the Anglo-Australian Observatory, the University of Durham, Oxford University, Rutherford Appleton Laboratory (RAL), the National Astronomical Observatory of Japan, Kyoto University and the Subaru Telescope.

The 8.2m mirror of the Subaru telescope (Fig. 1) directs light to the prime focus, located about 15 m away. A three element prime focus corrector (Fig. 2) provides a 0.5° diameter field of view optimized for the near infrared.

A 400 fiber positioner, Echidna, sits above the corrector in the prime focus unit. Echidna represents a radical change in the design of multi-fiber positioners. It was developed[2] as an alternative to more traditional pick and place instruments that could not position as many fibers in as small an area (400 in about 150 mm diameter). The Echidna positioner and focal plane imager, used to determine the fiber positions, are described in detail later.

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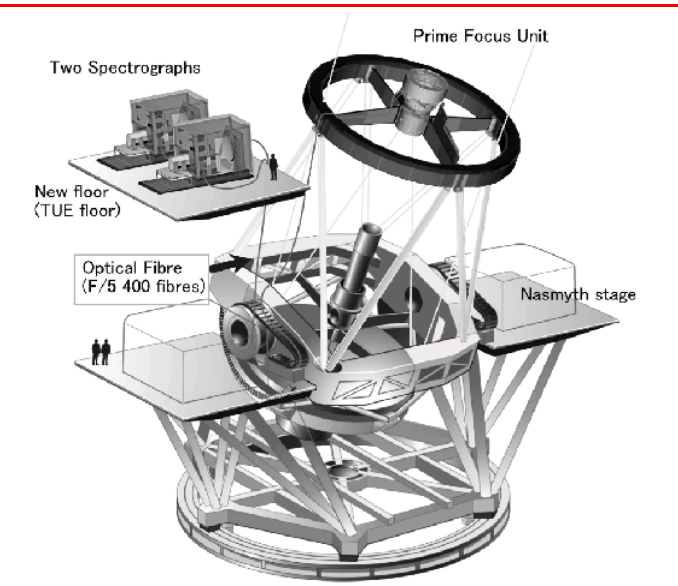

Fig. 1: CAD model of Subaru telescope, showing the locations of the prime focus unit, fiber routing, and the spectrographs.

At the top of the prime focus unit, the fibers leaving Echidna connect with long fibers which travel via the altitude axis to the two spectrographs (200 fibers to each) (Fig. 1). The connector is under development at the University of Durham and uses an array of accurately aligned GRIN (gradient index) lenses[3]. The connector not only allows for detaching the prime focus unit from the telescope but also provides a means of changing the focal ratio from f/2 to f/5 before injection into the longest run of fibers. The connector also provides for back-lighting the f/2 fibers as needed for controlling the positioning of the Echidna spines. The fiber link, consisting of ~20 km of optical fiber, will be permanently installed on the telescope structure.

The 400 fibers feed two identical spectrographs designed for faint spectral observations in the near-infrared. Based on the OH-suppression technique used in the Cambridge InfraRed Panoramic Astronomical Survey Spectrograph (CIRPASS), the spectrographs reduce the night sky background emission by physically masking the atmospheric emission lines. The spectrographs have two observing modes. The low resolution mode covers the wavelength range 0.9-1.8 μm in a single exposure at a resolution of R~500. In the high resolution mode one quarter of the wavelength range is imaged at a resolution of R~2200. A collaboration between RAL, the University of Oxford, and Kyoto University is designing and building the spectrographs[1].

The FMOS spectrographs will be housed on a specially built platform located above the right-hand Nasmyth platform as shown in Fig. 1. (Both the Nasmyth platforms of Subaru are already occupied).

2. PRIME FOCUS CORRECTOR

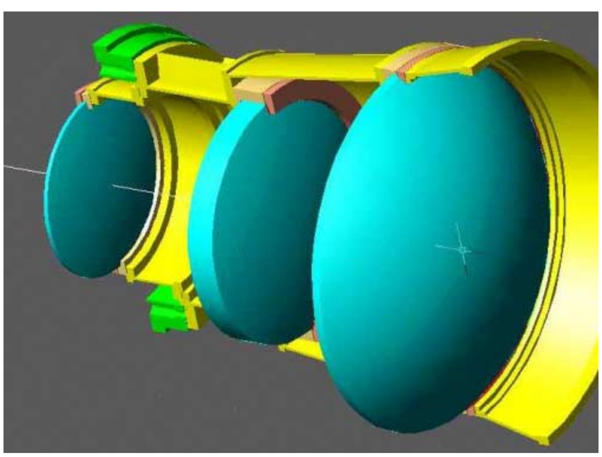

Fig. 2. Sectioned view of prime focus corrector.

2.1 General features

The main prime focus corrector requirements were: good imaging over the spectral range 0.9 to 1.8 μm; a flat telecentric focal surface; a final focal ratio > f/2; and a back focus of at least 200 mm.

Although the Echidna design is adaptable to a curved focal surface, a flat focal surface simplifies the attainment of accurate focus of spine tips and mounting of the modules. A telecentric focal surface aligns the chief ray with the fiber axis over the whole field, when the spines are at the centers of their ranges, and thus minimizes inefficiency due to misalignment of the telescope beam and the acceptance cone of the fiber.

Mechanically, the corrector must fit within the largely pre-existing prime focus unit (PFU) design and maintain a back focal distance of 200 mm to provide clearance for the FPI and the Shack-Hartmann unit.

2.2 Optical design

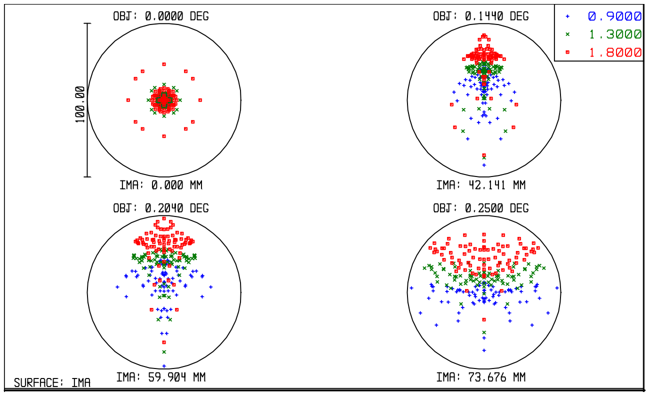

Fig. 3 Spot diagrams for wavelengths 0.9, 1.3, and 1.8 µm. Circles are 100 µm diameter, the same as the fiber cores. The spots are for the field center and radii enclosing 1/3, 2/3, and all the field area.

The corrector design produces images with rms radii exceeding 20 µm only in the outer area of the 30 arcmin diameter field, for wavelengths of 0.9 to 1.8 µm. With allowance for seeing and for the misalignment of the fiber axis with the telescope pupil when a spine is tilted, the proportion of radiation collected inside the 100µm diameter fiber core is affected very little by the optical aberrations. The beam focal ratio after the corrector is f/2.1, while the Subaru primary mirror is f/1.8. An earlier design to feed visible wavelength as well as near infrared spectrographs, included an atmospheric dispersion corrector (ADC), but plans for optical spectrographs were omitted, rendering an ADC unnecessary.

As shown in Fig. 2, the design incorporates three lens elements; all are of BSM51Y glass. The blank for the first element, 600 mm diameter and deeply curved, will be slumped to minimize the material to be removed.

2.3 Mechanical structure

A simple welded thin wall shell structure has been adopted. Such tubular structures are inherently stiff, readily fabricated and readily machined. It is also compact, which is required to fit the corrector into the prime focus unit. The shell is made in two sections to facilitate welding and machining.

Each lens is mounted in its own metal cell and compliant pads are used to limit mounting stresses on the glass. The cells are bolted to the shell so that alignment of the corrector may be made by working with the metal to metal interfaces between shell and cells. Since the second lens is buried within the shell, the easily accessible first and third lenses will be referred to it for alignment.

The corrector assembly is mounted via a thick aluminum adapter ring, visible in Fig. 2 near the level of the third lens element. This adapter ring will be mounted on a translator (provided as part of the PFU) which translates the corrector to compensate for deflection of the telescope structure. The mounting plane is some 350mm behind the center of gravity, and an overhanging moment of 500 Nm will be exerted on the mount.

3. ECHIDNA FIBER POSITIONER: BASIC CONCEPT AND MECHANICAL DESIGN

3.1 Background

The area of the Subaru field is about 10 times less than for the 2 degree field (2dF) facility at the Anglo-Australian Telescope prime focus. The required number of fibers is the same, so it was considered that the 2dF technique - placement of magnetic buttons, carrying prisms and fibers, by a robot - was not practical. Instead a concept has been developed in which each fiber is held in a spine, which is tilted so that its tip can be anywhere within a circle. For 400 fibers in a diameter of about 150mm, the pitch of fibers on a uniform triangular pattern is ~ 7 mm.

With 7 mm radius as the range for each spine, the success rate in allocating fibers to 400 targets randomly scattered over the field is ~ 90%. An example of how a random field of 400 objects can be allocated with an Echidna instrument is shown in Fig. 4. The large dots denote an unallocated target object and the small squares denote unallocated spines (with the exception of the 14 guide spines located in rows along both sides of the field of view). For spines that are allocated, an arrow indicates how the spine will reach its target object. In this test 33 out of 400 targets are unallocated -a success rate of ~92%. The detailed algorithms for allocating fibers to targets are described in Sec. 4.3.

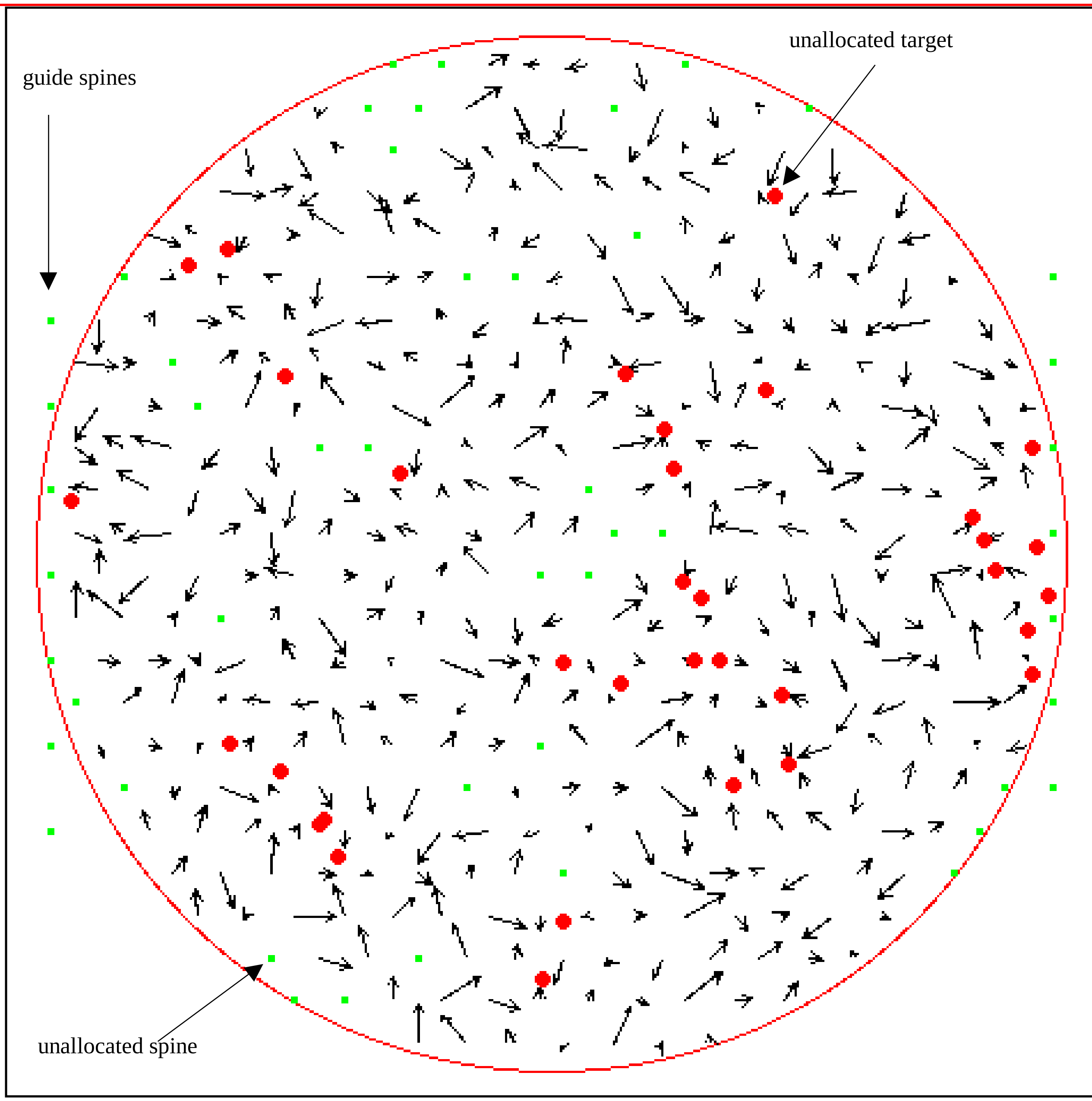

Fig. 4. Example of allocation of spines to 400 targets randomly scattered within the field. Arrow points are at targets, tails are at spine centers. 33 unallocated spines and 33 missed targets are indicated.

With the f/2.1 beam, a misalignment of the fiber axis with the telescope optical axis, due to the spine's tilt, of about 0.05 radian (roughly 10% of the beam diameter) is reckoned to be just acceptable. For 7 mm displacement this requires that the spine have a length of at least 140 mm.

3.2 Echidna spine construction

All Echidna science spines are identical. The spine and its components are illustrated in Fig. 5. Beginning at the cemented and polished optical fiber, a single spine consists of a stainless steel tapered tube cemented into a length of carbon fiber reinforced tube. The carbon fiber offers excellent stiffness to weight ratio, important for minimizing the spine sag. The tube is cemented into a stainless steel "pivot" ball bearing with a hole cut through its axis by electrical

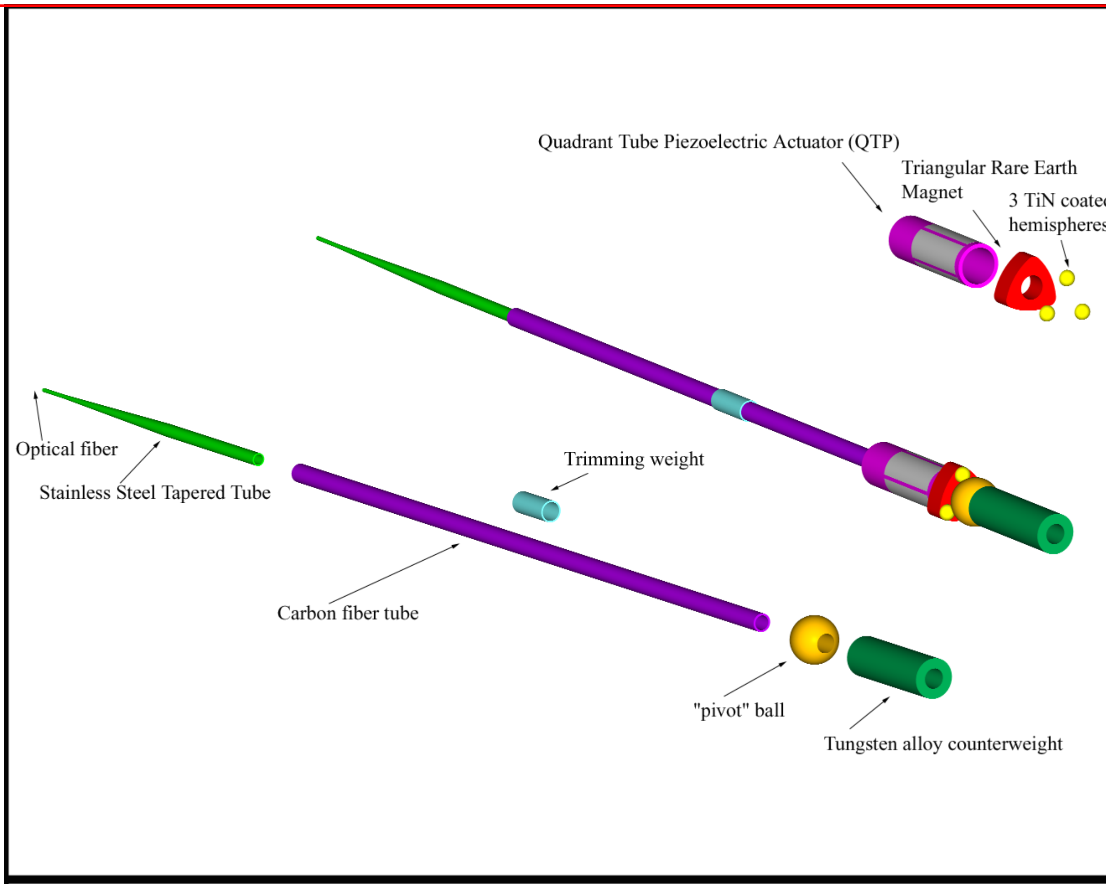

Fig. 5. Assembled spine inserted in mount (center); spine components (left); mount components (right).

discharge machining. As the spine must be balanced about the center of the pivot ball, a length of tungsten alloy tube is used for counterbalance. A small section of steel tube is cemented outside the carbon reinforced tube for fine adjustment of the balance. The optical fiber exits through the bore of the tungsten alloy counterweight. The spine length, measured from the center of the pivot ball to the fiber tip, is 160 mm. (Note this is slightly longer than the minimum length of 140 mm derived above, giving an improved optical performance). Lengths greater than 160 mm were not considered, primarily to limit the spine sag.

Each spine is inserted into a mount consisting of a near triangular section, rare earth magnet cemented to a quadrant tube piezoelectric actuator (QTP). Three titanium nitride coated steel hemispheres, cemented to the surface of the magnet, provide the contact points for support of the spine pivot ball. As all the ball bearings are magnetic, the spine is preloaded onto the contact points with a force much greater than the weight of the spine. The spine passes through the length of the QTP actuator. As a spine must tilt about 2.7° to obtain a patrol radius of 7 mm, the length of the QTP is restricted.

3.3 Spine dynamics

Each spine is driven by an actuator mount that, by a stick-slip ratcheting mechanism, is able to position the fiber tip to within 10 μm of any position in the patrol area of the spine. The QTP is a radially polarized tube of piezoelectric material. A single, continuous electrode is deposited onto the inner surface of the tube while on the outer surface there are four electrically isolated quadrant electrodes. The material between a quadrant electrode and the inner electrode expands or contracts in the radial direction when a voltage is applied between the inner and outer electrodes. There is a corresponding change in the length of the material that causes the QTP to bend. Furthermore, if an opposite voltage is applied across the opposing pair of electrodes, the bending is doubled. The magnitude of the bending is proportional to the voltage amplitude. Orthogonal bending of the QTP is obtained by applying DC voltages across the remaining pair of quadrant electrodes.

To drive an Echidna spine, a repetitive sawtooth voltage is applied across the electrodes. This produces asymmetrical acceleration of the QTP that is vital to producing a net tilt of the spine tip from one sawtooth cycle to the next. Referring to Fig. 6, the cycle can be summarized in three steps, though it should be noted that this is a simplified explanation:

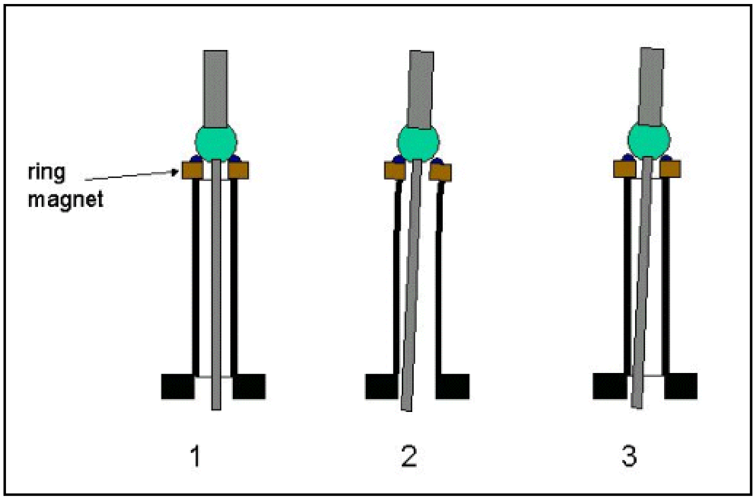

Fig. 6. Illustration of one cycle of spine drive (not to scale). Tilt is greatly exaggerated.

1. There is no applied voltage across the electrode pair. The spine is parallel to the axis of the QTP.

2. The QTP bends slowly as the applied voltage ramps up to the maximum value. Friction between the ball bearings of the mount and spine prevents the spine from sliding.

3. The QTP rapidly returns to its central position as the voltage decreases quickly to the original value. The mount acceleration overcomes the friction at the contacts between the balls and the spine retains some net tilt. A typical movement at the tip for each cycle is about 60µm for the largest voltage amplitude and about 10 µm with the small amplitude used for fine adjustment.

When a particular spine tip travel is required, the number of voltage cycles is applied which, by previous calibration, will result in the appropriate total tilt. However, variability in the step size necessitates iteration, first with coarse steps and later with fine ones, to reach the target position with the required accuracy of 10 µm.

3.4 Modular design

The actuator bases are cemented into a rectangular stainless steel “module”, with each module carrying 42 actuators (2 rows of 21). The Echidna positioner is constructed using 12 such modules, as shown in Fig. 7. The modular arrangement eases the construction of the positioner and provides a practical method for replacing a damaged module at the summit of Mauna Kea. The resulting rectangular array of spines overfills the circular field of view, such that only 400 of the 480 science spines are used to acquire targets.

So as to reduce the reconfiguration time dramatically, the spines are driven in parallel. The same voltage and frequency sawtooth signal, used to produce the spine movement, is sent to all spine actuators simultaneously. A series of electronic switches provides the method of switching input to individual spines on or off. The upper limit for the reconfiguration time for all 400 spines is 10 minutes, which, for this instrument, is limited by the fiber position measurement system.

3.5 Fiber position measurement system

The fiber positions are determined using a Focal Plane Imager (FPI), which takes images of backlit fibers, a similar concept to that used in the AAO 2dF positioner. The FPI consists of a telecentric lens coupled with a 2/3 inch format video camera mounted on an X/Y stage, roughly 150 mm ahead of the focal plane as shown in Fig. 8. The imaging

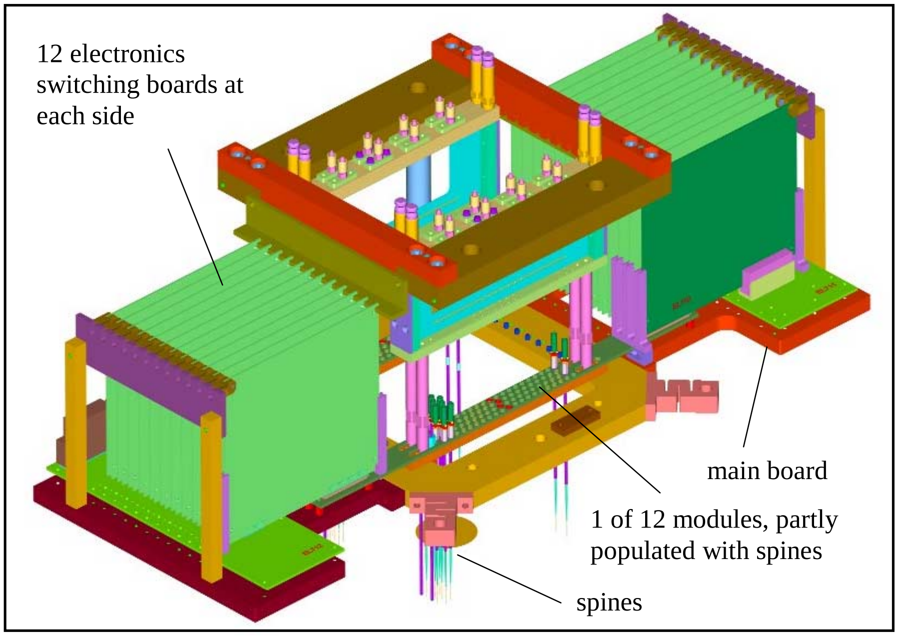

Fig. 7: Modular design of Echidna. The field of view is covered with 12 modules, each having 40 science spines and 2 guide spines. Two signal switching boards for each module are located at the sides of the unit.

system is able to record centroids for only a small subset of the 400 spines, approximately 12 backlit fibers at a time. Thus the FMOS field of view is split into 59 fields as shown in Fig. 9.

The FPI has another purpose; mapping the focal plane with a "sky" camera which is able to image 1-2 arcmin of sky. This provides a convenient calibration tool for the instrument. Field distortion of the prime-focus corrector can be mapped with the camera. The likely candidate for the sky camera is a high sensitivity Watec video camera, successfully tested recently on the AAT.

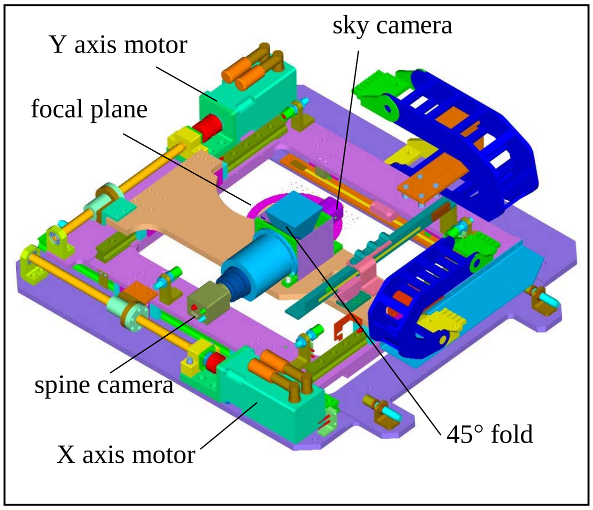

Fig. 8: Focal Plane Imager (FPI) shown inverted for clarity. It has two cameras: a fiber imaging system and a sky imager. In this view, light from the telescope comes from above.

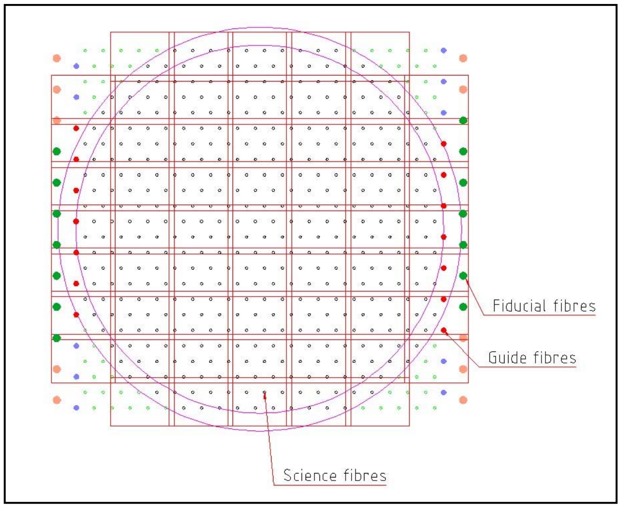

Fig.9: FPI frames superimposed onto the FMOS field of view; the locations of the science and guide spine home positions along with the fixed fiducials are indicated.

3.6 Auto-guiding

The Echidna instrument is responsible for fine-grained adjustments of the tracking of the telescope. This is achieved with the use of seven guide spines on each side of the field, each spine having a bundle of seven fibers. The outputs from these fibers are imaged onto a cooled CCD camera. Echidna's autoguiding software will analyze the resulting CCD images to determine appropriate corrections to the telescope azimuth and elevation and the instrument rotation and send them to the Subaru telescope control software.

4. ECHIDNA: ELECTRONIC AND SOFTWARE DESIGN

4.1 Electronics design

The electronics associated with driving a single Echidna spine are not difficult. All that is needed is a waveform generator, high voltage amplifier, high voltage (+/-150V) power supply, and interconnecting cabling. When one considers driving 400 spines independently along two axes, the complexity increases. At the design stage the electronics must be made practical, maintainable, and modular.

The method of driving the spines was one of the first design considerations. Ideally one would want to drive all of the spines simultaneously, thus reducing the total reconfiguration time and software complexity. This task should be accomplished with minimal associated electronics. In theory, all of the spines can be positioned simultaneously by only two amplifiers. A single drive signal is generated by the computer. The drive signal is composed of repeating sawtooth pulses. This signal is amplified by two amplifiers. One of the amplifiers has positive gain, and the other has negative gain. A simple switching network is associated with each spine. This switching network selects between the positive and negative drive signals, and it makes connection to the X or Y electrode of the piezo tube. Thus each spine can be moved in either axis and in either direction.

The above scheme has been implemented, although power constraints made it more practical to use four amplifiers instead of two. The amplifiers have been designed around Apex operational amplifiers. The switching network was incorporated using Nais surface mount solid state relays.

The next design challenge was that of where to put all the electronics. It was once assumed that all of the electronics would be in a single cooled enclosure. This proved not to be practical since over 800 wires would be needed to connect the switching network to the piezos. The large number of cables and connectors would have made maintenance very difficult. Instead, the switching electronics were designed as daughter cards which mounted on each end of each piezo module, as shown in Fig. 7. The switch cards are all identical and each controls one half module. Now only two cables are needed between the electronic enclosure and the Echidna platform. The first is for analog drive signals and telemetry, and the second is for digital control signals.

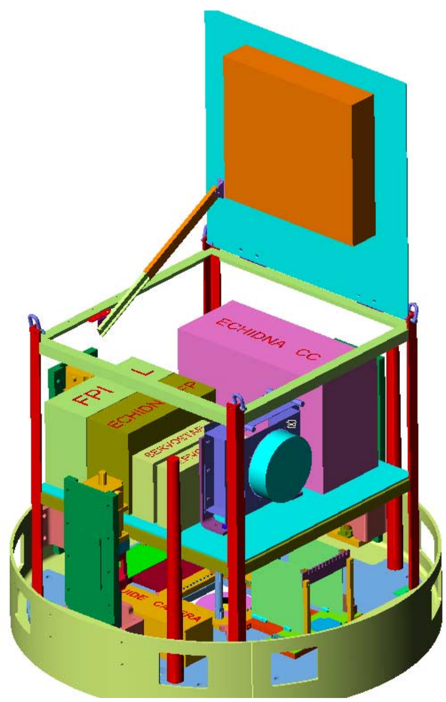

Fig. 10: Electronics units located above the Echidna positioner in the FMOS prime focus unit

In addition the AAO must provide control electronics for the FPI, cooled camera (used to image the guide fiber bundles), and for the back-illumination of all fibers (science, guide and fiducials). Much of this has been designed and, during the construction of the prototype system, assembled and tested. A rendered drawing of the electronics packaging is shown in Fig. 10.

4.2 Software overview

The Echidna instrument comprises a number of different software subsystems which are integrated together to form part of the FMOS instrument. The Echidna instrument control software is responsible for a number of tasks which can be broadly described as positioning each of the spines at the required position in preparation for an observation. This software executes on a diskless (remotely booted) Linux PC located in the Subaru PFU (just behind the spines). The control software is a mixture of low-level device drivers (written in C) and high-level control routines (written in C++). In the following sections, we describe some key features of Echidna's spine positioning software: the spine-to-object allocation algorithm, the fiber-encoding (back-illumination) algorithm, and spine calibration methods.

4.3 Spine-to-Object allocation algorithm

Prior to an observation, a target field configuration has to be prepared. This is achieved using Echidna's spine-to-object allocation software which accepts an input catalog of potential target objects and generates an optimal allocation for each of the 400 science spines. The software must take into consideration many constraints and parameters such as:

- ensuring neighboring spines do not "cross".
- maximizing the alignment of spines with the incoming beams (increases light throughput).
- soft priority (allows the Astronomer to indicate their preference for each target object in the event that not all objects can be allocated).
- minimizing the distance the spines must move (leads to faster configuration time).
- allowance for atmospheric refraction effects and mean RA/dec to apparent RA/dec conversions.

The core algorithm of the spine-to-object allocation software uses a breadth-first search, common in many chess programs. By starting with fibers adjacent to an unallocated object and successively altering the allocation of fibers further and further from the unallocated object, it is often possible to free-up an existing allocated spine (by allocating its object to another unallocated spine further afield) for use with the unallocated object. Empirical tests have shown that searching to a depth of 7 (i.e. altering the allocation of up to 7 spines) can yield a near-optimal configuration. A typical branching factor of 3 or 4 means that this software is very efficient and capable of running on most modern Unix workstations.

Simulations with the allocation software have shown that for many random fields with 400 input targets an allocation efficiency of 90% is achievable (an example is shown in Fig. 4). This leaves ~ 40 spines unallocated, of which most will be used for sky subtraction.

4.4 Configure fiber and back-illumination encoding

Once an allocation has been prepared using the spine-to-object allocation software, it can be downloaded to Echidna where the positioner software determines how to move the spines to the required positions. This is an iterative process that takes ~ 5 cycles. After each cycle, the positioner software uses the FPI and a back-illumination encoding pattern for spine position feedback. The time taken for the FPI to move from one frame to the next (~ 1s) is a major element of the reconfiguration time: around ten minutes for all 400 spines.

Driving a spine to any target position with a single set of x, y signals has an inherent inaccuracy of ~ 10%. Consequently, after driving a spine, the positioner must determine the new position of the spine and calculate a new offset to the target position, and drive the spine again. This process is repeated until the spine is within 10μm of the target position. This typically takes 3-4 cycles for a single spine, but a 5th cycle will usually be required when configuring a full field.

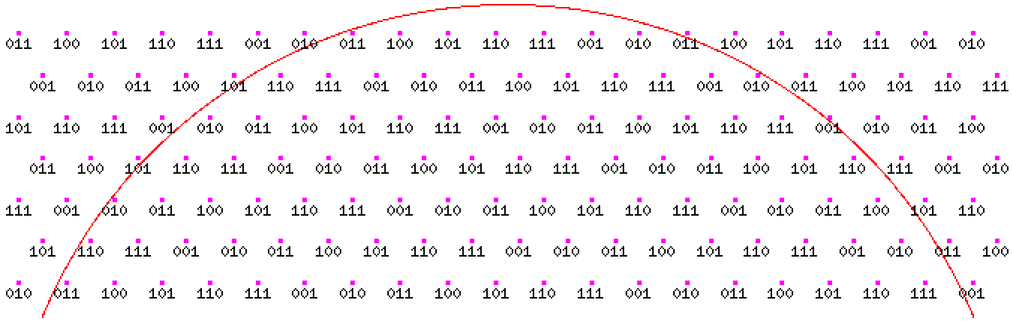

Fig. 11 Back-illumination encoding pattern used for the spines. (The arc denotes the Echidna field of view; the dots show the home positions of spines.) The 3 binary digits represent whether the LED is turned on (1) or off (0) for the spine in each of the 3 frames.

To determine the position of a spine, it is back-illuminated and imaged using the spine camera on the FPI (Sec. 3.5). The back-illumination procedure for the Echidna is more complex than for other fiber multi-object instruments developed at the AAO (e.g. 2dF, 6dF, OzPoz). This complexity is necessary as Echidna must distinguish between many spines in an image which can overlap in complex ways. To resolve the ambiguity of overlapping spines, each spine is associated with a 3-bit number representing a back-illumination encoding pattern. As illustrated in Fig. 11, seven distinct encoding patterns are used.

To locate the positions of the spine tips, the fiber imaging camera on the FPI gantry is positioned to view a subset of spines. Spines that could be located in the spine camera field-of-view are then back-illuminated three times according to their encoding pattern and imaged (three times) by the spine camera. The control software then processes the three frames and determines the position of all spines in the camera field-of-view.

4.5 Calibration of movement of individual spine

When sent an identical signal, the step sizes and directions of different spines are not identical. This is due to small inherent physical differences between spines and the 3-hemisphere piezo mounts - causing unique individual characteristics. Each spine has to be individually calibrated, to allow the control software to more accurately estimate the driving signals required to position the spine. This indirectly improves the performance of the spines and reduces the total field configuration time.

Additionally, subtle (non-predictable) temporal variations in the performance of individual spines cause small repeatability errors in positioning. To smooth these errors, the Echidna positioning software maintains the calibration database for each individual spine in (pseudo) real-time whilst configuring fields. This self-calibration mechanism improves reliability and quickly detects misbehaving spines.

4.6 Avoiding spine collisions

The Echidna control software must ensure that spines do not collide with each other. A collision would not physically harm the spines, however, it would detract from the spine performance and could cause spines to become "crossed". Crossed spines oppose each other in their direction of travel and prohibit accurate positioning. With up to 400 spines being driven in parallel and each spine constrained to moving along 2 near-orthogonal axes, avoiding collisions is a critical function of the control software.

The spine-to-object allocation software contains an algorithm to ensure that spines are not allocated to targets that would cause them to cross - this alleviates many of the potential causes of collision. However, there still remains the potential for spines to collide when configuring a field. This largely stems from situations where spines are positioned very closely to one another, or where spines must move past each other on their way to their target positions.

Care is also taken to avoid collisions when configuring a new field. Driving spines from their position in an old field to their position in a new field is dependant upon the sequence of fields being observed, which is not predictable with any certainty. Currently, the control software blindly drives all spines to their home position before configuring a new field. It is considered "blind" because the FPI is not used to determine the positions of the spines afterwards (it would take too long) - they are assumed to be exactly in their home position when calculating the required offset to the target position.

5. CURRENT STATUS

The AAO FMOS project is mid-way through the final design stage. As part of the preliminary design a single module, half-filled with spines, was assembled together with a single-axis version of the FPI. The assembly and testing of the prototype system, shown in Fig.12 and 13, was of great practical value to the project.

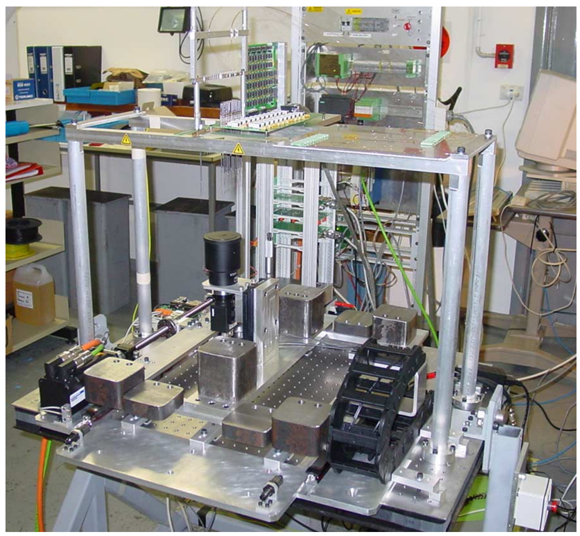

Fig. 12: Single-axis prototype of the FPI. The metal blocks replicate the expected loading on the X-axis motor.

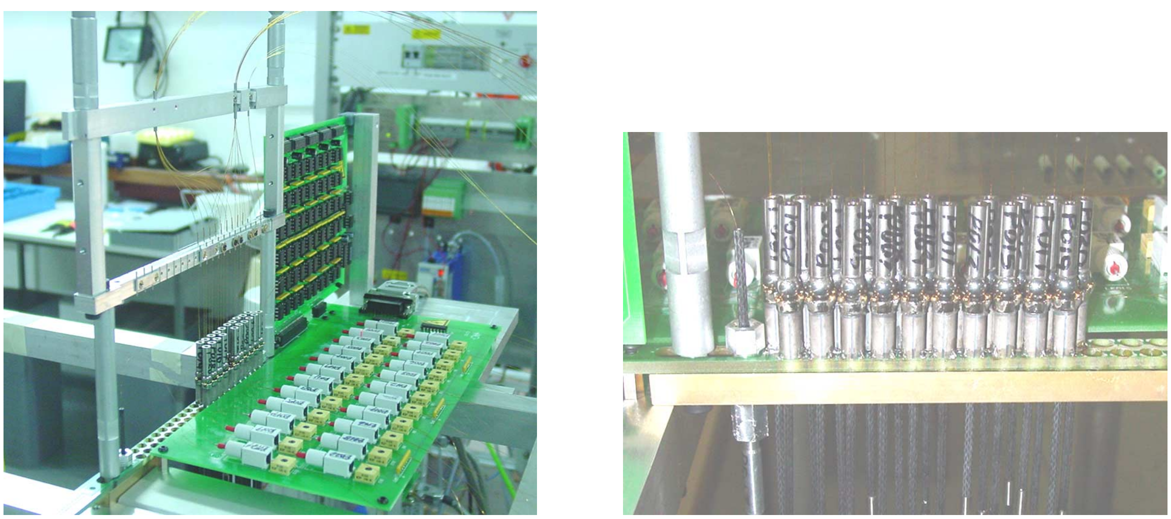

Fig. 13: Left: the half-filled prototype module. The LEDs for back-illuminating the fiber are to the right.
Right: a close-up of the half-filled module, showing the required packing density of the spines in Echidna.

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