A Fiber Positioner Robot for the Gran Telescopio Canarias

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ABSTRACT

Fiber-fed spectrographs dedicated to observing massive portions of the sky are increasingly being more demanded within the astronomical community. For all the fiber-fed instruments, the primordial and common problem is the positioning of the fiber ends, which must match the position of the objects of a target field on the sky. Amongst the different approaches found in the state of the art, actuator arrays are one of the best. Indeed, an actuator array is able to position all the fiber heads simultaneously, thus making the reconfiguration time extremely short and the instrument efficiency high. The SIDE group\textsuperscript{*} at the Instituto de Astrofísica de Andalucía, together with the industrial company AVS and the University of Barcelona, has been developing an actuator suitable for a large and scalable array. A real-scale prototype has been built and tested in order to validate its innovative design concept, as well as to verify the fulfillment of the mechanical requirements. The present article describes both the concept design and the test procedures and conditions. The main results are shown and a full justification of the validity of the proposed concept is provided.

Keywords: astronomical instrumentation – fiber positioner – fiber fed spectrograph

1. INTRODUCTION

Extremely important results in observational astrophysics are obtained today through large databases of spectra or images (e.g. SDSS, 2dFGRS). In order to allow this statistical approach to science, survey instruments are becoming more and more necessary. Such instruments are dedicated to observing massive portions of the sky, and must be as efficient as possible in order to minimize times, therefore the largest possible number of objects must be observed at the same time. Concerning Spectroscopy, there are two main types of Multi-Object instruments: multi-slit spectrographs and fiber-fed spectrographs. Both offer advantages and disadvantages, but the most versatile type for object collection is the fiber-fed device. For all the fiber-fed instruments, the primordial and common problem is the positioning of the fiber ends, which must match the position of the objects of a target field on the sky. For each field to be observed, the configuration of the fibers is different, so, approximately every hour of an observing night, all the positions of the fibers must be changed. Unless a dedicated person takes care of it (as for the SDSS), there are two broad groups of devices (usually called robots) for this task: pick and place devices or actuator arrays moving one fiber head each (see Smith et al.\textsuperscript{1} for a general review, or Haynes et al.\textsuperscript{2} for a review on actuator technology).

A pick and place device has one moving gripper which grabs one fiber head from its parking position and places it in position, usually on a magnetic plate; it can move one fiber head at a time, thus reconfiguration time scales with the number of fiber heads. This reconfiguration time is essentially time lost from observation (e.g. Autofib at WHT, Flames at VLT). An actuator array is able to position all the fiber heads simultaneously, making the reconfiguration time extremely short and the instrument efficiency high (e.g. LAMOST, Echidna)

The SIDE group at IAA, together with the industrial company AVS and the University of Barcelona, has been developing an actuator suitable for a large and scalable array. The mechanical design presented here is

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the result of a development based on an idea employed in the LAMOST project (see Zhang et al.\textsuperscript{3}), improved by the LBNL in Berkeley (see Schlegel et al.\textsuperscript{4}) and finally developed into a substantially different design and a prototype. The present article describes both the concept design and the test procedures and conditions. The main results are shown and a full justification of the validity of the proposed concept is provided.

2. THE FOCAL PLANE ARRAY

This section is devoted to describing the robot as a complete set of actuators which fills the focal plane of the telescope. The concept used is a single actuator for each fiber head to be positioned, then the focal plane is populated with an array of such actuators, distributed with hexagonal pattern, each devoted to observing a single object. In a few words, this Fiber Positioner is a collection of actuators, all identical, distributed over an array which covers the focal plane. Each actuator can position a fiber head over a disc which it will be called Patrol Disc. The focal plane is then covered by these Patrol Discs so that all positions can be reached by at least one actuator (see Fig. 1). Of course, some parts of the focal plane can be reached by more than one actuator, hence the possibility of collisions. Fig. 2 shows a view of a sample subset of the complete array, with 19 actuators in hexagonal pattern.

This concept offers many advantages with respect to others. Concerning the scientific advantages, reconfiguration times are extremely short (thus observation overheads basically depend on detector readout times and calibrations). In addition the differential atmospheric dispersion (see Donnelly et al.\textsuperscript{5}) can be corrected in real time, thus a very large field of view can be used more efficiently. Such correction is called ADT (Atmospheric Differential Tracking) throughout this article, referring not to a telescope tracking but to the differential atmospheric dispersion real-time compensation of the affected actuators. Concerning the mechanics or hardware, the difficulties which can arise from the need of placing the actuators on a curved (spherical) field of view are further
Figure 2. A view of a subset of the actuator array mounted on their holder (here, 19 units are shown as an example).

detailed in the next section. This concept is extremely robust, scalable and easy to service and maintain (failure of one actuator causes the loss of one object only). There is a drawback concerning the science: the actuators cannot be densely packed onto a small portion of the field of view, so the system is efficient for rather uniform distributions of objects. This deficiency is compensated by the time efficiency of this design. Concerning the control and software, an efficient algorithm must be developed to control 2000 motors, while avoiding collisions between fiber heads.

Although our group has faced the Fiber Positioner from a broad point of view (holder, focal plane topology, collision problems), this article will concentrate on a single actuator as an example of array unit, for which we built and tested a prototype.

3. APPLICABLE BOUNDARY CONDITIONS

The boundary conditions from which the main geometrical and envelope requirements are defined concern the telescope focus where such device would be mounted. In practical terms, the Nasmyth Focus at the GTC Telescope has been used as a reference. Indeed, such reference sets a reasonable framework within the potential instrumentation for 8-10m telescope. Thus, the actuator was originally designed for a 992 mm field of view (equivalent to 20 arcmin) and a density of objects of $3.19 \text{Obj \cdot arcmin}^{-2}$, which set the number of actuators (1003 units). The applicable Focal Plane is a concave spherical cap with 3574 mm of radius of curvature. The hexagonal pattern packing has been chosen for the array of actuators since it provides the densest population. Thus, the centre-to-centre distance between actuators derived from the above constraints is 29.2 mm. Other important factors to be known about the telescope are the (foreseen) pointing error (0.1 arcsec), the plate scale (825 $\mu$/arcsec) and the focal length set at F/15. Another boundary condition comes from the fact that the original fiber head was formed by a honeycomb-shaped 7-microlens array, which focused the light into 7 fibers bundled together. The circumscribed diameter of the 7-microlens array is 1.2 mm. The actuator is limited, on one side, by the interface of the chassis with the Focal Plane Array holder and, on the other side, by the mechanical references of the Fibers Button (see Fig. 3).

The actuator coordinate system used through this work was defined as follows: Z is the optical axis (the axis along which the light travels) and the plane XY is orthogonal to it. As a result, a displacement along Z produces de-focus while a displacement on the plane XY produces de-center of the image. It is also relevant the angle between the Fiber Button axis and Z, which reverts directly on the budget of the angular error of the fiber with respect to the optical axis. The manufacturing and mounting errors of the fibers bundle and microlenses on the Fibers Button are beyond the scope of the present work.
Figure 3. A view of the applicable interfaces of the actuator prototype. The small panels (left and right) show the interfaces with the Fiber Button (coloured green), and the central panel shows the interface with the actuator’s array holder (coloured green).

Table 1. Actuator basic requirements

| Item                        | Value                          |
|-----------------------------|--------------------------------|
| Packing Pattern Geometry    | Hexagonal                      |
| Distance between actuator centres | 29.2 mm              |
| X/Y Position Repeatability  | 40 $\mu$m                     |
| X/Y Position Accuracy       | 100 $\mu$m                    |
| Z max defocus error         | ±140 $\mu$m                   |
| Max angular tilt            | ±1 mrad                       |
| Reconfiguration time        | 60 sec                        |
| Working temperature         | −10 + 30°C                    |
| Weight of the array         | 750 $Kg$ (Holder not included) |
| Lifetime                    | 10 years                      |

4. MECHANICAL REQUIREMENTS

The mechanical requirements of the Fiber Positioner are shown in Table 1. In order to understand the origin of some of the requirements, it is necessary to define the errors which affect one actuator and distinguish between the errors for which subsequent software compensation is feasible and those for which it is not. It is clear that the requirements shown in Table 1 must be fulfilled by the actuator affected by these last errors (because it is too expensive to compensate them). Sources of XY errors are the following:

1. XY De-center of the actuators housings machined in the Focal Plane Array Holder: Here the shape of the Focal Plane has heavy consequences in terms of error budget. According to the boundary conditions mentioned above, the Focal plane is a spherical cap, which implies that all the actuators housing on the Focal Plane Array must point (within certain tolerance) to the centre of curvature of the Focal Plane. From the manufacturing point of view, this presents a much higher degree of complexity than the case of a flat focal plane and errors are more likely.
2. Dimensional errors of the actuator affecting the position of the fiberhead on its Patrol Disc: indeed, the manufacturing and assembly errors applied to the mechanical chain from the chassis to the part which holds the fiber bundle may lead to a decenter of the Patrol Disc with respect to its theoretical location. This would add to the fiberhead position errors due to the actuator itself.

3. Gearing errors: due to machining errors in the commercial gearboxes used in the actuator, noticeable XY errors may result in the final position of the fiberhead.

While error 1 above is part of the array holder budget and its characterization involves accurate measurement on one part only (the holder), errors 2 and 3 individually affect each of the 1003 actuators of the array, thus any additional process needed to mitigate these would revert in extremely high costs for the device. It is therefore assumed here that only error 1 could be characterized and compensated by software, once the Fiber Positioner is assembled, and so the requirements shown in Table 1 must be fulfilled by the actuator affected by errors 2 and 3.

Concerning de-center, the maximum error has been taken as 10% of the incircle diameter of the microlenses set, which yields 120 µ. However, this figure includes the errors of microlenses and fibers manufacture and mounting, which have been budgeted at 66 µ (according to the state-of-art fiber optics technology). As a result, 100 µ radius is the value applicable to the actuator.

Concerning the tilt angle of the fiberhead, the main driver is the admissible angular deviation of the light beam entering the fibres: 2 mrad. This error is not compensable and it adds to tilt errors of both the Focal Plane Array holder and the fiberhead/microlens assembly. Once these last ones are subtracted, the value of 1 mrad is left for the actuator.

Concerning the defocus, optical analysis shows that a defocus error of 400 µ would imply only 1% of energy losses. This is due to the large focal length of GTC. Once again, this error is not compensable. The main budgets here to be taken into account come from the actuator and the Focal Plane Array Holder. 350 µ have been conservatively assigned to the holder due to the difficulties of machining a spherical surface. Therefore, 140 µ are left and applicable to the actuator.

Concerning the XY precision, it must fit with the pointing error of the telescope (0.1 arcsec), which means 40 µ radius at the Focal Plane.

According to the GTC requirements, the Nasmyth Rotator can withstand 2400 kg with no auxiliary support. This figure includes 1003 actuators, the Focal Plane Array holder and the mechanical structure for attachment to the Nasmyth Rotator. The weight budget for the 1003 actuators only is 750 kg.

Finally, the reconfiguration time of the actuator array must be comparable to the time spent in reading out the detector and data archiving, in order to minimize overheads. Thus, 60 sec has been set.

5. THE ACTUATOR CONCEPT DESIGN

5.1 The mechanical design

The mechanical design presented here is the result of a development based on an idea employed in the LAMOST project, improved by the LBNL in Berkeley; the Cobra actuator (see Fisher et al.6) also has many similarities with this design. The basic design of the actuator was developed by the company AVS in collaboration with the IAA-CSIC and can be seen in Fig. 4. This design is substantially different from both the LAMOST and the LBNL designs; we believe that, mainly, robustness, reliability and simplicity are improved with respect to these. The fiber head is brought around through two rotations in cascade: the first rotation, called ROT1 (or R1), involves the internal cylinder of the actuator (in which the motor for the second rotation is embedded), and takes place with respect to the hexagonal frame which should be attached to the actuators’ holder. The second rotation, called ROT2 (or R2), moves an arm which ends into a clamp where the fiber head is held. This movement takes place with respect to the ROT1 rotating cylinder. A slot (visible in Fig. 4) is cut into the main cylinder, in order to accommodate the fiber which runs from the fiber head to the back of the actuator. The fiber is both twisted and bent, but this takes place over a length of about 25 cm and the fiber is protected by a plastic pipe. The electronics board is planned to sit at the back of the actuator, attached to the internal rotating
Figure 4. A view of the assembled actuator prototype (left), with its hexagonal steady frame and the rotating internal cylinder. The other view (right) is a zoom-into the R2 rotation. The arrows show the direction to reach the zero stop of each axis. The slot cut into the main rotating cylinder to accommodate the fibers is also visible.

Figure 5. The rotation directions of the actuator. P is the fiber head centre, O is the centre of R1 and O' is the centre of R2.

cylinder, so that less cables need to be twisted (only the power and signal for the board, instead of the cables for the two motors). Counter-posed directions minimize the total twisting of the fibers/cables with respect to their rest position. Fig. 5 shows how the rotation directions were chosen. There are physical stops which limit the range of the two rotations, so that the optical fibers and cables cannot be twisted beyond a safe amount. The stops allow about 365° for R1 and about 230° for R2. One step motor is used for each axis, with a reducer.
gearbox and an incremental encoder. For convenience, one motor is run at full steps (R1), while the other runs at half steps (R2). A design review (PDR) by AAO and LBNL engineers took place in late 2008 and many useful suggestions were given which would further improve the final actuator.

5.2 The control electronics

The Fiber positioner robot electronics has two main tasks:

- Control the actuator arm (slave controller)
- Communicate with the master controller

Each actuator has a dedicated control electronics (see Fig. 6) fixed at the actuator rear part. This electronics provides a mean to solve both tasks with a limited size and power budget.

Control of the actuator arm. The actuator controller (Fig. 6) has the following requirements:

1. Control the two step motors in a closed loop operation mode in order to move the actuator arm with the required precision and reconfiguration time.
2. Implement a safety low-level protocol to avoid, detect and report to the Master controller any collisions between neighbouring robot arms.
3. Perform an actuator logical zero calibration without using an electronic limit switch detector.

The actuator controller is based in a 32 bits Coldfire V1 micro-controller with an extended timer operation functions in order to control the 2 steppers motors and read the encoders information. It is important to prevent any heat source inside the telescope focal plane, thus the micro-controller and all electronic devices must be low power in the active (robot positioning period) and sleep modes (observation period). The motors used in the prototype were 8mm diameter stepper motors, manufactured by Faulhaber, each moving one axis in combination with a 1:120 gearbox and a quadrature encoder with 32 lines resolution. This motor and gear selection produces enough torque to move the fiber button and enough holding torque to hold the science fiber position securely. It is interesting to note the difficulty to calibrate the actuator logical zero by using a spring buffer due to the elastic stop of the gearbox. It has been necessary to implement a procedure to recover a non-elastic step movement through the encoder measurement.

Communication with the master controller. All the ~1000 robot actuators are controlled by a Master computer thought a CAN Bus 2. A network (see Fig. 7) in a Master-Slave operation mode. Each actuator has a CANbus transceiver with a CAN address provided by a serial number circuit in order to be identified. The CAN transceiver used in the actuator controller can not drive the ~1000 actuator network. Due to the transceiver fan-out limitation, it is necessary to use a network switch to interconnect all actuators in a tree topology.
6. SCOPE OF THE ACTUATOR PROTOTYPE

A prototype of the actuator was manufactured in order to submit it to a comprehensive testing plan aimed to check whether the mentioned requirements can be fulfilled by this design.

From the mechanical point of view, the prototype is an exact copy of an actuator. Therefore, if the prototype fulfils the requirements, a real actuator also does. The main differences lie on the button and the control electronics. Indeed, a special button (Test Button) has been designed and manufactured in order to improve the measurement procedures (see Fig. 8). This button presents appropriate surfaces for being measured by the 3D coordinate measuring machine.

Concerning the control electronics used in the prototype, this was different from the one planned for a real actuator. A rigid breadboard electronics has been used for the tests, instead of the encapsulated flexible PCB (see Fig. 9) foreseen in the actuator design. No major consequences derived from this issue: the encapsulated PCB has negligible influence on the mechanical performance (the real PCB is connected to the rotating part of the actuator through a rolled flat contact part).

Finally, a remark is due here to the fact that the performance presented is relative to the discrete grid of
positions (Fig. 10) of the Patrol Disc, defined by the finite resolution of the step motors. In other words, only positions belonging to this grid have been submitted to test. In general, the position of an object rarely matches a point of the grid (composed by more than 23 million reachable positions) which implies an extra source of error which is not within the scope of the present work. Anyway, the resolution available in ROT1 and ROT2 limits this error to 5.5 microns in the less favourable cases (outer areas of the Patrol Disc).

The resulting grid of positions is such that any random position on the Patrol Disc can be approximated by a grid point with no more than 5.5\( \mu \)m of error.

When several actuators are mounted in array on focal plane, their Patrol Discs overlap and collisions amongst fiber heads are possible. In particular, collisions are possible for a fiber head when it is outside a circle which we call “Security Circle” (see detail of Fig. 1). This risk can be canceled by a clever control software.

7. TESTING PROCEDURES

The testing of the prototype has been planned by means of two different experimental setups: an optical setup for the measurements where high X-Y resolution over a tiny FoV was sufficient, and a mechanical setup (based on a 3D coordinate measuring machine) for the measurements where high precision over a measuring range of several millimeters across the Patrol Disc was required. This dual approach on the testing method was imposed by logistics reasons: the 3D coordinate measuring machine had very limited availability to our group, thus the need of the optical setup. Also, when dealing with a prototype, high flexibility during the tests is very important, so the comprehensive set of repeatability tests has been implemented in-house at the IAA through the optical setup, while the tests about position accuracy are planned to take place at IMH (Instituto de Máquina-Herramienta, Elgóibar, Spain). This set of measurements is much smaller than that of the repeatability tests and, at this stage, is still pending, therefore only the optical setup is detailed here.

One drawback of the optical setup was that no tip/tilt or defocus could be measured.

As stated previously, we will use the convention that the plane X-Y contains the Patrol Disc, and the Z coordinate is parallel to the actuator’s long axis, positive from the back to the front of the actuator.

Figure 9. A view of the real control electronics foreseen for one actuator. The central panel shows a general view of the electronics attached to the back of the actuator. The bottom-left panel shows a detail of the flexible contact to connect the rotating part to the fixed structure. The right panel shows a detail of the central hole for the fiber optics.
Figure 10. Example (with much reduced number of points) of the actuator’s grid of reachable positions. The denser zone in the bottom-right part of the picture is due to the superposition of points because of the extra run of 5 degrees of R1 beyond a whole turn. The multiple semicircles over the whole Patrol Disc are simply the path of the fiber head when moved in R2.

7.1 Optical setup

This setup is based on a microscope with a hi-res camera attached (see Fig. 11). Both the microscope and the prototype are mounted on multiple-stage sliding supports, thus providing the capacity of measuring at any point of the Patrol Disc. A 2 µ-size pinhole is attached to the Test Button of the prototype. Both supports are mounted on a rigid steel plate which, in turn, is kinetically held by means of three screws on the test bench. In addition, a cold lamp is used to lighten the setup. This way, the light coming through the pinhole is captured by the camera attached to the microscope. By connecting the camera to a laptop computer, it is easy to capture and store images of the spot (projected pinhole). The magnification of this optical setup allows capturing a FoV of about 780 × 580 µ on a picture of 640 × 480 pixels, resulting into a scale of 1.22 µ/pix. Due to the relaxed requirement in Z (400 µ), we measured only X-Y repeatability, with confidence that the behaviour in Z was far below the corresponding requirement. The tests so implemented have produced a comprehensive series of pictures, whose spot positions have been analyzed through the image-processing package IRAF and, finally, by statistics routines. Finally, in order to ensure that any thermal drift is avoided over the duration of a single test, an air fan is placed next to the measuring area. Fig. 12 shows the layout of the key points (the centres of both rotations, the centre of the Test Button and the pinhole) involved in the optical tests, both for ROT1 and ROT2. Note that the item which is physically measured by the optical setup is the pinhole spot, whose location lies beyond the Patrol Disc. Therefore, the data process must include a corrector factor in order to translate the magnitudes measured at the pinhole to the nominal radius. This has the advantage of increasing the accuracy of the measurements. For ROT1, the nominal radius is that of the Patrol Disc, i.e. 16.86 mm, with ROT2 set to the maximal extension (2400 half-steps nominally). For ROT2, the nominal radius is the distance between the centre of ROT2 and the centre of the Fiber Button, 8.43 mm.
8. PERFORMANCE AND TEST RESULTS

The tests which have been implemented for a full mechanical verification of the prototype are explained in detail through this section.

8.1 Stepper motors performance

8.1.1 Stepping reliability

For the present work, the electronics was not yet developed for reading the encoders of the motors. However, the reliability of the electronics about the number of steps performed by the motors had to be proved. This test was implemented on the motor+gearbox alone (not integrated in the prototype) in order to avoid any effect from the rest of the mechanism. It simply consisted of addressing several angular positions to the motors. The back axis of the motor was marked so that a reference could be visually checked. Since a motor turn implies 20 steps, the positions addressed were always an integer multiple of 20. Thus, the mark at the back of the motor axis should always stop at the same place. A camera viewing the back of the motor allowed a detailed visual check (see Fig. 13).

8.1.2 Energy mode for the motors

A parameter that was found important for the motors performance is the energy mode which is set once a certain position is reached. Indeed, the current to the motor can be configured as to be kept either “disabled” or “enabled” once the movement has finished. Therefore, this test consisted of running series of 20 half-steps (one by one) at different domains of the angular range of ROT2, both with “disable” and “enable” configurations. As
a result, the configuration leading to a better performance in terms of homogeneity about the amplitude of the steps was the selected one for the implementation of further tests. The measurements were only implemented on ROT2, but the conclusions so obtained were also applied to ROT1 since both rotations are driven by identical motors. When the current was “disabled”, the RMS relative to the mean step was found to be $\sigma = 5.95\%$; when the current was “enabled”, the RMS relative to the mean step was found to be $\sigma = 3.38\%$. The “enabled” mode was then programmed by default into the low level software of the control electronics.

8.2 Re-configuration time performance

The re-configuration time has been estimated through a software simulation of a worst-case event. The simulation reproduces the situation of several neighbouring actuators and the time needed to disentangle a situation of conflict, i.e. when collision amongst them would occur with straight movements. The simulated worst-case event also involved the longest runs of the two axes of one actuator, from a start position to a target position across the Patrol Disc. In such case, the re-configuration time (with axes speed of 300 full-step sec$^{-1}$ in ROT1 and 300 half-step sec$^{-1}$ in ROT2) was about 65 seconds.

This slightly exceed the requirement value, but it must be noted that the estimation is extremely conservative, as it is based on a worst-case that software simulations prove to be very unlikely. Also, if necessary, the axis speed of the motors could probably be increased.

It can be stated that, in the great majority of cases, the re-configuration time requirement is met, and the extra delay added by the few worst cases is negligible.

8.3 Precision tests

These measurements have been implemented by means of the optical setup mentioned above.

8.3.1 Approach mode

Although the gearboxes here selected are labeled “zero-backlash” by the supplier, this test was performed in order to check whether it made any difference to approach a certain angular position from one side or the other. Strictly, a zero-backlash transmission should not behave differently when changing the direction from which a position is approached. By the way, this test was also useful to check whether, in spite of its preloaded floating mount, the extra 1:4 gearing stage of ROT1 included some backlash. The test consisted of approaching different target positions, each of them from two start positions. For a certain target position, each start position was located at a different side as regard to the target. For the movements from the start positions to the targets, two options were studied.

**Single Turn mode.** The movement from a start position to the target is made in a single movement. This
means that the rotation direction to the target position changes when the starting position is on one side or the other of the target position.

**Single Direction mode.** the target position is approached always from the same direction, and such direction was defined clockwise for ROT1 and counter-clockwise for ROT2. This means that, if the start point is located between the zero and the target, the movement equals the single turn mode. Otherwise, if the start point is located between the target and the 365° hard stop, the movement is done in two stages: one from the start point up to an intermediate point and, secondly, one from this intermediate point up to the target. The intermediate point is located between the zero and the target, three motor-steps away from the target.

Although the dispersion of the data points was of the order of a few microns in all cases, the Single Direction mode gave slightly better results and therefore was set as the default approach mode for the actuator. Note that, by comparing the results of ROT1 and ROT2, this test also shows that the 1:4 gearing stage of ROT1 is hardly affected by any backlash.

### 8.3.2 Repeatability tests of ROT1 and ROT2

For the tests here included, some definitions are required in order to better understand the protocols described next. A target position is the position which is being measured. A start position is a position from which the movement to achieve the target position starts. Therefore, the optical setup is tuned in order to roughly center the target position on the field of view of the camera, as well as to properly focus the pinhole spot. These tests were performed for ROT1 and ROT2 separately. For ROT1, 21 target points were defined, and 11 target points were defined for ROT2, the difference is due to the smaller range of ROT2 (see Fig. 12). These points give the reasonable sampling of one target position every 480 steps (for ROT1) and one target position every 240 half-steps (for ROT2). Each target position was measured using the rest of the points as starting points (20 start points for ROT1; 10 start points for ROT2), and with five iterations for each pair start/target positions. Thus, each target position has produced 100 measurements for ROT1 and 50 for ROT2. This comprehensive series of measurement has, consequently, produced 2100 measurements for ROT1 and 1100 measurements for ROT2. For each measurement a picture is captured with the camera. From each picture, the coordinates of the spot centroid are found. For each target position, the mean position of the distribution of centroids (100 items for ROT1; 50 items for ROT2) is found, as well as the standard deviation ($\sigma$). In addition, the size of the dispersion box of the distribution is found ($\Delta$). Such data are shown in Table 2 for ROT1, and Table 3 for ROT2. Since the DoFs of the prototype are rotational, a polar coordinates system fits better with the present data process, which means that the size of the dispersion boxes, as well as the standard deviation, will be given along the angular and the radial directions. This data process has been implemented for all the target positions. A further treatment of the data consisted of overlapping the distributions of all the target points with the mean centroid as a reference. From this “overall-distribution”, the standard deviation was again found, as well as the confidence box for 100% of the data.

The aim of this process lies on providing some few parameters which may give key information about the repeatability of the prototype. The results obtained were as follows:

- **ROT1**: Polar components of the standard deviation on 100% of the data are $\sigma_T = 2.7\mu$ (tangential value) and $\sigma_R = 0.8\mu$ (radial value).  100% of the data fell into a box of $\pm 8.7\mu$ in tangential direction and $\pm 5.7\mu$ in radius.

- **ROT2**: Polar components of the standard deviation on 100% of the data are $\sigma_T = 1.3\mu$ (tangential value) and $\sigma_R = 0.3\mu$ (radial value). 100% of the data fell into a box of $\pm 3.6\mu$ in tangential direction and $\pm 1.0\mu$ in radius.

Thus, the prototype can be said to provide an overall repeatability of $\sigma_{TOT} = 3.1\mu$, the 100% of events being enclosed in a box of $\pm 12.3\mu$. This performance is well within the requirements (40 $\mu$ radius) at 100% level of confidence.
### Table 2. ROT1 repeatability performance

| Target | $\sigma_T$ | $\sigma_R$ | $\Delta_T$ | $\Delta_R$ | $\sigma_{tot}$ |
|--------|------------|------------|------------|------------|----------------|
| A      | 3.31       | 0.31       | ± 5.42     | ± 0.72     | 3.33           |
| B      | 2.00       | 1.39       | ± 3.90     | ± 2.58     | 2.44           |
| C      | 2.41       | 0.77       | ± 5.11     | ± 1.69     | 2.53           |
| D      | 2.96       | 1.44       | ± 6.33     | ± 3.93     | 3.29           |
| E      | 1.52       | 2.17       | ± 3.77     | ± 5.08     | 2.65           |
| F      | 3.12       | 0.55       | ± 5.68     | ± 1.27     | 3.17           |
| G      | 2.48       | 0.38       | ± 5.64     | ± 0.70     | 2.51           |
| H      | 3.00       | 0.33       | ± 5.20     | ± 0.79     | 3.02           |
| I      | 2.59       | 0.81       | ± 5.70     | ± 1.94     | 2.72           |
| J      | 2.65       | 0.41       | ± 4.64     | ± 0.81     | 2.69           |
| K      | 4.25       | 1.32       | ± 8.71     | ± 2.51     | 4.45           |
| L      | 1.89       | 0.21       | ± 4.55     | ± 0.59     | 1.91           |
| M      | 2.97       | 0.33       | ± 4.63     | ± 0.67     | 2.99           |
| N      | 2.59       | 0.60       | ± 5.33     | ± 1.45     | 2.65           |
| P      | 3.38       | 0.32       | ± 5.45     | ± 0.64     | 3.40           |
| Q      | 1.07       | 0.51       | ± 3.17     | ± 0.87     | 1.18           |
| R      | 2.33       | 0.37       | ± 4.02     | ± 0.91     | 2.36           |
| S      | 0.96       | 0.37       | ± 2.28     | ± 0.76     | 1.03           |
| T      | 3.32       | 0.26       | ± 5.14     | ± 0.61     | 3.33           |
| U      | 1.38       | 0.22       | ± 3.61     | ± 0.51     | 1.39           |
| V      | 3.23       | 0.64       | ± 5.64     | ± 2.16     | 3.30           |

### Table 3. ROT2 repeatability performance

| Target | $\sigma_T$ | $\sigma_R$ | $\Delta_T$ | $\Delta_R$ | $\sigma_{tot}$ |
|--------|------------|------------|------------|------------|----------------|
| A      | 1.52       | 0.34       | ± 3.19     | ± 0.64     | 1.56           |
| B      | 1.40       | 0.16       | ± 2.68     | ± 0.39     | 1.41           |
| C      | 1.27       | 0.44       | ± 2.36     | ± 0.68     | 1.35           |
| D      | 1.75       | 0.55       | ± 2.43     | ± 0.80     | 1.83           |
| E      | 2.07       | 0.38       | ± 2.92     | ± 0.81     | 2.10           |
| F      | 1.22       | 0.19       | ± 2.44     | ± 0.34     | 1.24           |
| G      | 1.01       | 0.30       | ± 1.94     | ± 0.90     | 1.05           |
| H      | 0.64       | 0.17       | ± 0.94     | ± 0.59     | 0.67           |
| I      | 0.70       | 0.18       | ± 1.48     | ± 0.57     | 0.73           |
| J      | 0.51       | 0.14       | ± 0.81     | ± 0.33     | 0.53           |
| K      | 0.74       | 0.16       | ± 1.31     | ± 0.53     | 0.76           |
8.3.3 Soft-zero tests

There is a “soft-zero” position for each of the rotations. A “soft-zero” position is the real zero position to which all the angular positions of the rotation are referred. A software routine has been designed to achieve this position. Once the rotation has been driven up to the physical stop, it turns from there until an index mark on the encoder is found. Then, the motor stops turning at this point. Through the present test the repeatability of the soft-zero positions of ROT2 have been measured. The same test on ROT1 was not possible because of a problem with the encoder of the ROT1 motor. The dispersion so found will be taken into account for the results from the accuracy tests. Indeed, the accuracy at certain position is affected by the repeatability of the soft-zero in the case of power failure. Since such a failure would imply a reset of the soft-zero positions, a repeatability error on this position would affect all the positions of that rotation. The routine above described was performed 45 times, the overall dispersion box (at 100% confidence) and the overall standard deviation so obtained being: \( \Delta = \pm 5.5 \mu, \sigma = 3.97 \mu. \)

8.4 Lifetime tests

Finally, the prototype was submitted to a non-stop run for seven days in order to check if very long runs could affect its performance. This accelerated test allowed simulating the entire lifetime of the actuator. Indeed, each day of run is approximately equivalent to one year of operation at the telescope. Once again, in order to set realistic conditions for the present test, a randomised routine was implemented. The prototype was thus driven continuously through a sequence of random positions, during seven days. In fact, the present test was much tougher than normal operation at the telescope because of the non-stop running. Once this test was finished a few positions were measured again in order to check whether the performance had changed. No significant variations were observed as compared to the performance of the prototype before the lifetime test.

9. CONCLUSIONS AND FURTHER TASKS

The mechanical solution here provided for a fiber positioner actuator fits by far the requirements in terms of repeatability: 12.3 \( \mu \) was obtained as maximal radius of error (40 \( \mu \) was required). Although this parameter is not directly applicable to the operation conditions (it is quite unlikely to repeat several times a certain position during observations at the telescope, within the lifetime of an actuator), it gives a significant feeling about the good performance of the mechanism.

The procedure of approaching any target points always from the same direction has been set by default since it gives better results in terms of repeatability.

The radial component of the repeatability error (both in ROT1 and ROT2) is clearly lower than the polar component. This means that the guiding of both DoFs is extremely accurate.

The worst-case reconfiguration time slightly exceeds the time requirement, but preliminary simulations show that such worst-case events are quite rare, thus the requirement should be fulfilled during most of the operation time.

By using the same design concept, this solution can be extensible to smaller sizes by a factor down to 0.8.

Thermal issues are involved by default because the results shown here comprehend any eventual drift produced by temperature variations affecting the experimental setup and the prototype (motor energy mode is permanently enabled) during the tests. Therefore, these results are on the conservative side. Anyway, this issue was already taken into account when the experimental setup was designed (the test environment was cooled by a fan and a cold lamp was used).

The main task still pending is the testing of the absolute position error of the actuator.

The present work has presented a concept for a fiber positioner actuator, easily scalable for large focal planes, with very high performance in terms of repeatability. Although the absolute position measurements are still pending (to be held at IMH in summer 2010 through a 3D coordinate measuring machine) the concept here presented has successfully passed all the tests done so far.

There is a patent pending for the actuator concept design.
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