Mechatronics for micrometric optical fiber positioning in a telescope focal plane

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***Abstract*—The *NOAO 4-meter Mayall Telescope (Kitt Peak, Arizona, EEUU)* will be the basis of the worldwide research project *BigBOSS* [1], [2], witch allows the simultaneous observation of thousands of galaxies and quasars and provide significant advances in the study of the Dark Energy. To achieve this, BigBOSS uses an array of 5000 mini-robots responsible for positioning optical fibers. These will focus the radiation of each target into a three spectrograph system that will analyse the obtained signals. To do this, these positioners are able to place the fibers with an accuracy of 5 μm, within a maximum time of 16 s and with very low consumption levels. This surpasses the performance of all mechatronic positioners designed for this type of applications.**

I. INTRODUCTION

After more than 10 years of research and project approach, the creation of the largest spectroscopic map of the deep universe has been launched under the name of *"BigBOSS "* (*Big Baryon Oscillation Spectroscopic Survey* [1]). This, based on the progress made by the *SDSS-III* into his survey *BOSS*, will collect 20 million galaxies and quasars redshifts, to make a map with a volume 10 times higher than the best achieved to date. This offers important elements and extreme precision distances for the scientific community.

To achieve these objectives, BigBOSS will use the *NOAO 4-meter Mayall Telescope (Kitt Peak, Arizona, USA)* on which will be mounted an spectrograph system that will study in depth the properties of the universe and shed light about the nature and properties of the Dark Energy.

In order to study simultaneously the radiation emitted by thousands of celestial bodies, focusing on discrete points of the focal plane of the telescope (stars, galaxies and quasars), the project BigBOSS will use 5000 optical fibers. They will be guided to the exact point of light exposure through ad hoc robots. The array of robots will be installed in a 1 m in diameter metal mesh (figure 1) that is the focal surface of the telescope.

The position of each robot will be decided in a central unit that stores the relative positions of the different galactic bodies to study and generates a motion pattern for each robot.

Because of the structure of the robot's arms, it exists an specific shared position area between each robot and its neighbours. For this reason, after pattern generation and verification of the absence of collisions, the central unit notifies each robot the exact position where the fiber must be placed within its range of action. After sending this command, the master software will run a repositioning algorithm to avoid collision between the positioner arms of two or more adjacent robots, sending, if necessary, a new position order. After the placement, the central unit backlights each one of the 5000 fibers using an internal light system and checks the correct position of these, through an image analysis performed by a CCD camera attached to the front of the telescope, which checks the relative position of each fiber according to a static pattern of positions. This will used to calibrate each robot for future uses and to study the error in the image obtained.

Once the positioning of the fibers in the focal plane of the instrument is made, it will begin an exposure of approximately 20 minutes from observed field. After this, a new repositioning of the fibers will start, in order to focus the fibers for a new exposure of 5000 new targets.

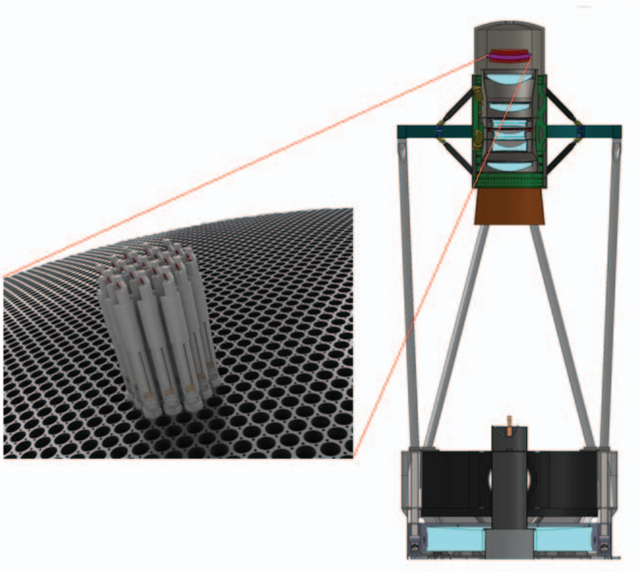

Fig. 1. Telescope optical lay-out and focal plane detail with a cluster of 19 robots (courtesy of AVS)

The stated goal of this project is to achieve the overall positioning of the 5000 fibers in less than 60 seconds. This involves a challenge, because the smaller times achieved to date, in similar positioners, are in the order of several minutes, with a much smaller number of fibers. Apart of that, very low levels of power consumption are necessary, because the high number of existing robots in the focal plane.

This paper will describe the mechatronics of the coplanar positioner developed by the Spanish team for the BigBOSS project. On the other hand, it will explain the innovations from the electronics point of view that will be provided to the project, and also will present preliminary experimental results obtained during the last performed test ran with the positioner.

II. COPLANAR POSITIONER

The 5000 actuators responsible for positioning the fiber at the point of exposure are mechatronic systems (figure 2) that should be installed in the focal plane mesh. They are composed of two mini-stepper motors that put every fiber in his exposure point coplanarly, based on the model Θ - Θ. That is, both engines move the fiber in the same plane, angularly, with two degrees of freedom.

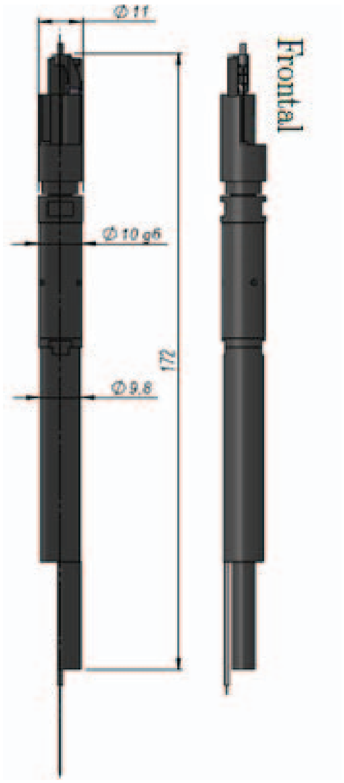

Fig. 2. Coplanar Positioner designed by AVS in collaboration with the IAA-CSIC

The project requirement limits the positioning of the 5000 fibers in less than 60 seconds. However, this fiber positioner places in up to 16 seconds. Apart of that, it must be added the repositioning time, required for the placement algorithm (to avoid collisions between neighbour systems), and the latency time it takes for the information to arrive from the central unit to each 5000 actuators. In table I, the performance increase achieved in this new system is compared to similar projects [4], [3], [5], [1].

TABLE I. COMPARATIVE TABLE OF SIMILAR PROJECTS

Project	Model	Number of fibers	Precision	Time
LAMOST [4]	Θ-Θ	4000	40 μm	600 s
Cobra [5]	Θ-Φ	2400	5 μm	? s
BigBOSS-Spain [1]	Θ-Θ	5000	5 μm	<60 s
BigBOSS-Berkeley [3]	R-Θ	5000	5 μm	<60 s

The engines used in this positioner are mini-stepper motors. They have a clear advantage over those used in similar projects; The fact of not being piezoelectric motors such as those used in the Cobra project [5], enables the use of *chopping current* (section III). This process consists to send to the engines pulsed signals. These signals are generated increasing the current to a pre-configured maximum and making it zero after reaching this maximum, creating a modulated PWM signal to the needs of each coil in this motor. This process is generated either in movement or when the motor is stopped (being able to generate only in the first case), guaranteeing to keep the engine warm in certain situations (bad weather, etc..). All this introduces a great innovation, and will be detailed in section III.

Furthermore, each motor can generate 25 nNm of maximum torque. However, the positioner is designed to support a maximum total torque of 10 nNm, which will be sufficient to position the fiber with errors of 5 μm.

The fiber placement on the positioning circumference of each robot is performed by rotating a main axis R1 placed at the positioner centroid (figure 3), from which extends a main arm L1 of 3,464 mm ideally. And a secondary axis R2 placed at the end of the main arm, from which extends the secondary arm L2 of 3,464 mm ideally, in the end of which will place the fiber head responsible for capturing the radiation.

The main axis rotation is performed counter-clockwise, with a maximum angle of 360° or 27520 steps on the motor 1. Furthermore, the secondary axis rotation is performed clockwise with an angle of 180° or 5120 steps on the motor 2.

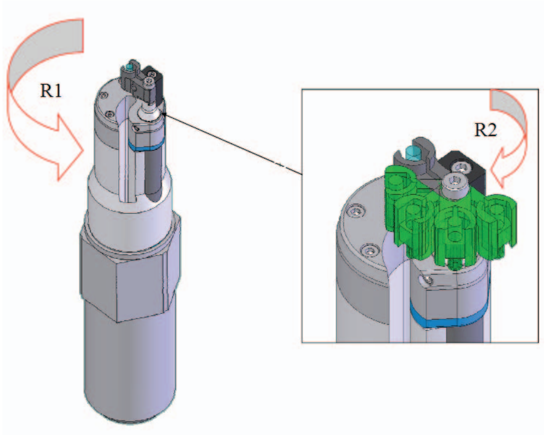

Fig. 3. Detail of the coplanar positioner arm

However, both motor 1 and motor 2 can be sent beyond

360° and 180° respectively, up to the physical limit of the system (365° and 185°). This situation is extremely delicate, because an error in the step can potentially cause physical damage on the positioner. For this reason, a 5° security angle is kept on each motor and the controller software does not allow to exceed 360° and 180°.

Finally, the optical fiber is guided to the exposure point, on the end of arm L2 through a pipe located inside the robot chassis. It ensures that the fiber will not suffer undesired twisting caused by the movement of the positioner axes, maintaining as far as possible the signal clean out of distortion and minimizing losses.

III. CONTROL ELECTRONICS

All placement orders will be sent from superior communication nodes through an I^2C bus tree [6]. This receives commands from the host computer and distributes them to each actuator, through multiplexers and repeaters systems. The control electronics designed for these positioners will be responsible for, on the one hand, processing received commands and act accordingly, and on the other hand, constantly monitoring the temperature and position of the actuator, alerting of any unexpected value, in order to avoid fatal damage.

The main limitations presented in this project are, among others, the surface of the hardware and the current consumption of it. Therefore, due to the large number of positioners that coexist in the focal plane of the telescope, the consumption of each unit must not be very high. On the other hand, because the proximity of the actuators, the hardware should be as smaller as posible, having to be encapsulated in the chassis of each robot, so its surface will not exceed 1.5 cm^2, respecting the 0.8 cm internal diameter of the cylindrical chassis. Furthermore, the temperature of both actuators and the electronics must be very accurately monitored, because an increase on these will introduce distortions in the obtained image. For all this, the design of these electronics is based on low power and the ability to integrate its components in the specified area.

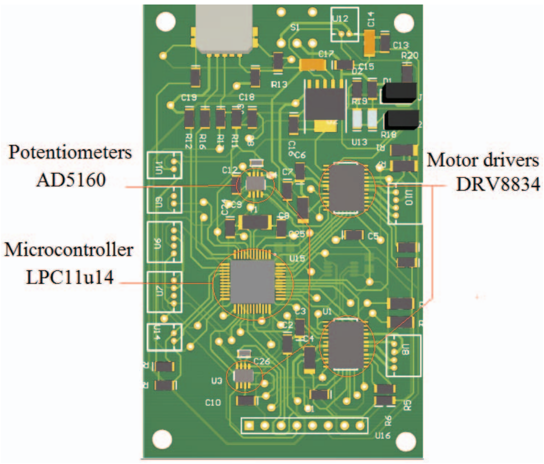

Fig. 4. Prototipe to final electronics design

The main component of the system is the LPC11U14, a 32-bit microcontroller from NXP, in charge of receiving commands from the top node, processing them and managing information flowing into the actuator. In this electronics can also highlight two low power and high performance drivers DRV8834 from Texas Instruments, responsible of giving sufficient current to each motor, monitoring possible overload in them and controlling the chopping current as well as operating modes (half, full or microstep). These drivers are supported on two digital potentiometers AD5160 from Analog Devices, which control the voltage drop across two of its control terminals, determining the maximum chopping current each driver will deliver to the motor. Finally, the electronics include three temperature sensors TC72 from Microchip, one embedded in the PCB board and one installed in each motor.

To optimize the consumption of the electronics, the control system can run in two modes, Active and Sleep. The first one is used to process data, to monitor constants and to position the engine, whereas the second one is used in waiting command periods, reducing consumption to a minimum when not required. Tables II and III show the consumption of each part of the system.

Considering the motors and drivers supply of 5 V and 3.3 V for the other electronics, reached levels of total power consumption are shown in table IV.

TABLE II. COMPONENTS CURRENT CONSUMPTION IN mA

Component	Active	Sleep
LPC11u14	2	0.36
DRV8834	2.4	0.0006
TC72	0.25	0.0001
AD5160	0.003	0.003

TABLE III. OVERALL CURRENT CONSUMPTION IN mA

Active	Sleep
7.56	0.37

TABLE IV. OVERALL POWER CONSUMPTION IN mW

Mode	Motor 1	Motor 2	Drivers	Electronics	Total
Running	200.000	170.000	24.000	9.095	403.095
Sleeping	0.000	0.000	0.006	1.224	1.218

The first innovative feature of this system is to control the temperature by software limiting the chopping current. This can be modulated to the needs of each motor windings over periods of movement or steadily in standby moments when the system is waiting for commands. In the second case, limiting the current to low values, it is able to maintain a constant temperature in engines without moving, adapting it to environmental characteristics. Thus, under conditions of very low ambient temperature, the chopping current is limited in stationary periods, at high values, increasing the temperature in each engine and offsetting the damage in mobility that freezing may cause in the actuators mechanism, while they remain unemployed waiting for new moves. Moreover, handling the chopping current, allows to control the torque generate for each motor, offering solutions to problems occurring in freezing conditions.

Finally, the microcontroller and mechanics used allow to optimize positioning time versus other control systems that preceded this. However, we have implemented a decisive algorithm, that allows to achieve the best times results, respecting the robot integrity, reducing the position errors and ensuring not to lose steps.

Due to the design of the mechanics of each actuator, the R2 axis is induced a number of steps with the R1 axis movement. This could make, during rotation of R1, to overcome the physical limit of R2. To avoid this situation, we have designed control algorithms embedded in electronics. They continuously monitor the position of the two axis and move accordingly, correcting undesired movement in the R2 axis and optimizing axis positioning time.

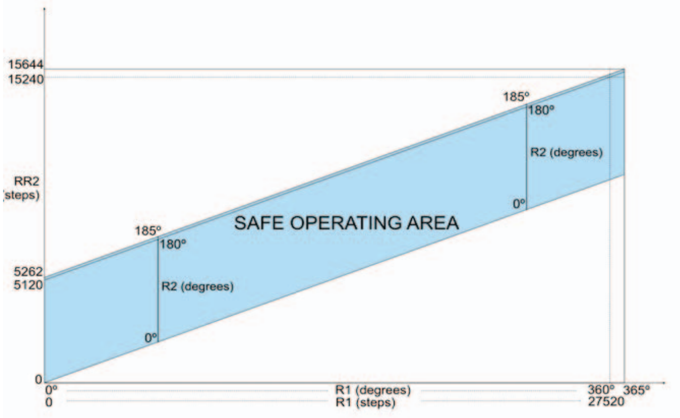

Fig. 5. Safe Operating Area

Figure 5 represents the SOA (Safe Operating Area). This is the operation area within the robot can perform, without damaging the mechanism. This figure represents the actual steps (RR2) in the R2 axis (steps in R2 with the induced ones), versus the steps in the R1 axis.

In order to fill all the functions described above, this system bases its performance on the commands management received from superior communications nodes. During the middle stages of the electronics development, control commands that managed in detail all system operation have been programmed. As in other communication protocols, these commands are formed by three bytes, one with the header and two with data. The command set presented in table V shows the basic commands to control all functions. However, the final design of these electronics does not have all these features, because they have been integrated into the internal system control algorithms.

TABLE V. COMMAND SET

Command	Data	Description
MOVE	Absolute position	Sends an absolute position
TEMP	Sensor number	Read a temperature value
CCHOP	Potenciometer voltage value	Set the maximum chopping current
SCHOP	Control mode	Set the chopping mode
VEL	Steps/second value	Set the motor speed

IV. EXPERIMENTS AND RESULTS

For this system, several preliminary performance tests have been run at the *Instituto de Astrofísica de Andalucía [9]* (IAA-CSIC) and the *Laurence Berkeley National Laboratory [8]* (LBNL), proving that the positioner does not lose steps and places the fiber in a bounded box error. These were performed in environments with temperature and vibration controlled by operating the system for hours taking it to high stress levels. These tests have been carried out in two phases, the first one, without performing a previous calibration and the second one, calibrating the positioner according to the actual length of the arms L1 and L2 in order to find the robot exact centroid.

First, positioning tests (figure 6 and 7) have been performed to estimate the existing error between the positions reached by the actuator and the theoretical one. On the one hand, in blue, target movements are represented, on the other, in green the real position reached by the robot.

After performing nine times the same positioning test shown in figure 6, calibrating the variables involved after the completion of each test, significant improvements are achieved (figure 7), coming to get rms errors of about 7 μm (table VI).

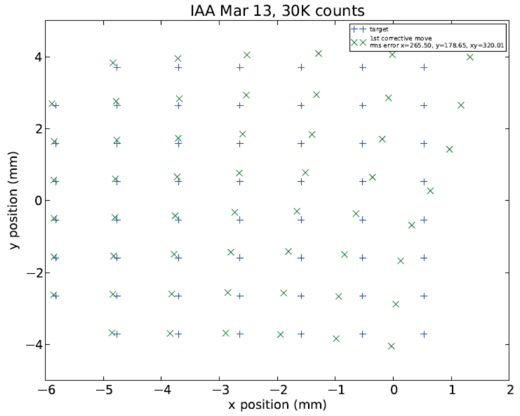

Fig. 6. Position test without calibration

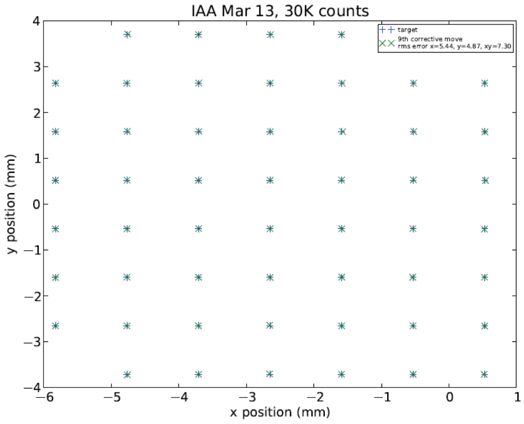

Fig. 7. Position test after calibration

TABLE VI. ERRORS IN μM REACHED IN THE TESTS

Test	RMS	Mean	Maximum
1	320.0	99.6	880.2
2	108.8	10.9	287.4
3	47.9	2.8	149.6
4	26.8	5.0	105.0
5	16.6	3.0	70.3
6	11.4	1.3	46.3
7	10.4	1.3	29.4
8	9.6	2.6	33.9
9	7.3	1.6	21.7

On the other hand, it is important to stand out the effect of hysteresis that appears in the position of the fiber, when it is placed at the same point coming from different positions. This effect is caused by the inner workings of mechanics. However, the error introduced is framed within the accepted limits.

Several tests have been conducted to study the effects of hysteresis (figure 9) and the system repeatability, bringing the robot to a same central point from four equidistant points (figure 8). In them, error boxes are obtained by movement up to 4 μm x 0.75 μm and errors introduced by hysteresis between 20 μm and 40 μm. However, after the completion of these tests, it is observed the good repeatability of the system.

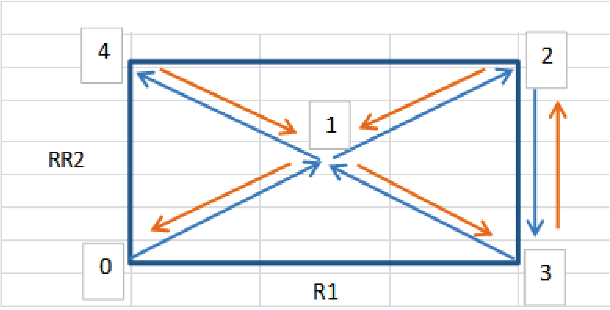

Fig. 8. Repeatability test points

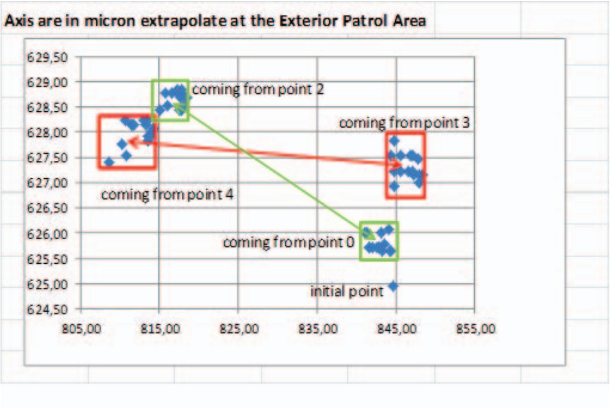

Fig. 9. Repeatability test

Finally, different tests have been performed to study the positioner tilt errors respect to the light incidence plane of the fiber head (figure 10). Again, after performing a calibration of the positioner variables to get the real value of the robot centroid, a significant improvement in these errors achieving values as 0.06° of maximum error, 0.035° of mean error and 0.019° of RMS error can be seen.

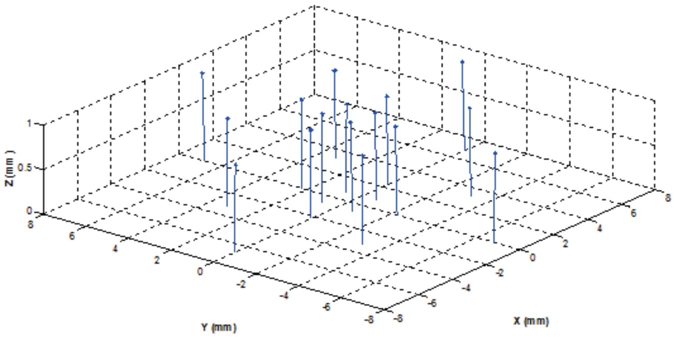

Fig. 10. Tilt test after calibration

V. CONCLUSIONS

Making a comparison with similar positioners that currently exist, the system designed for the BigBOSS project introduces clear improvements.

On the one hand, the positioning time achieved with the electronics and the coplanar system allows to optimize the process, substantially increasing the performance of the system, allowing to take a larger number of images in a shorter time. Moreover, at present, systems involving independent robotic positioners dedicated to each fiber have a very high consumption. However, the orientation of this design to micro-consumption, allows to achieve very low levels, limiting the overall system power consumption of 5000 units and minimizing the heat dissipation in the focal plane. Finally, the design of the temperature control by controlling the chopping current guarantees better performance in adverse conditions, reducing the need for maintenance of the system and securing the capacity for positioning and taking images in all situations.

On the other hand, studies with the coplanar positioner and control electronics reveal the need for positioners calibration prior to final installation in the telescope's focal plane, due to the non-ideality of the components used. However, the results obtained by performing various tests stand out the good system repeatability and the low value of the errors obtained in different positios.

VI. ACKNOWLEDGMENTS

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