Design of a Theta/Phi Fiber Positioner Robot for the Sloan Digital Sky Survey V

Ricardo Araujo[a], Mohamed Bouri[b], Christopher Brandon[c], Stefane Caseiro[d], Denis Gillet[e], Loic Grossen[a], Luzius Kronig[a], Matin Macktoobian[e], Thomas O'Brien[c], Richard W. Pogge[c], Sarah Tuttle[f], and Jean-Paul Kneib[a]

[a]Laboratory of Astrophysics (LASTRO), EPFL, Lausanne, Switzerland
[b]Biorobotics Laboratory (REHAssist), EPFL, Lausanne, Switzerland
[c]The Ohio State University, Columbus, Ohio, USA
[d]Micro Precision Systems (MPS), Bienne, Switzerland
[e]Research Group for Interaction Systems (REACT), EPFL, Lausanne, Switzerland
[f]University of Washington, Seattle, USA

ABSTRACT

The Sloan Digital Sky Survey V (SDSS-V) is an all-sky spectroscopic survey of > 6 million objects, designed to decode the history of the Milky Way, reveal the inner workings of stars, investigate the origin of solar systems, and track the growth of supermassive black holes across the Universe.[1] This paper describes the design of the theta/phi fiber positioner robots that are being produced to be integrated in the Focal Plane System (FPS) of the SDSS-V telescopes. For each installation, 500 robots are being manufactured, more than 800 units have already been received from the manufacturer and validated. Mechanical, electronic and firmware designs are presented in the current paper in detail. We will expose the different iterations of the prototypes that were developed, built and tested and ultimately allowed to achieve the end version that meets the requested science requirements. The fiber positioner robot is carrying 3 optical fibers integrated into a single snowflake ferrule. Two of the fibers are science fibers connected to two different spectrographs, and the third fiber is used for metrology. The robot is capable of positioning the fibers with a planar accuracy better than 50 microns with a first blind move within its workspace of a diameter of 44.8mm. With a complementary fiber viewing camera (FVC) and the backlighted metrology fiber to perform a few small corrections moves, the positioner can reach a sub 5-micron precision on the fiber position.

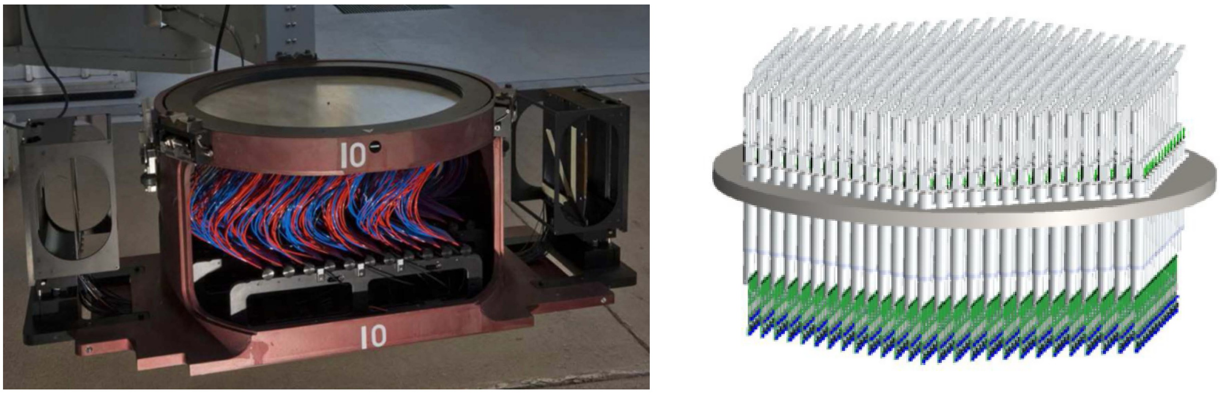
Keywords: telescope, fiber positioner, robot, SDSS-V

1. INTRODUCTION

The Sloan Sky Digital Survey (SDSS) just started its fifth iteration. The focal plane system (FPS) will be updated from fiber manual plug operations(see Fig. 1(a)) to a robotic system. Each telescope will be equipped with 500 Fiber Positioner Units (FPUs), allowing the fibers to be moved to target locations automatically and in a speed efficient way (see Fig. 1(b)). The FPS will provide an increased cadence for the survey and a more modular and agile system for target selection.

Each FPU is a two degree of freedom SCARA type robot designed to perform within the given specifications and allowing a rapid reconfiguration of the focal plane. Every FPU is composed of a mechanical assembly allowing accurate motion of the fibers and mounting on the FPS main plate and an electronic board with custom firmware performing the control of the actuators and the communication with main control system that determines the trajectories to be followed by the FPUs in order to reach the target and avoid collisions with neighbouring units.

Further author information: (Send correspondence to Ricardo Araujo)
Ricardo Araujo: E-mail: ricardo.araujo@epfl.ch



(a) (b)

Figure 1. Plug plate system[2] (a) and plate system with 500 FPUs (b) (reproduced from[3])

2. DESIGN

The design of the FPUs is based on the requirements that are fulfilled by the SDSS-IV survey. As the spectrographs used for SDSS-IV and SDSS-V are the same, no degradation on the throughput nor the resolution is allowed.

Table 1, summarizes the main requirements for each FPU.

Table 1. Requirements for the FPUs.

Parameter	**Requirement**
XY Error first move iteration	$<$ 50 µm rms
XY Error 2nd/3rd iteration	$<$ 5 µm max (metrology dependent)
Z Error (defocus)	$<$ 70 µm
Tilt Error	$<$ 0.3° rms
Reconfiguration time	$<$ 3 minutes spec, 2 minutes goal (including metrology)
Power while active	$<$ 2 watts
Power while idle	$<$ 0.5 watts
Operational Lifetime	300k targets / 10 years / positioner
Workspace	Annular shape, $r_{outer} \sim 2\times\ r_{inner}$
Operational temperature	-20°C to +40°C
Maximum relative humidity	80%
Fiber Payload	3 per positioner
Size of fiber positioner robot	$<$ 25 mm diameter, 380 mm max (incl. electronics)
Mass of a fiber positioner robot	$<$250 g (total for 500 positioners 125 kg)

2.1 Mechanical

The mechanical assembly of the FPUs is composed of a main housing and two serial arms (α and β) that allow full coverage of the workspace (see Fig. 2). Each arm is actuated using a brush less DC motor (BLDC) and an high ratio gear box that provides accurate positioning at the output and makes the system non back driveable, such that the system can be powered off during observations. On the prototypes the motion of the alpha arm was done using 12 mm diameter motor and a 879:1 ratio zero backlash spur gear heads, and the beta arm using 6 mm

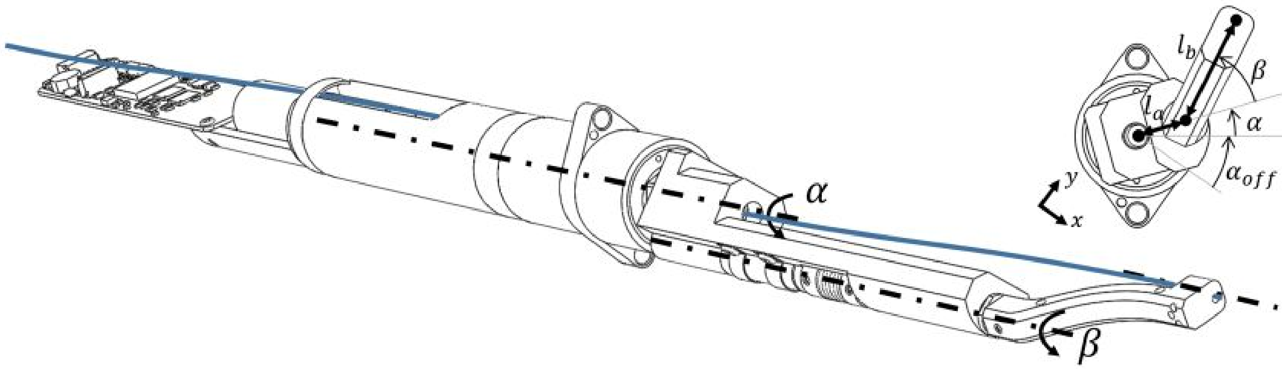


Figure 2. Model of P1 prototype and its α and β arms (reproduced from[3])

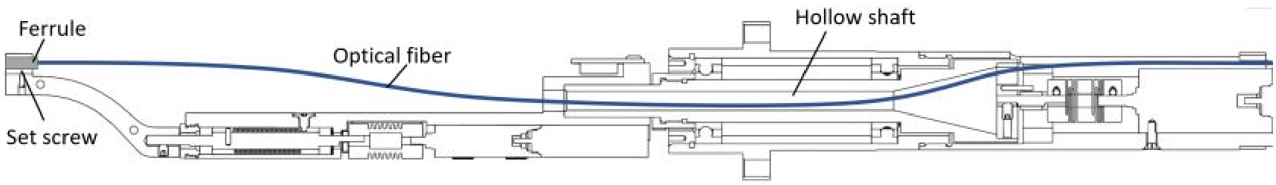


Figure 3. Hollow shaft for fiber path (reproduced from[3])

diameter motor and a 1024:1 planetary gear heads. Both arms have a range of motion of at least 370° to allow a full coverage of the work space and dual configurations for any target (right hand or left hand configuration).

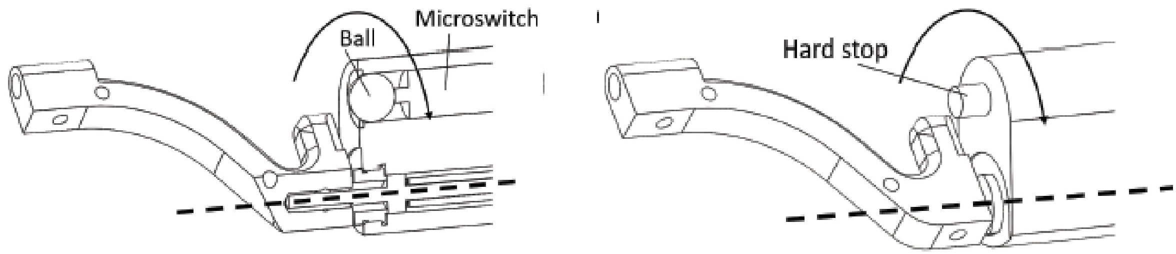
The fiber guidance is done through the middle of the unit. In order to reduce the torsion of the fiber and mechanical stress applied to it, a hollow shaft is used to allow the fiber to go through the main mechanical elements (see Fig. 3). The first prototypes were built to provide fixation for three independent ferrules at the tip of the beta arm, so that three fibers could be installed. Two fibers are used for science (one for the visible spectrum and one for the infrared spectrum) and a third fiber is used for metrology. The latest prototype have been built with only a single custom ferrule provision. Indeed the FPS system will use a single ferrule equipped with three fibers in order to allow easier installation and maintenance of the system.

The datum's reference for both arms was done using microball switches on the first prototypes (Fig. 4(a)), but due to aging issues and costs, the datums have been replaced by a more simple but robust and repeatable hard stop feature (Fig. 4(b)) . The datum is calibrated by driving the arms until a collision is detected with the hard stops.

One last important feature is the play reduction. In order to achieve the required accuracy and repeatability, the actuators have been designed with play reduced features. Two different features have been used. The simplest one to implement, was using play reduced gear boxes available off the shelf from manufacturers. The second was using a custom torsion spring on the beta arm to reduce the backlash, this feature is possible since the output only moves within around one turn at the output (Fig. 5).

2.2 Electronic

A custom electronic board has been developed and is part of the FPUs. The rectangular dimensions are required because of the mechanical constraints of the system. Majors parts of the design are the connectorization, the power stage, the core controller and the motor drives. The connector has been chosen in order to provide the possibility of daisy chaining the FPUs. Indeed, in order to reduce the amount of cables inside the FPS and



(a) (b)

Figure 4. Datum's view: microswitch on the left (a) and hardstop pin on the right (b) (reproduced from[3])

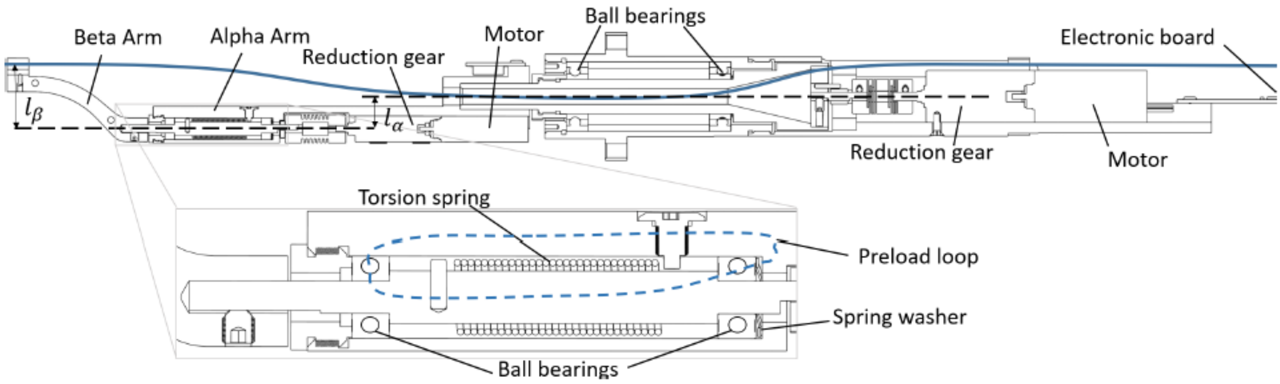


Figure 5. Mechanical design detailed view (reproduced from[3])

facilitate the mounting and maintenance of FPUs, the electronics has been designed to be used in a daisy chain configuration for up to 24 units. The power stage has been designed to be able to operate from a 9 to 24 VDC power input, and provides the two main voltages internally. A 6 V supply for driving the motors and a 3.3 V supply to power the control and communication electronics. The core controller is based on an Cortex ARM micro controller and using a custom bootloader and firmware, provides communication, calibration and control features to the FPU. The communication is done through a CAN bus and at rate of 1Mb/s and up to 50 units can be used on the same bus. In order to evaluate the communication performance and avoid any issues, a tst bench with 50 electronic boards has been assembled and used for several communication tests (Fig. 7). Finally a drive stage enables the micro controller to drive the motors and read back the analog hall sensors values for control and collision detection purposes. In order to reduce the power consumption, many electronics features can be turned off individually (like the hall sensors, the motors drives, the communication drive, etc...).

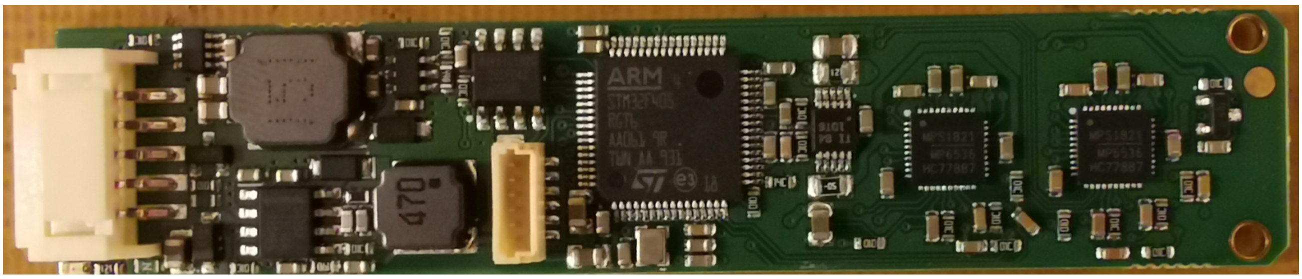


Figure 6. Electronics

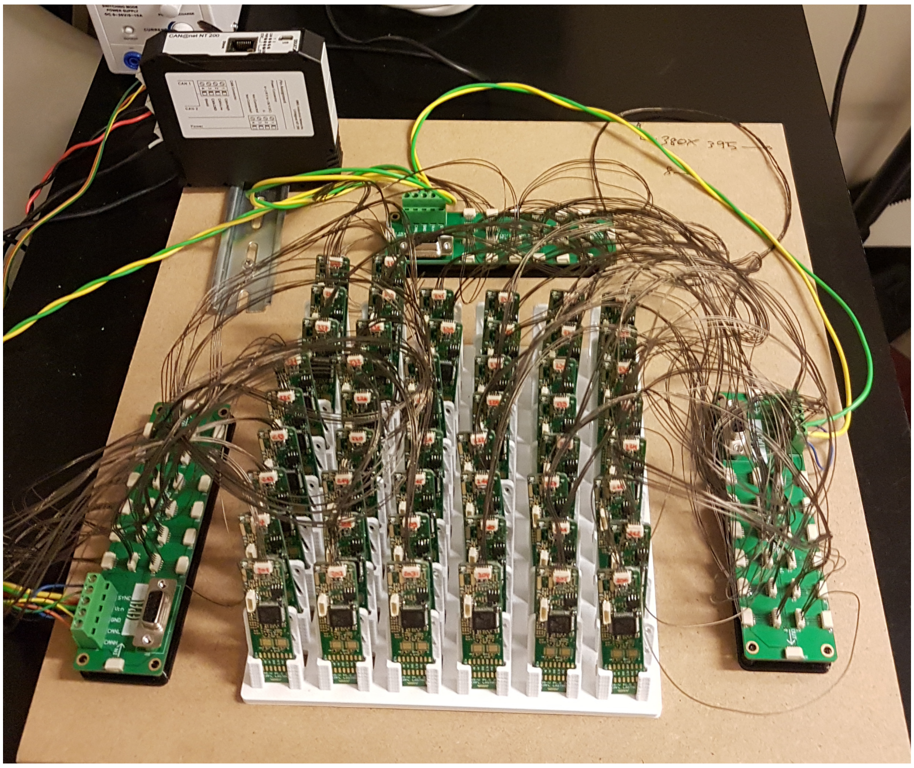


Figure 7. Communication test bench

2.3 Firmware

The firmware operating on the FPUs is composed of two main parts: the bootloader and the main firmware.

The custom bootloader allows to configure some factory settings and to perform main firmware upgrades via the CAN communication bus. The major feature that has been extensively tested is the firmware upgrade to allow in-situ upgrades in case of required bug corrections or updated features to be provided after installation on the telescopes.

The main firmware is in charge of the motion control and all associated tasks. The control of the motors is very versatile and can be done using closed loop control, open loop control, collision detection and many other features.[4] The main features are the accurate control of the actuators that is achieved using a closed loop control during normal operation. The analog hall sensors on the motors allow for a very efficient control and a collision detection feature that would stop any motion and prevent any damage of the FPUs in case of any incident. Another implemented feature is the calibration of the datums and of the control parameters (feed forward) for driving the motors. The firmware is cable of auto calibration for several parameters, allowing an easier maintenance of the system.

3. PROTOTYPES

Several iterations of the prototypes have been built (both mechanical and electronic). Each iteration has been extensively tested and results used to improve the following iterations, an example of a prototype built is shown in Fig. 8.

In order to test the different prototypes, custom test benches and protocols[5] have been used to validate and improve the design. The key parameters, such as non linearity (example in Fig. 9), hysteresis (example in Fig. 10) and repeatability are measured and analyzed in order to verify performance and improve, if possible, the design. Tests at the full temperature range were performed to validate the designs. Simulated lifetime testing has also

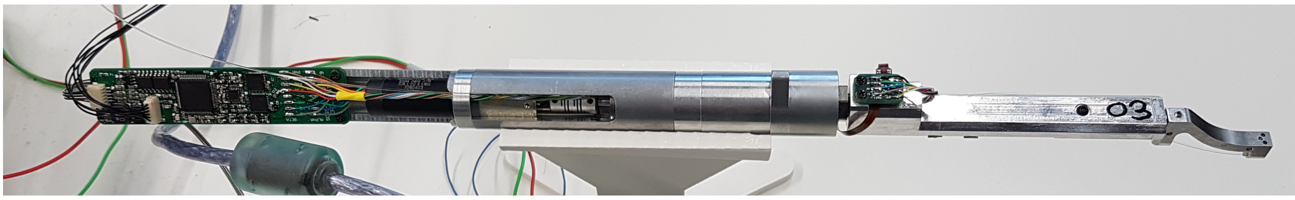


Figure 8. P1 prototype built

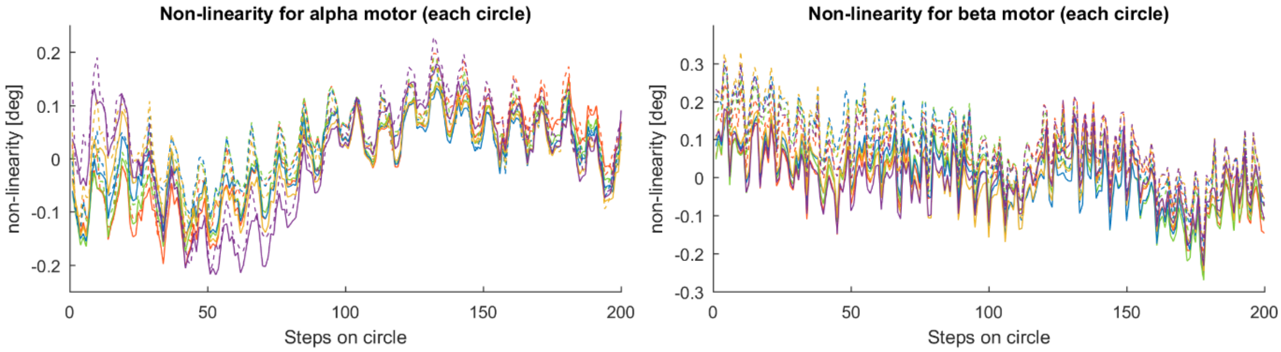


Figure 9. FPU prototype non linearity example

been done to verify that the amount of targets required by the project could be achieve without significant loss in performance.

The major design changes that have been done during the iterations are enumerated in the following paragraphs. For every iteration designed, several units were built, tested and operated together (example in Fig. 11).

General rigidity of the system has been improved by using stiff coupling between gear boxes output shafts and arms. Indeed some couplings were not stiff enough, specially for the β arm and the repeatability was very poor. The final FPU design is done without coupling units by fixating the gear boxes shafts to the arms. Also in order to improve the α arm rigidity the final version of the FPU is designed with a similar spring system for play reduction as the β arm and planetary gears.

During the tests, it has been noticed that the motors present a cogging torque, and thus when powering off the FPUs the arms might slightly move. In order to solve this issue, a small current needs to be applied to the motors so that the position is kept. Since the power consumption is important in order to minimize the heat generated, the electronic has been added with features that allow disabling several components, as communication and hall

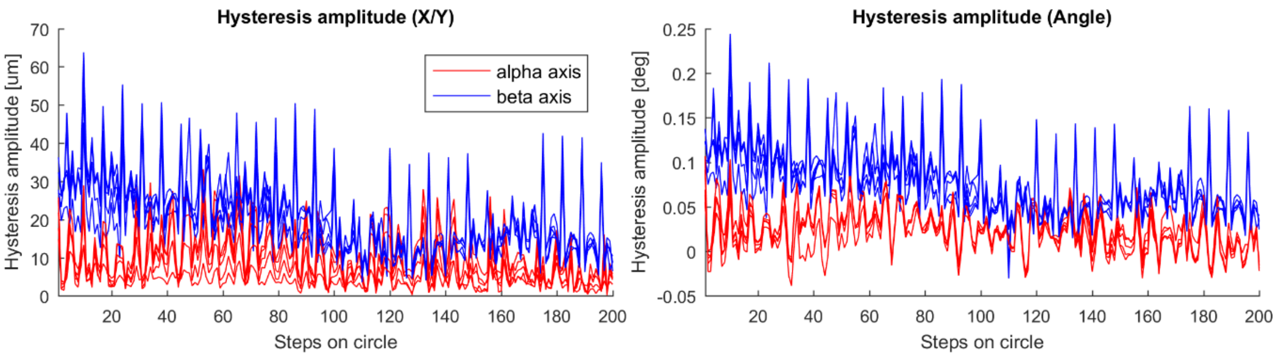


Figure 10. FPU prototype hysteresis example

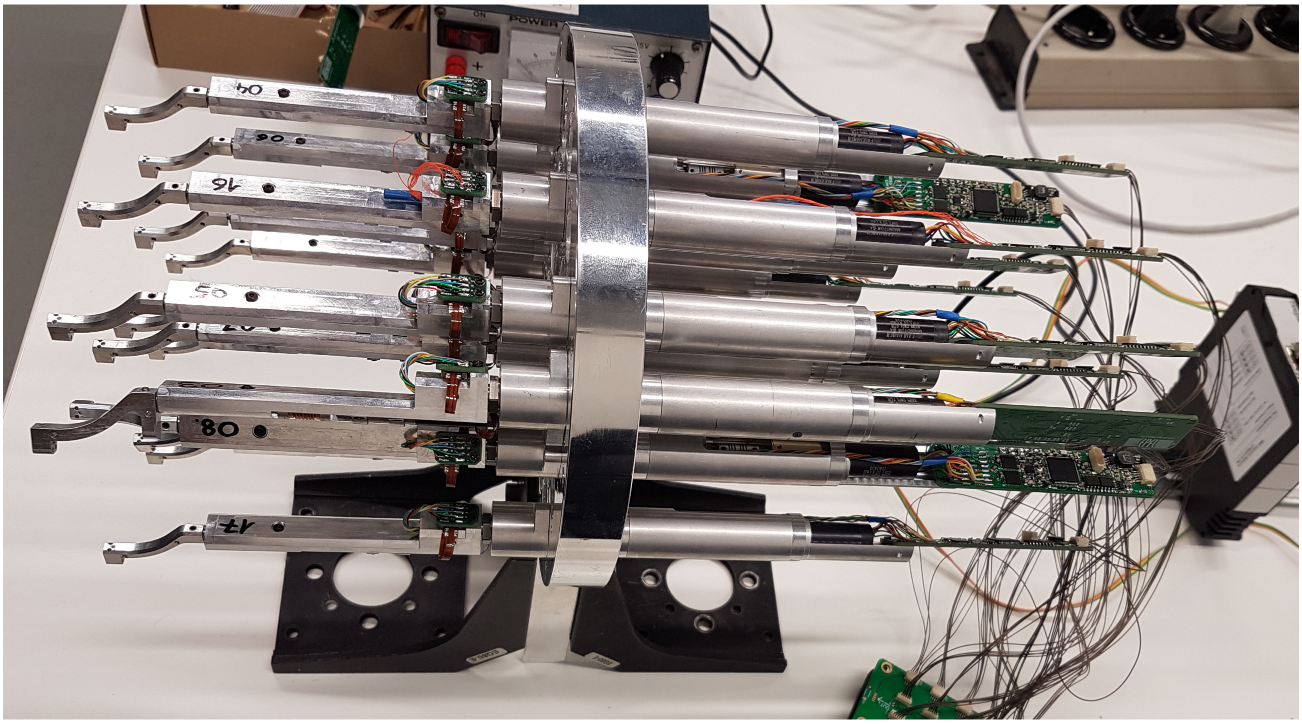
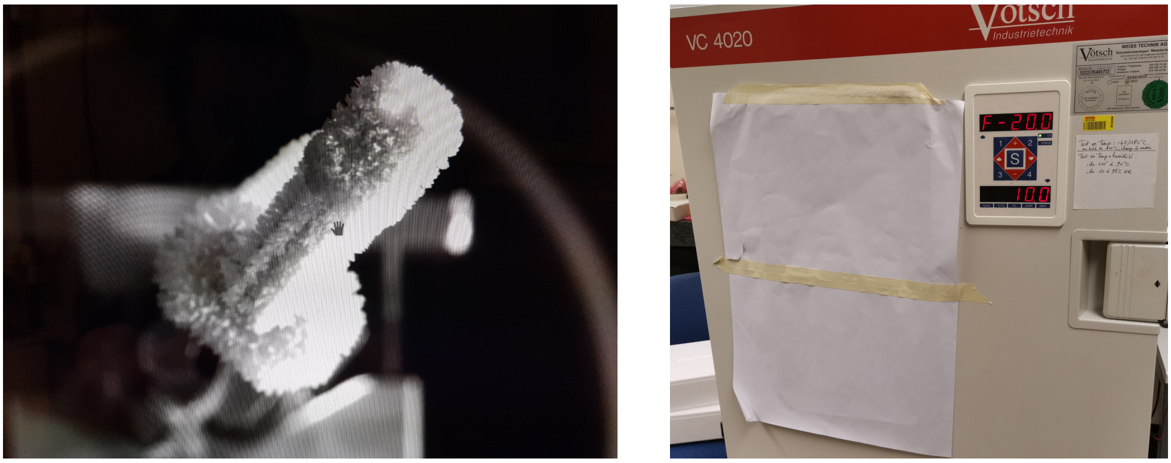


Figure 11. Mini prototype woke



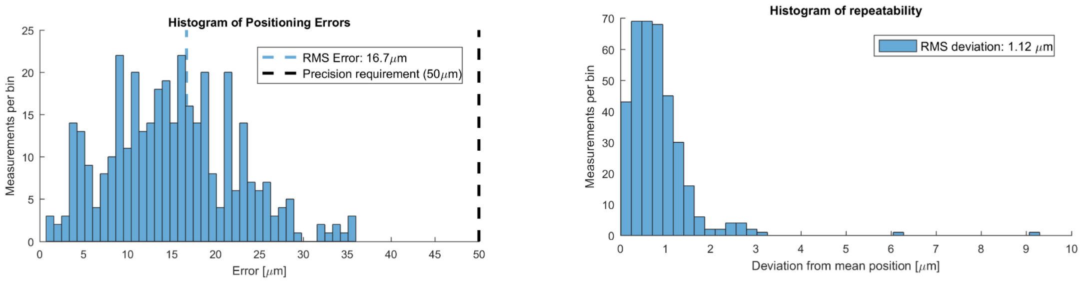
(a) (b)

Figure 12. Temperature testing: on the left a frozen beta arm (a) still operating, on the right the thermal chamber used for testing (b)

sensors, during idle state. This way during observation a minimal power is used to maintain the position of the arms.

Material and design of the spring used for play reduction has been reworked in order to compensate a loss of preload at low temperatures. After some testing it has been noticed that the fiction at low temperature was causing issues and the preload on the β arm was not performing as designed. During temperature testing, the units were pushed below the requirements, but even at very low temperature and with ice forming around the beta arm, the FPUs were still operating (Fig. 12).

After all the improvement done and changes performed to the design, the last batch of prototypes built was



(a) (b)

Figure 13. Results of positioner error (a) and repeatability (b) after at final prototype iteration

performing within the requirements and was used as basis for a public call for tender for the manufacturing of all the FPUs that will be used on the telescopes and spares, the results on the performance are well in the specification and suit the need. An example of positioning error and repeatability are shown in Fig. 13.

4. CONCLUSION

After the different prototypes iterations and extensive tests performed, the design is meeting all the requirements and the production was validated also using a first batch of pre series provided by the vendor. The design has been adapted to provide solution to all the challenges that were encountered and fulfill the needs of the project.

The production of all the FPUs is continuing and should be finished early 2021 and installed on both telescopes during spring and summer 2021.

All the manufactured FPUs are being tested and random units from the main production are being used for extensive testing including lifetime testing to mitigate any risks that could impact the performance and the operation on the telescopes.

5. DISCLOSURES

The authors declare that there is no conflict of interest.

ACKNOWLEDGMENTS

This project was supported by the SNF/FLARE grants (SDSS-V: 20FL21-18577) and through contribution from the ARC/SDSS-V funding. The authors would like to thank the workshops ATME and ATPR from EPFL for the production of the mechanical parts for the prototypes.

Funding for the Sloan Digital Sky Survey V has been provided by the Alfred P. Sloan Foundation, the Heising-Simons Foundation, and the Participating Institutions. SDSS acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS web site is www.sdss5.org.

SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration, including the Carnegie Institution for Science, Chilean National Time Allocation Committee (CN-TAC) ratified researchers, the Gotham Participation Group, Harvard University, The Johns Hopkins University, L'Ecole polytechnique fédérale de Lausanne (EPFL), Leibniz-Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Extraterrestrische Physik (MPE), Nanjing University, National Astronomical Observatories of China (NAOC), New Mexico State University, The Ohio State University, Pennsylvania State University, Smithsonian Astrophysical Observatory, Space Telescope Science Institute (STScI), the Stellar Astrophysics Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Illinois at Urbana-Champaign, University of Toronto, University of Utah, University of Virginia, and Yale University.

REFERENCES

[1] Kollmeier, J. A., Zasowski, G., Rix, H.-W., Johns, M., Anderson, S. F., Drory, N., Johnson, J. A., Pogge, R. W., Bird, J. C., Blanc, G. A., Brownstein, J. R., Crane, J. D., Lee, N. M. D., Klaene, M. A., Kreckel, K., MacDonald, N., Merloni, A., Ness, M. K., O'Brien, T., Sanchez-Gallego, J. R., Sayres, C. C., Shen, Y., Thakar, A. R., Tkachenko, A., Aerts, C., Blanton, M. R., Eisenstein, D. J., Holtzman, J. A., Maoz, D., Nandra, K., Rockosi, C., Weinberg, D. H., Bovy, J., Casey, A. R., Chaname, J., Clerc, N., Conroy, C., Eracleous, M., Gänsicke, B. T., Hekker, S., Horne, K., Kauffmann, J., McQuinn, K. B. W., Pellegrini, E. W., Schinnerer, E., Schlafly, E. F., Schwope, A. D., Seibert, M., Teske, J. K., and van Saders, J. L., "Sdss-v: Pioneering panoptic spectroscopy," (2017).

[2] Smee, S. A., Gunn, J. E., Uomoto, A., Roe, N., Schlegel, D., Rockosi, C. M., Carr, M. A., Leger, F., Dawson, K. S., Olmstead, M. D., and et al., "The multi-object, fiber-fed spectrographs for the sloan digital sky survey and the baryon oscillation spectroscopic survey," *The Astronomical Journal* **146**, 32 (Jul 2013).

[3] Kronig, L., "Precision positioning of microrobots for multi-object spectrographs," *EPFL thesis* (2020).

[4] Kronig, L., Hörler, P., Caseiro, S., Grossen, L., Araujo, R., Kneib, J.-P., and Bouri, M., "Precision Control of Miniature SCARA Robots for Multi-Object Spectrographs," *Journal of Optomechatronics* (2020).

[5] Kronig, L., Hörler, P., Caseiro, S., Grossen, L., Araujo, R., Kneib, J.-P., and Bouri, M., "Optical test procedure for characterization and calibration of robotic fiber positioners for multiobject spectrographs," *Journal of Astronomical Telescopes, Instruments, and Systems* **6**(1), 1 – 21 (2020).