Test results of the SDSS-V fiber micro-positioners

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ABSTRACT

This paper will focus on the testing, validation and performance of the ongoing SDSS-V fiber positioners production. The tested critical parameters include positioning accuracy calibration and validation, fiber misalignment control as well as lifetime test and thermal reliability check over the large temperature scale encountered in the telescopes. The presented results give a good overview on the general design performance and on the general reliability the complete robotic positioning system will achieve.

Keywords: Telescope, fiber positioner, test procedures, validation procedures, SDSS-V

1. INTRODUCTION

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 [5]. Though these topics are already core of astronomical surveys since many years, there is still a tremendous amount of data required to test the different models and improve our understanding of the expansion of the universe. To do so, several hundreds of fibers must to be positioned precisely in the focal plane of a telescope to observe multiple targets at once. In the past few years, it became clear using micro-robots for this task would allow for several benefits, including observation dead-time reduction, target selection modularity and reduction of human error probability during fiber insertion. Alongside these benefits, new challenges also came up, such as guaranteeing positioning accuracy or operation reliability. To minimize the risks involved with each of these challenges, continuous testing was performed on the produced robots to ensure these parameters were under control. The testing tools developed during the prototyping stages were improved and adapted to the large series scale to improve their reliability, time-efficiency and operation simplicity.

2. SYSTEM OVERVIEW

2.1 Fiber positioner overview

The fiber positioner is a robot with a SCARA architecture and the fiber tips in the end actuator. Each robot carries 3 fibers: one metrology fiber to perform a feedback on the position, a science fiber for visible light and another science fiber for infrared light. These infrared fibers are fed into a spectrograph to measure the redshift of the incoming light. The robot has 2 arms, denominated alpha for the first arm and beta for the second arm that carries the fibers (Figure 1). Each arm moves using a brushless motor with analog hall sensors and a high reduction-ratio gear. A backlash compensation mechanism is integrated in each arm that allows almost hysteresis-free operation [1].

Each positioner possesses its own control electronic (Figure 2). It receives the commands *via* a CAN bus and a microcontroller handles the subsequent motor control. The motors are controlled in closed loop using the built-in hall sensors as well as an internally calibrated feed-forward [1].

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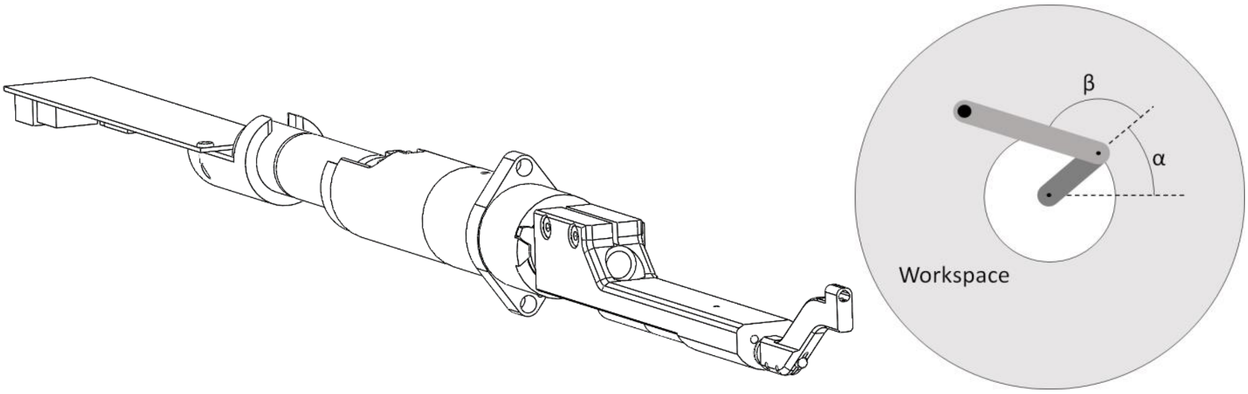


Figure 1: The fiber positioner used in the telescope, manufactured by MPS© (left) and the positioner workspace (right)

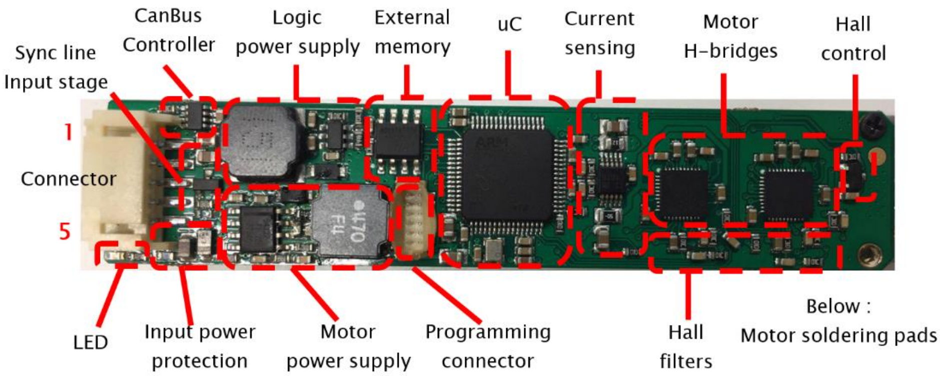
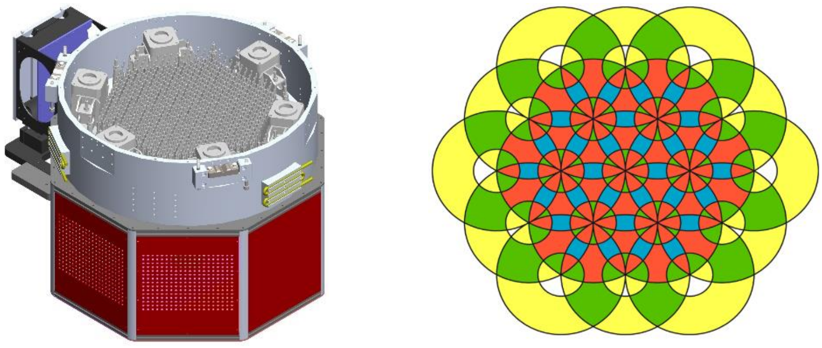


Figure 2: The electronic present on each positioner

2.2 Telescope configuration

The telescope uses several hundreds of robots spread over the hexagonal focal plate to maximize coverage. A trade-off had to be made regarding the number of robots, with cost, maintenance, cooling, installation and complexity on one side and number of simultaneously observable targets on the other. As the currently installed spectrograph could not be upgraded due to limited funding, the number of robots was set to match the number of inputs, namely 500. Fixed fiducials are also placed in the focal plane to measure the plane's deformation and thermal dilatation (Figure 3). A metrology camera is pointed at the focal plate and is able to precisely measure the position of each fiber and fiducial for a precise corrective feedback.



Color	Number of positioner reaching the zone
Yellow	1
Green	2
Red	3
Blue	4

Figure 3: Left: The complete focal plate model of one of the telescopes. The 500 robots are placed in the hexagonal focal plate alongside with the fiducials (reproduced from [2]). Right: The workspace of each robot overlaps with its neighbors, requiring precise control to avoid collisions but allowing better target assignment (reproduced from [3]).

3. TESTS

In order to ensure proper operation of the robots once they are installed in the telescope, they undergo a series of tests on 3 different benches prior to installation:

1. The XY bench, able to measure the spatial position of the fiber
2. The tilt bench, able to measure the spatial position and orientation of the fiber
3. The thermal bench, able to measure the spatial position of the fiber and vary the environment temperature

These tests ensure the robots meet the fabrication requirements listed in Table 1, hence meeting the science requirements.

Table 1: Fabrication requirements of the positioner

Designation	Requirement	Description
Alpha arm length	7.4±0.1mm	The alpha arm radius
Beta arm length	15±0.12mm	The beta arm radius
RMS repeatability	2.5µm	The RMS positioning error when the same target is given to the positioner
Max hysteresis	0.3°	The maximal angular error when approaching a position from the counterclockwise direction and the clockwise direction
Max non-linearity	0.6°	Non-linearity describes the difference between the measured arm angle and the commanded angle. It accounts for gear imperfections [1]
Maximal roundness deviation	20µm	The maximal radial deviation between an optimal circle and the measured position when the arm performs this circle
RMS tilt	0.2°	The RMS tilt of the fiber end relative to the focal plate normal vector
Max tilt	0.4°	The maximal tilt of the fiber end relative to the focal plate normal vector
Temperature range	[-15;40] °C	The functioning temperature range
Max position error	5µm	The maximal positioning error after 1 blind move (moves using the positioner model) and 2 correction moves (performed using the metrology camera feedback)
Number of moves	300’000	The positioner must be able to move to at least 300’000 targets

3.1 XY bench

The XY bench can measure the XY position of the fiber tip in a simulated focal plane. The positioner is held in a V-shaped groove and secured in place using a spring-loaded V-shaped counter-groove (Figure 4). To accommodate for the high production rate, each XY bench can accommodate 7 positioners at once (Figure 6) and 4 benches were built: 2 at the MPS factory for their internal quality control and 2 at EPFL for further quality control. A camera, whose distortion field is precisely calibrated, is headed towards the positioners to capture the position of the back-illuminated metrology fiber (Figure 5). The positioners are spaced in such a manner that their workspaces do not overlap, avoiding any collision if a robot wasn’t functional. The production bench is based on the development prototype from [4].

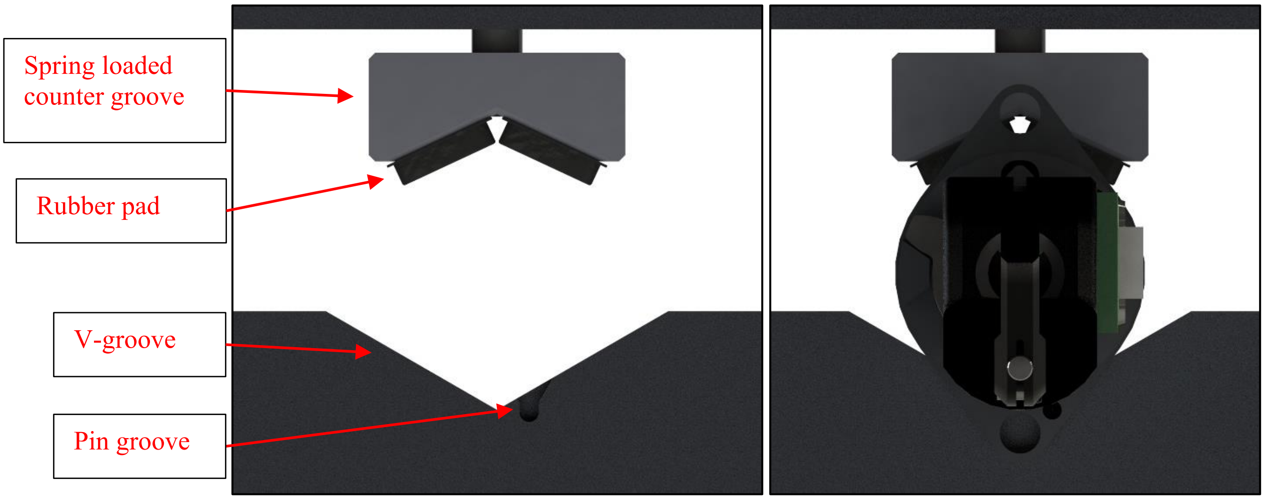


Figure 4: Empty slot (left) and with a positioner installed (right)

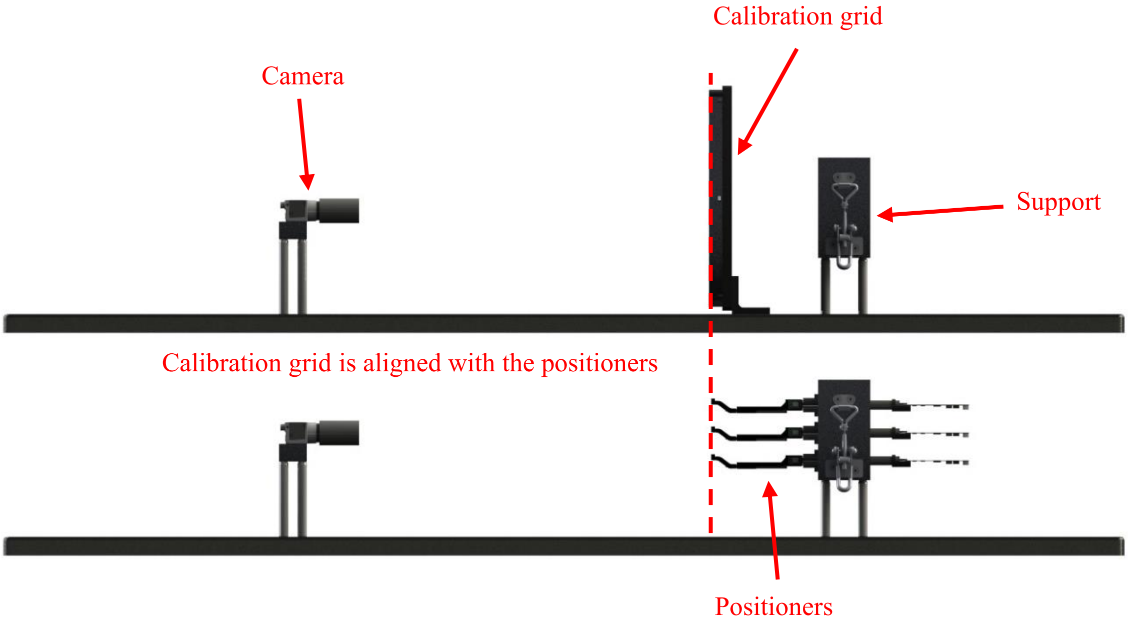


Figure 5: The camera distortion field is calibrated on the virtual focal plane (top) and the positioners tips are aligned with the virtual focal plane (bottom)

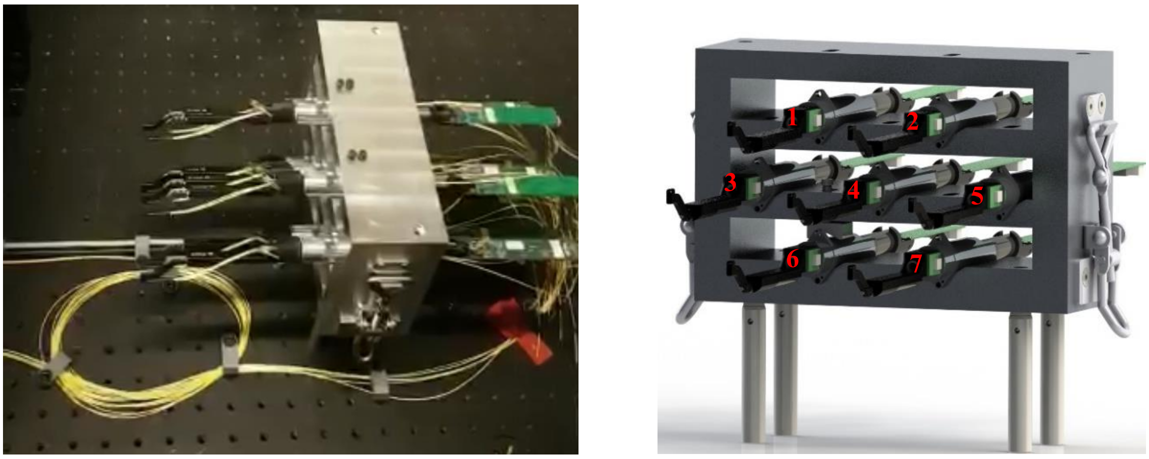


Figure 6: Positioners being tested in the XY bench (left) and the slots configuration (right)

2 steps are performed on this bench: the positioner calibration and the XY validation. The calibration is necessary in order to achieve the required precision in the minimal number of correction moves. It also ensures precise displacement to avoid any collision with nearby robots once installed on the telescope. To do so, the positioner moves each axis to 200 evenly spaced and known positions along the workspace, first in the counterclockwise direction and then in the clockwise direction to account for hysteresis. While one axis moves, the other is commanded to stay still to calibrate each axis independently. There are 5 different still position for each axis, ensuring the calibration is valid along the whole workspace. The whole process is repeated 3 times to measure the repeatability and add robustness to the data. The calibration builds up a model we can use to precisely control each robot. This model is then validated during the second step. 200 random targets are distributed over the workspace of the robot and the error to each target is measured. If the error was greater than the maximal position error (5µm), a correction move is applied. If each target could be reached in less than 2 correction moves, the robot is validated. This validation is repeated 5 times with the same targets to validate the repeatability and ensure the robustness of the robot.

The XY bench is also used for lifetime testing. The calibration and validation steps are repeated until the performance is too degraded of the maximal number of moves has been reached successfully. The calibration is the same as performed before, with 200 steps, 5 still positions and 3 repetitions, but the validation step is extended to 1'000 targets repeated 5 times. Only the validation targets are counted as "moves" regarding the lifetime validation process as the calibration steps are too small. After a target is reached successfully, the robot refolds to its initial position (fully extended arms), doubling the move distance. To validate the 300'000 moves, only 150'000 targets are therefore necessary.

3.2 Tilt bench

The tilt bench measures the misalignment of each component in the system. It measures the position of the fiber tip as well as the position of the image of the light comping out of the fiber at a calibrated distance. Since the ray is going through a converging lens, the light image will move only if the light is not travelling straight (Figure 8). Hence, by moving each axis independently, the misalignment of each axis can be retrieved [4].

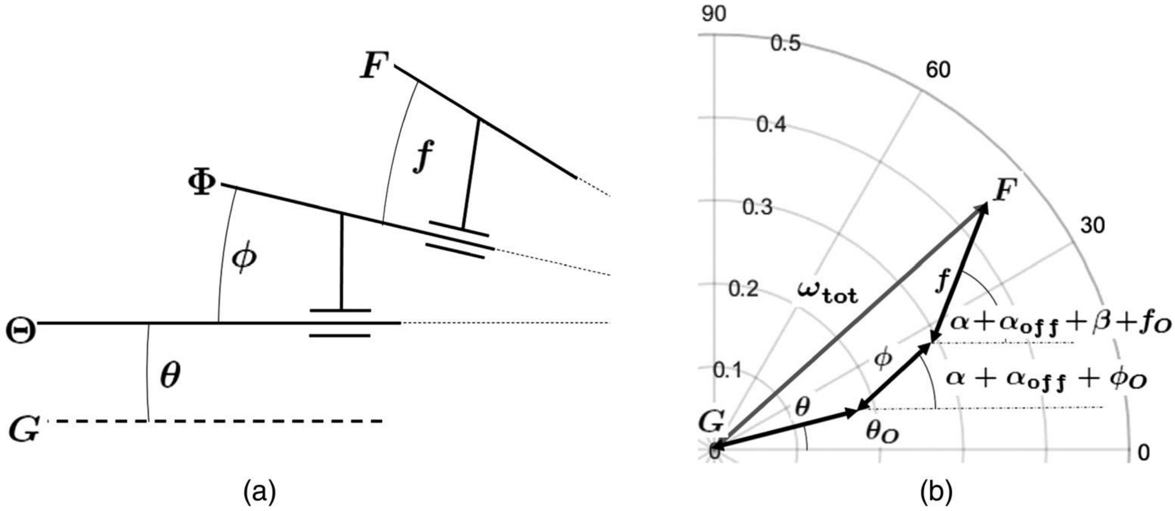


Figure 7: (a) The definition of the angular alignment of the V-groove, ferrule axis, and rotation axes is shown. (b) The kinematics of the alignment model. The overall tilt angle ω_{tot} of the positioner at motor positions α and β is obtained by adding the alignment angles θ , ϕ, and f as vector sum (small angle approximation). Reproduced from [4].

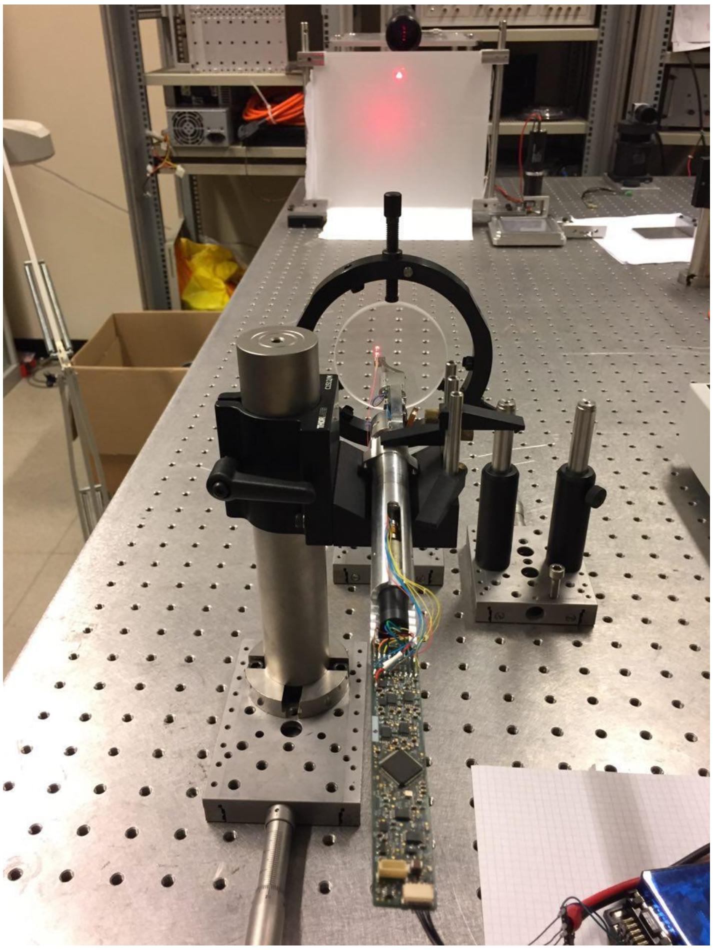


Figure 8: The tilt test bench verifies the alignment of the positioner's axes.

3.3 Thermal bench

The thermal bench is a XY bench that suits only 1 positioner built inside a thermal chamber. The chamber allows for temperature and humidity control. The temperature is maintained as stable as possible during the test. During the preseries, results showed no problems in going above the ambient temperature, but some robots had difficulties going below -10°C. As each test is very time consuming, the series robots were only tested for -15°C.

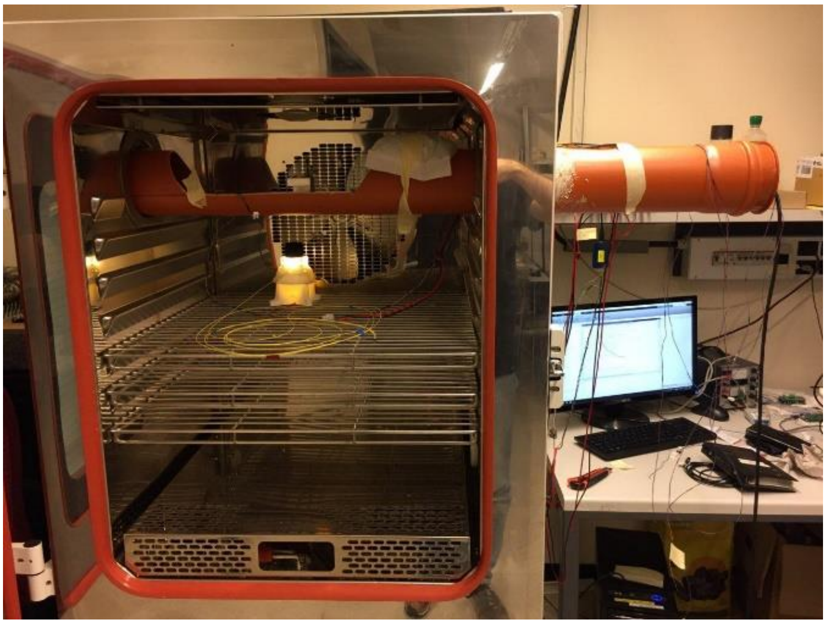


Figure 9: The thermal test bench changes the environmental conditions to ensure the robots can sustain the climate they will encounter in the telescope.

3.4 Procedures

Not all the robots were verified for every metric. Table 2 shows the number of robots that are tested for each metric.

Table 2: Number of positioners doing each test

Production	# positioners	XY test	Tilt test	Temperature	Lifetime
Pre-series	30	30	30	10	7
Series (tested)	852	852	188	3	28
Series (to be tested)	348	348	50	10	0

4. RESULTS

4.1 XY position

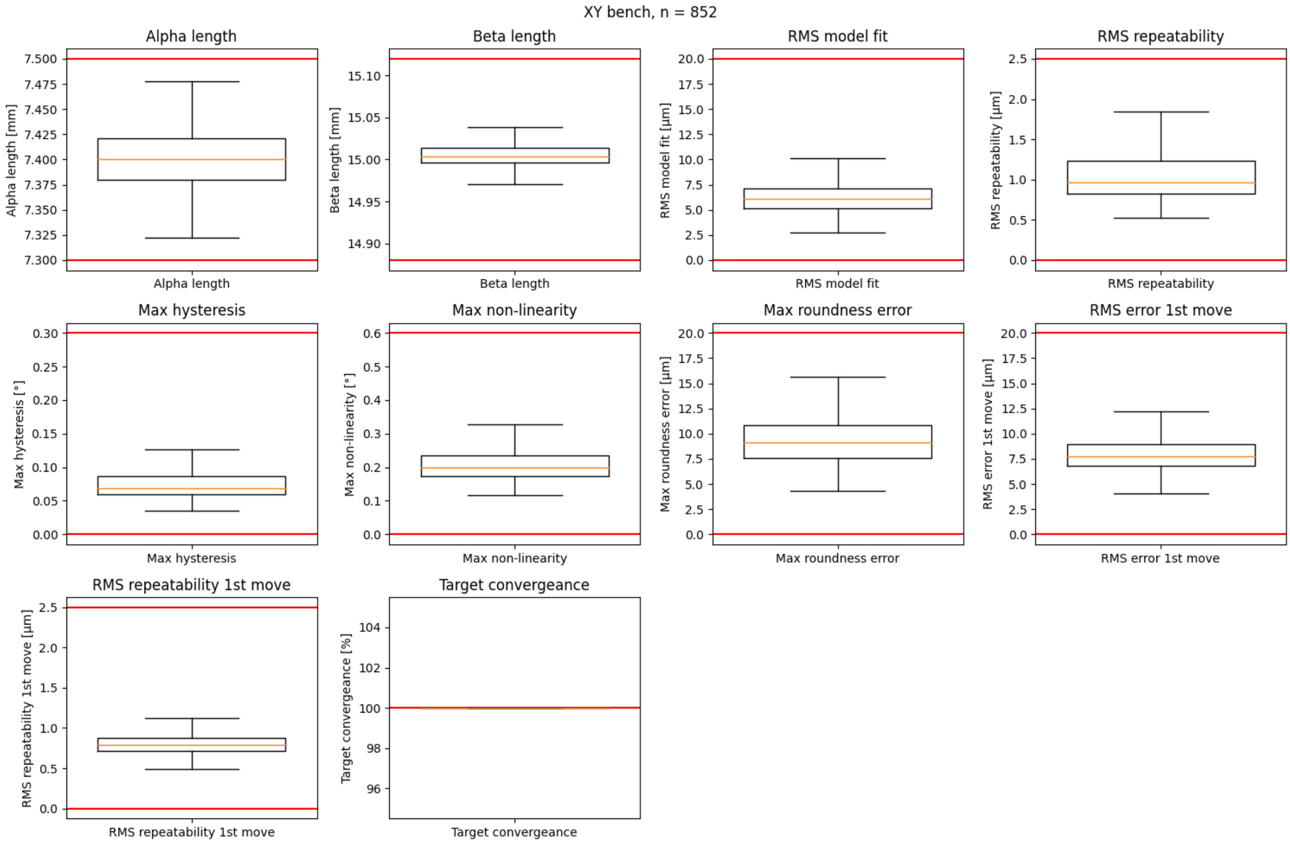


Figure 10: XY test results. All the critical parameters are shown. For sake of readability, outliers are not shown in the plots. The orange line symbolizes the median of the data, the box the 1st and 3rd quantile and the error bars the standard deviation. The red lines symbolize the requirements range.

Every positioner is tested 3 times: 1 time at the factory, 1 time at EPFL arrival and 1 time after the PCB board impermeabilization. The results show good requirements compliance (Figure 10) and overall, the series is ready for use in the telescope. Out of the 852 positioners tested, 20 failed the test and were sent back to the factory.

The arm lengths ensure the planned workspace will be reachable. Overall, the model of the positioner is very accurate, with a median RMS error of about 6µm (RMS model fit). This model accuracy is confirmed by the error of the blind test move (RMS error 1st move) which is about 7.5µm. The repeatability is also very small and approaches the measurement limits of the test setup. Both the calibration repeatability (RMS Repeatability) and the blind move repeatability (RMS repeatability 1st move) have a median value of less than 1µm. This ensures a quick convergence while using the optical feedback camera to correct the target position. Indeed, the target convergence ratio is 100% with a very small standard deviation.

The results are also reassuring regarding the collision avoidance: with a small hysteresis, small non-linearity and small roundness error, the real trajectory the robot will stick close to the planned trajectory.

4.2 Tilt

Figure 11: Tilt test results. All the critical parameters are shown. For sake of readability, outliers are not shown in the plots. The orange line symbolizes the median of the data, the box the 1st and 3rd quantile and the error bars the standard deviation. The red lines symbolize the requirements range.

The tilt test is critical to ensure correct part fabrication and assembly. The tilt must be as close to zero as possible to ensure the fiber is aligned with the incoming cosmic rays. The higher the tilt, the more light is likely to bounce off the fiber surface and the less light ultimately reaches the spectrograph. Out of the 188 positioners tested, 1 failed the test by a small amount.

As shown by the results (Figure 11), the overall alignment error is inside the requirements. The maximal alignment error is even close to the RMS requirements, demonstrating the design is robust.

4.3 Thermal

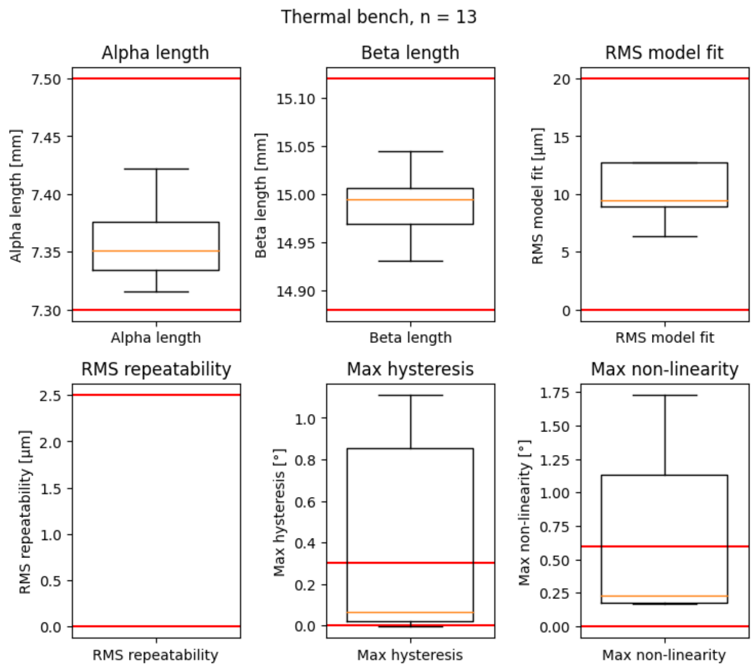


Figure 12: Thermal test results. All the critical parameters are shown. For sake of readability, outliers are not shown in the plots. The orange line symbolizes the median of the data, the box the 1st and 3rd quantile and the error bars the standard deviation. The red lines symbolize the requirements range.

All the thermal tests were performed between -15°C and -12°C and the data comes mostly from the preseries. At his temperature, the camera is outside its specification range and the measurements accuracy gets worse. Because of this, no repeatability measurement could be done as the data was too erratic. Out of the 13 positioners tested, 6 failed the test.

As the data in Figure 12 show, the results are worse than what was required. This can be partially explained by the fact that those tests were performed on the preseries only. The results show there is a hysteresis issue with almost one fourth of the tested positioners. This hysteresis issue is caused by the beta arm losing its preconstraint, either due to the grease used to lubricate the spring and the axis or the grease contained in the motor gear. This issue was corrected for the series but could only be verified for 3 positioners so far. This indicates the positioners do not perform well in the high beta range when they are too cold. Luckily, this is not an issue as the target assignment and collision avoidance software that is in development only uses the beta arm up to 180°, so one-half turn. When tested with this new configuration, all the hysteresis results are within specification and the positioner is therefore usable on the telescope.

4.4 Lifetime

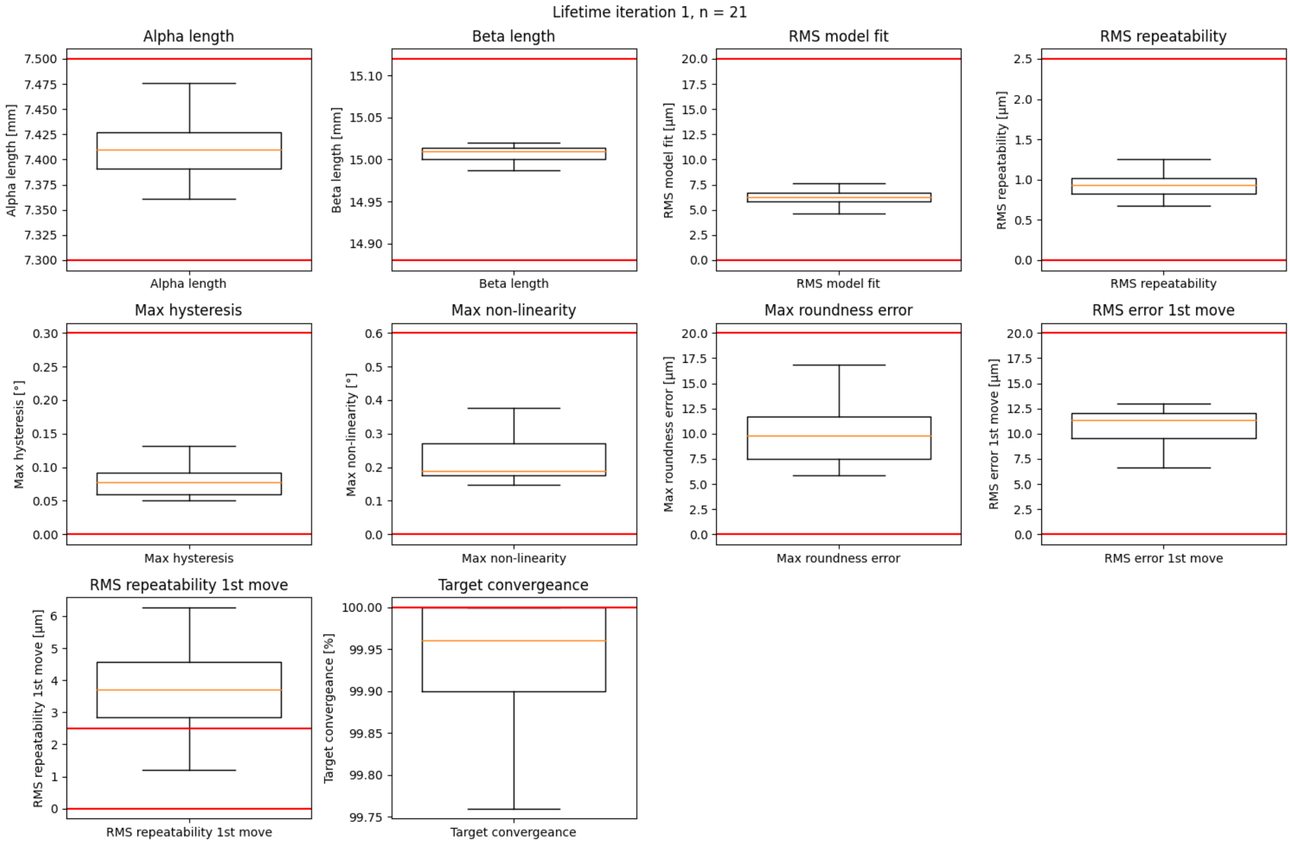


Figure 13: Lifetime results at the first iteration (10'000 moves). All the critical parameters are shown. For sake of readability, outliers are not shown in the plots. The orange line symbolizes the median of the data, the box the 1st and 3rd quantile and the error bars the standard deviation. The red lines symbolize the requirements range.

To assess the aging of the positioners, an accelerated test runs the positioner quickly from one target to the other, until 300'000 moves are reached. As shown in Figure 13, the results of the first iteration are close to the results of the XY validation (Figure 10), except for the RMS repeatability of the first move. This can be explained by the higher number of targets and the fact that the positioner always returns to its origin (alpha and beta arm angles = 0) after a target is reached. Also, the motors are on a higher duty cycle as during the calibration and for a much longer time, meaning the room temperature variations start becoming visible. Overall, this decline in repeatability is the cause of the lower target convergence ratio, leaving 0.05% of the targets over 5µm error after the blind move and 2 correction moves. This first iteration is now our baseline we can compare the future iterations to.

The final result of the lifetime is the 30th iteration (Figure 14). As we can see, the results mostly show a higher standard deviation and worse median values due to the wear-out of the mechanical parts. The parameter that suffers the most from the ageing is the RMS repeatability of the positioner, going from less than 1µm to approximately 2.5µm. This has a visible impact on the target convergence ratio, as demonstrated by the 0.2% targets with error more than 5µm. Overall, the positioners remain in good shape after 300’000 moves and are still usable, despite a small performance degradation. The uncorrected targets were usually lying by approximatively 7µm error, so 2µm over the requirement but still an oder of magnitude below the smallest fiber core diameter (120µm).

This test highlighted some design flaws that were assessed. Out of the 28 positioners taking the test, 7 were stopped during the process because of terrible results or mechanical failure. These allowed to correct the underlying problems (unpolymerized glue leading to motor detachment or beta preload spring wearing out).

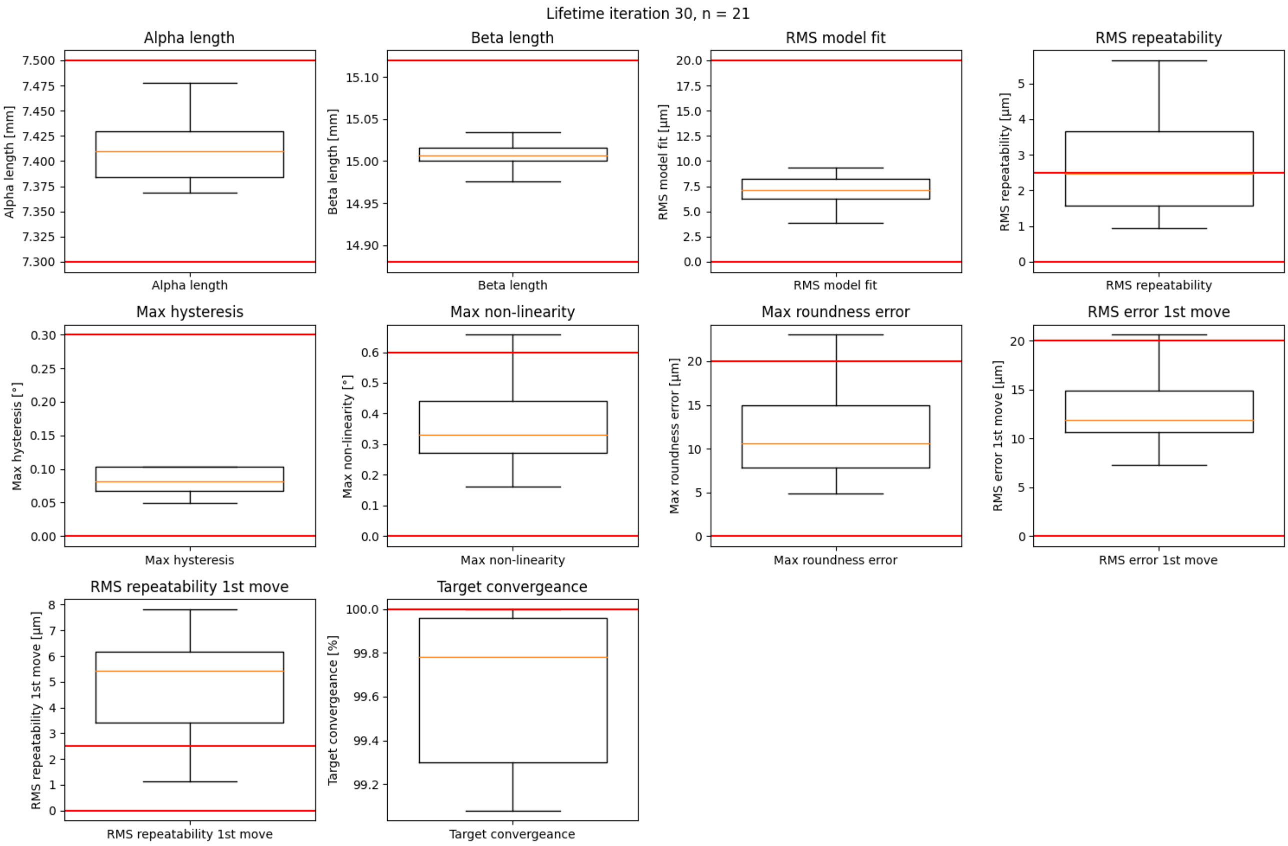


Figure 14: Lifetime results at the 30th iteration (300’000 moves). All the critical parameters are shown. For sake of readability, outliers are not shown in the plots. The orange line symbolizes the median of the data, the box the 1st and 3rd quantile and the error bars the standard deviation. The red lines symbolize the requirements range.

5. CONCLUSION

The testing methods shown in this presentation were used to test the SDSS-V fiber positioners. These methods were developed prior to this specific work and improved for the series testing. The results presented great confidence on the positioner’s ability to successfully fulfill its task, with more that 99.95% of the targets being below 5µm error with 10’000 consecutive moves and more than 99.80% after 300’000 moves. The positioners also show a small fiber misalignment, ensuring the light is captured with little losses. This ensures the positioner will be able to successfully replace the current fiber-placement method in the new focal plane system.

DISCLOSURES

The authors declare that there is no conflict of interest.

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