A Robotic Focal Plane System for the Sloan Digital Sky Survey V

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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. This paper describes the design and construction of two robotic Focal Plane System (FPS) units that will replace the traditional SDSS fiber plug-plate systems at the Sloan and du Pont telescopes for SDSS-V. Each FPS deploys 500 zonal fiber positioners that allow us to reconfigure the fibers onto a new target field within 2-3 minutes of acquisition. Each positioner carries three fibers: two science fibers that feed the BOSS and APOGEE spectrographs and a third back-illuminated metrology fiber is used in conjunction with a telescope-mounted Fiber Viewing Camera (FVC) to measure the absolute positions of the fiber heads. The 300 APOGEE fibers are distributed among the 500 positioners to maximize common field coverage. A set of fiber-illuminated fiducials distributed in and around the positioner array establish a fixed reference frame for the FVC system. Finally, six CCD cameras mounted around the periphery of the focal plane provide acquisition, guiding, and focus monitoring functions. The FPS is a key enabling technology of the SDSS-V Milky Way and Black Hole Mapper surveys.

Keywords: SDSS, ground-based OIR instrumentation, massively-multiplexed spectroscopy, robotic fiber positioners

1. INTRODUCTION

All of the Sloan Digital Sky Survey's (SDSS) spectroscopic surveys to date have employed optical fibers plugged by hand into the now-iconic drilled aluminum disks that many astronomers use as office décor. Plug plates have the virtue of simplicity and they have proven highly adaptable as subsequent SDSS surveys evolved beyond BOSS to APOGEE, eBOSS, and MaNGA. At night observers deploy up to 9 cartridges holding plates drilled many months in advance, selected ~12 hours in advance and then fitted out with fibers during the day. The number of fields that may be observed is limited by the maximum number of cartridges (9) that can be staged at one time given available space. Each cartridge exchange takes 15- to 20-minute overhead, so the combination of space and overheads results in an optimal observing cadence of roughly 1-hour per field.

The ambitious science goals envisioned for After SDSS-IV (AS4) survey concepts required a faster cadence with a nominal visit duration of 15 minutes per field and the ability to obtain BOSS and APOGEE spectroscopy on a single field (if not on the same targets) during a visit. These requirements are impractical to accomplish using the plug plate system. In January 2017 an internal collaboration committee chaired by Connie Rockosi[1] evaluated the technical feasibility of replacing the SDSS fiber plug-plates with robotic fiber positioners and recommended designs based on zonal positioners as the preferred technology.

In April 2017, at the invitation of the AS4 management council we developed a concept for a robotic Focal Plane System (henceforth FPS) that became part of the successful Sloan Foundation proposal that allowed us to formally launch

SDSS-V[2] in January 2018, when we presented a conceptual design for the FPS at the official SDSS-V kick-off meeting in Pasadena in January 2018. During the first half of 2018 we built the core FPS team from among current and prospective SDSS-V collaborators and developed a preliminary design that passed a Preliminary Design Review (PDR) held in Columbus, Ohio, on 2018 November 15. This was followed by more design and prototyping work leading to a Final Design Review (FDR) in Pasadena on 2019 April 25-26, whereupon we moved forward to the build phase that we are currently in.

A robotic fiber positioner system offers many advantages for SDSS-V:

1. Reduction of fiber re-configuration time to 2-3 minutes, allowing efficient use of shorter exposures for bright targets in the Milky Way and increasing the number of fields that may be observed on a typical night by a factor of 3 to 4.
2. Positioners cab carry fibers for both BOSS[3] and APOGEE[4] spectrographs, allowing survey planners to mix visible and near-infrared spectroscopic targets in a single field (though any given positioner may be assigned to only one spectrograph at a time).
3. Fiber positions can be set at the start of observations to account for the median differential atmospheric refraction during the visit, increasing the range of available observing windows for each target field and thus enhancing observing flexibility.
4. While most fields will be pre-planned to maximize observing efficiency, in principle new fiber assignments can be made during a night, enabling just-in-time fiber assignment for observations of transients and other targets of opportunity.

The FPS builds on the technological developments responsible for the many robotic fiber instruments now coming into operation that deploy many thousands of fiber positioners: 5000 robots in DESI[5], 2400 robots in PFS[6], 1000 robots in WEAVE[7] and MOONS[8], and 2400 echidnas in 4MOST[9]. These projects have pioneered many of the key enabling technologies and approaches that inform the design of the FPS. Because of our smaller team, stringent budget, and aggressive schedule, we are taking a conservative approach and so the FPS is a largely derivative instrument: we are adopting existing solutions and leveraging our teams' experiences with DESI and MOONS, projects that have already completed extensive relevant design studies and prototyping activities and arrived at important design decisions that inform and confirm our approaches. This means we do not have to reproduce all their design studies and prototyping experiments to have confidence in adopting/adapting a particular approach to the FPS. There is no need to re-invent technologies or repeat experiments that have already been demonstrated and well documented. This approach allows us to focus development efforts on the primary new capabilities: rapid and accurate focal plane configuration, replacement of guide and focus fibers with imaging cameras, and simultaneous use of BOSS and APOGEE, unique to the requirements of SDSS-V.

Insofar as practical, our primary design philosophy has been "do no harm": to preserve the field of view and basic position and focus accuracy of the current plug plate system, reuse the existing spectrographs and telescope interfaces with minimal modification where possible, and to re-use/adapt as many elements of the existing cartridge architecture as are practical. However, "do no harm" does not mean "do nothing"; beyond enabling the new survey science programs the FPS units will have a significant impact on SDSS observatory operations. Previous surveys have transitioned almost seamlessly from one iteration to the next by because they all used the same basic plug-plate infrastructure. The biggest change is that instead of up to 9 cartridge exchanges per night, the FPS will be mounted on the telescopes for months at a time. Systems designed for repeated mount/dismount cycles are no longer needed. Observers will no longer need to go outside to manually change cartridges, and the observing cadence will increase from one field per hour to ~3 fields per hour. Calibrations will likely be more stable and thus need to be less frequent because the instrument is not changing hourly, requiring the development and qualification of new protocols for calibrations. Fibers will likely need to be cleaned less often as they are rarely handled if at all and effectively enclosed within the FPS unit. The teams of fiber pluggers and infrastructure to support them will be retired or reassigned, and space allocated for the handling and storage of plates, cartridges, and their associated fixtures will become available for other uses. Because the deployment of the FPS units will be a major perturbation of night-time and daytime operations, a part of the work of the FPS team will be cultural as well as technical, working with the operations staff at both LCO and APO to help make the changes needed to operate and maintain them.

2. SDSS-V FOCAL PLANE SYSTEM

We are building two FPS units: one for the 2.5-m Sloan Foundation Telescope[10] at Apache Point Observatory (FPS-APO) and one for the 2.5-m Irene du Pont Telescope[11] at Las Campanas Observatory (FPS-LCO). Each FPS unit has 500 zonal fiber positioners in a hexagonal array. Each positioner carries three fibers: two science fibers (one BOSS and one APOGEE, but only 300 are connected to APOGEE at one time), and one back-illuminated metrology fiber. The 300 APOGEE fibers are distributed among the 500 positioners to maximize common field coverage. Fiber-illuminated fiducials (FIFs) fill in the rest of the hex array and circumscribe it to establish a fixed reference frame against which robot positions are measured using a Fiber Viewing Camera (FVC), and guide cameras are mounted around the periphery of the robot array for guiding, acquisition, and focus. Renderings of the FPS system is shown in Figure 1. A schematic of the robot patrol field layout and distribution of guide cameras is shown in Figure 2.

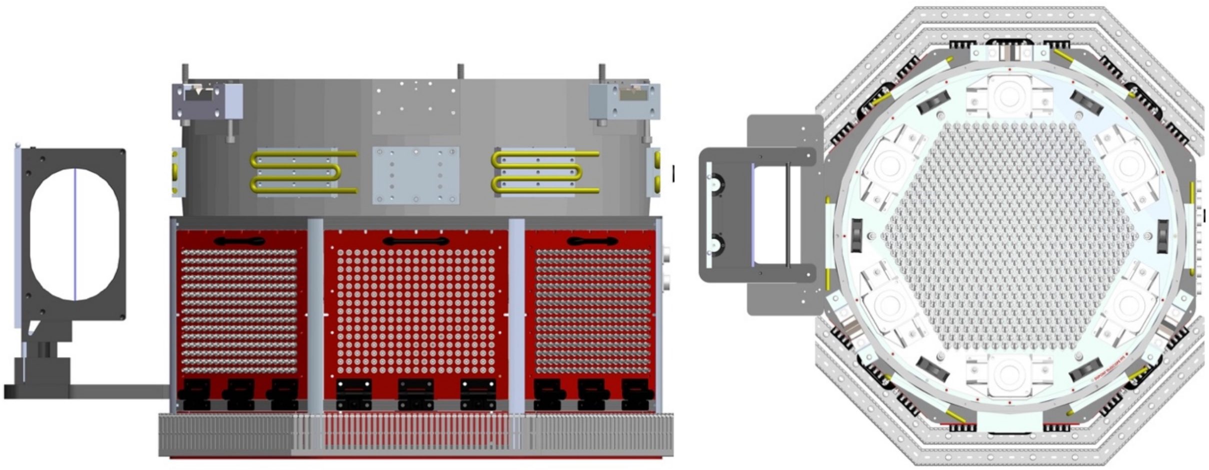

Figure 1: Solidworks rendering of an FPS unit. Left: side view showing the BOSS slit head (left) and fiber patch panels. Right: top view showing the robotic fiber positioners, GFA cameras, and elements of the fiber routing and cooling system.

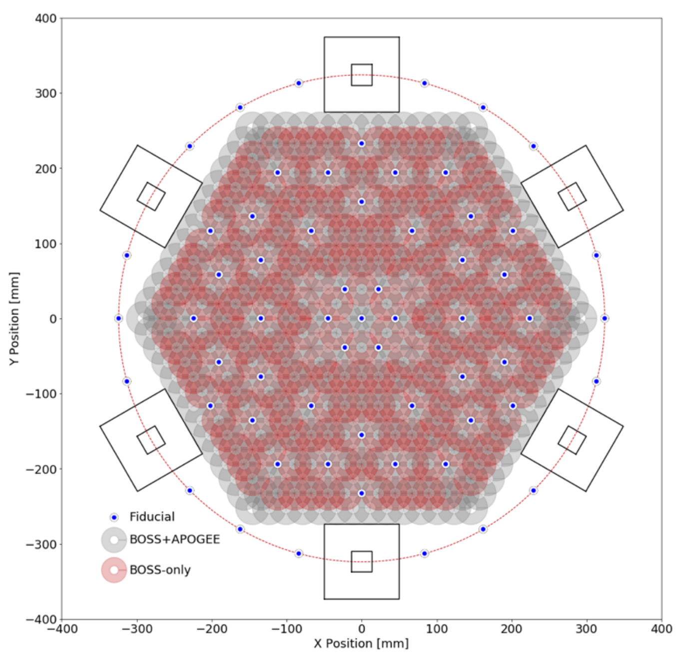

Figure 2: FPS focal plane layout showing robotic fiber positioners (colored +s and annuli), fiber-illuminated fiducials (blue & white circles), and guide camera locations (black squares). Gray and red transparent circles show the positioner patrol fields for BOSS+APOGEE and BOSS-only fiber robots, respectively.

The current Sloan telescope corrector lens produces a non-telecentric focal plane: the chief rays at each location are not perpendicular to the local surface of best focus. Plug plates compensate by drilling fiber holes at an angle so that when the plate is bent to match the nominal focal plane fibers are nearly aligned with the chief rays at each location. The current corrector also has different visible and near-IR focal surfaces, and relatively poorer IR throughput and image quality. A team from JHU has designed a new 3-element corrector that is being fabricated by Thales-SESO for the Sloan Telescope. The FPS-APO unit is being designed for the new corrector and cannot be installed at the Sloan telescope until the new corrector is commissioned.

At LCO we will use the existing du Pont telescope Gascoigne corrector. While it delivers a telecentric focal plane with slightly different optimal focal surfaces for visible and near-IR light, optical modeling shows there is a compromise visible/near-IR focus surface that balances focus and telecentricity and allows us to keep the BOSS and APOGEE coplanar. This obviates the need to entertain complicated options like stepped fibers in separate ferrules or microlenses to achieve acceptable visible-to-NIR images for the science fibers.

The FPS consists of these primary subsystems:

2.1 Fiber Positioner Robots (FPRs)

500 two-axis zonal fiber positioners arrayed in a hexagonal pattern with overlapping patrol fields, each carrying 3 fibers: BOSS, APOGEE, and metrology. The positioners were designed by the EPFL AstroRobotics team and are being fabricated by MPS Faulhaber. EPFL led FPR procurement and testing. See papers by Araujo et al.[12] and Grossen et al.[13] in these proceedings for details.

2.2 Optical Fiber Assemblies (OFAs)

These are the visible and near-IR science fibers that run from the robotic positioners to the BOSS and APOGEE spectrographs, and the metrology fibers on each robot that will be back-illuminated for the Fiber Viewing Camera (FVC) system. Robot fibers are mounted together using a novel fiber-in-glass capillary ferrule developed in collaboration with FiberTech Optica. All fibers are connectorized to facilitate removal and replacement of individual robots with spares while the errant units are repaired or retired. New APOGEE tributary fiber bundles to connect the APOGEE science fibers to the APOGEE science fiber feed were designed in collaboration with Computer Crafts, Inc. A new monolithic BOSS spectrograph slit head and tributary fiber system is being fabricated by Durham University. BOSS and Metrology fiber is Polymicro FBP120170190 enhanced blue fiber with 120 μm cores and APOGEE fiber is Polymicro FIP120170190 infrared fiber. This is the same fiber used by SDSS in the past. Custom octagonal IR fiber drawn by Polymicro is used in the APOGEE tributaries.

2.3 Guide/Focus/Acquisition (GFA) Cameras

Each FPS carries six (6) CCD imaging cameras mounted around the periphery of the positioner array to take images of the night sky for guiding, focus, and acquisition. These cameras replace the guide, focus, and alignment fiber bundles used by the current plug plate system. The FPS GFAs are Finger Lakes Instrumentation MicroLine ML4240 2Kx2K CCD imaging cameras mounted on the same curved support plate as the fiber positioners.

2.4 Fiber-Illuminated Fiducials (FIFs)

Fixed fiber-illuminated fibers are distributed across the focal plane to provide a fiducial reference coordinate system as part of the metrology system. They use fixed versions of the same metrology fibers carried by the positioner robots and are illuminated by the same fiber back illumination (FBI) system. This ensures that the FIFs have the same intensity and numerical aperture as the robot metrology fibers, and so imaged the same way by the Fiber Viewing Camera. The FIF mechanical bodies were designed by OSU and fabricated by Southeastern Machining, and the fiducial fiber tails were fabricated by FiberTech Optica.

2.5 Mechanical Structure & Thermal Enclosure

This is the mechanical structure that carries the fiber positioners with their optical fiber assemblies, FIFs, and GFA cameras on a curved plate matching the telescope focal surface. The precision curved focal plates were designed by OSU and fabricated by Tapemation Large Precision Machining. The FPS units are mounted to the telescope using the same latching mechanisms as the original plug-plate cartridges. The structure also acts as a thermal enclosure that uses glycol heat exchangers to carry off waste heat from the positioners and GFA cameras. The final curved mounting plate was finished to a precision of ±20 μm RMS.

2.6 Fiber Viewing Camera (FVC)

This is a commercial large-format (8Kx6K) CCD camera mated with a custom optical system (lenses, pickoff mirrors, and narrow-band filter) mounted in a periscope configuration at a fixed location just above the primary mirrors to image the positioner metrology fibers and FIFs illuminated by the Fiber Back Illuminator (FBI) system. The FVC uses a narrow-band "laser-line" filter optimized for the λ640nm LEDs used by the FBI to reduce parasitic backgrounds and enhance spot contrast. The FVC optomechanical system is being designed and built at OSU. The first FVC system was built for the du Pont telescope and tested during an engineering run in late January 2020. See Jurgenson et al.[14] in these proceedings for details of the FVC system.

2.7 Fiber Back Illuminator (FBI)

This system back illuminates the FIFs and metrology fibers. It consists of two commercial 4-inch LabSphere integrating spheres mounted on each FPS. Fiber tributaries connect to the integrating spheres and fan out into ST connector panels to feed light to 600 fibers (positioner metrology and FIF) with light from λ640nm LED illuminators under remote control. When the LEDs are lit, the FIFs and positioner metrology fiber tips become visible to the FVC system CCD camera. The connectorized metrology fiber bundles that connect the integrating spheres to the instrument are being fabricated by FiberTech Optica.

2.8 Instrument Electronics Box (IEB)

This is an outboard box mounted next to an FPS on the telescope that distributes switched power and ethernet to FPS onboard systems, provides environmental monitoring (temperature and humidity) inside the thermal enclosure, and carries point-of-use control computers for the GFAs, and distributes drive power and CAN communication busses for the fiber positioner robots. The IEB is being designed and built at OSU following designs derived from OSU's work on MODS and DESI.

3. FPS REQUIREMENTS

3.1 Origin of Requirements

Science survey planning carried out by the SDSS-V Milky Way Mapper (MWM) and Black Hole Mapper (BHM) teams adopted as the baseline assumption that the performance of FPS+BOSS and FPS+APOGEE will be the same as achieved during SDSS-IV. Because we are replacing the plug-plate system but keeping the same spectrographs, none of our design choices should degrade the throughput or resolution delivered by these spectrographs. The introduction of a new 3-element telecentric corrector at the Sloan Telescope with a common optical/NIR focal surface, and the ability of the robots to precisely position fibers in real-time, and improved fiber coupling and calibration systems being deployed with the FPS systems should all work in the direction of improving end-to-end performance of the overall system, exceeding the expectations of our conservative "do no harm" design approach.

Our design approached defined requirements for fiber choices (baseline: same type of fibers as used currently), precision of fiber placement by robots (baseline: as good as with plug plates, goal better), and precision of guiding and focus (baseline: same as current experience, goal better). The maximum number of fibers accepted by a single BOSS or APOGEE spectrograph limits the number of robots we can deploy, and desire to cover as much of the current field of view as possible with the positioner array sets requirements on how to optimize the distribution of fibers and their robots in the focal plane. The coherent fiber bundles used for guiding and focus stars in the plug-plate system will be replaced with direct imaging cameras mounted around the outside of the science field, setting requirements for field of view and imaging sensitivity, but also greatly increasing the sensitivity of the guider system overall.

A key science driver from survey planning is a requirement for rapid fiber positioner reconfiguration to enable a faster survey cadence without loss of efficiency due to setup overhead when pointing to a new field. The surveys have adopted a nominal observing quantum of 15 minutes per field visit, which sets requirements for efficiency and accuracy of the positioner motion (blind pointing and offsets applied based on input from an external positioner metrology system). This in turn sets requirements for the metrology camera exposure and readout times, measurement speed and accuracy, etc.

Finally, the FPS units must fit on the telescopes, stay within telescope mass and moment limits, and be safe for observatory personnel to handle without danger to themselves or the equipment. Because of the decades-old legacy of Sloan, the run-up to a final FPS design required us to undertake an extensive discovery effort to identify sources of definitive engineering drawings for the telescopes and their interfaces, including conversion of electronic drawings from obsolete sources (or redrawing them from paper or screen sources when import from, e.g., GenCAD to SolidWorks, failed to produce acceptable results), and asking observatory personnel to make measurements to confirm as-built dimensions empirically when multiple drawings were in disagreement. We are grateful for the help and patience of observatory personnel at both sites as we worked through this process, the result is better documentation at both sites.

3.2 Robotic Fiber Positioners

Table 1 summarizes the requirements of the robotic fiber positioner units.

Table 1: Robotic Fiber Positioner Requirements

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} ~2×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)

Note that the reconfiguration time requirement includes the time for FVC metrology exposures, readout, and analysis. Three (3) minutes is the baseline requirement provided by SDSS-V, and 2 minutes is a goal for performance we hope to achieve with the end-to-end system after refinement of the fiber viewing metrology system in practice.

Note also that operating temperature and humidity limits are not the same as the allowed ranges for observing operations. The maximum humidity limit of 80% is lower than the closure limits (85%) at the observatories because the fiber positioner mechanisms are effectively enclosed within the FPS and not directly exposed to ambient humid air in the same way that telescope mirrors and support structures are. Similarly, the minimum operating temperature of –20°C is lower than the operational closure temperature (–10°C) for both sites but is a good engineering goal to ensure continued operation near the coldest observing limit. Both sets of environmental limits are commensurate with ranges used in industry for non-condensing conditions, even though both limits are difficult to quantify or measure in practice.

3.3 Fiber Viewing System

The requirement of accurate fiber positioning for targeting and rapid reconfiguration of the positioners when pointing to a new field sets numerous requirements for the Fiber Viewing system in terms of image quality of the optics and characteristics of the camera. We were guided in some of these technical requirements by the FVC system for the DESI spectrograph that the OSU team learned of when designing and building the Commissioning Instrument (CI) for DESI.

Jurgenson et al.[14] in these proceedings describes the metrology approach and how we intend to realize the requirements listed in Table 2.

Table 2: Fiber Viewing Camera (FVC) System Requirements

Parameter	**Requirement**
Absolute Position Measurement	3 μm RMS
Nearest-Neighbor Distances	1 mm
Exposure Time	~1-2 seconds
Readout Time	~5 seconds
Computation time	1-2 seconds
Image Quality	Near diffraction-limited across the FoV

The absolute position measurement refers to precision with which a fiber spot image's intensity centroid measured on the FVC CCD in pixels is converted to equivalent units of microns in the focal plane. This requirement is satisfied by a combination of signal from the fiducial and metrology fibers (centroid precision to first order is the FWHM of the observed spot divided by the signal-to-noise ratio) and the scale factor of the imaging optics and CCD pixel pitch of the FVC camera. The image quality and nearest-neighbor specification is part of the CCD and re-imaging optics optimization. Both provide the main requirements driving the optical design and camera choice presented in the metrology document.

Exposure, readout, and computation times are related to FVC system efficiency – how fast it takes to make the measurements needed by a metrology iteration. Readout time is basically set to the best we can expect from available cameras, and the camera chosen (FLI ML50100) has been demonstrated to readout in 5 seconds (end of exposure to FITS file written completely to the local disk) in lab tests at OSU. Exposure time is a loose requirement, as we can push as much light through the system as we want to keep exposure times short, but it does set a requirement on the shutter speed which is readily met by all commercial camera shutters.

Finally, the compute time specification is based on known algorithms for object finding, centroid measurement, and fitting coordinate transformations. In practice this will be achieved by tuning up the system based on ZEMAX models with the as-built optics and by making more time-consuming measurements to calibrate the FVC system at the telescope than would be used during observing that will give us a set of robust priors to speed convergence of coordinate transformation fitting (once we measure nominal linear and high-order distortion terms, we can start closer the answer).

3.4 Fiber Positioner Distribution in the Focal Plane

The design requirements for the distribution of fibers across the focal plane are set by the following facts about the system:

- Each BOSS spectrograph can accept a maximum of 500 120 μm fibers along its slit. This limits us to 500 total robots to cover the field of view because there will be one BOSS spectrograph at each telescope.
- Each APOGEE spectrograph can accept a maximum of 300 120 μm fibers into its vacuum enclosure. This means while every robot can carry an APOGEE slit, only 300 of the 500 may be connected to APOGEE at any given time.
- Robots must cover the nominal 650 mm diameter telescope FoV with minimal gaps. This is best done with a regular hexagonal tiling.
- The survey teams want to have the same area per field for APOGEE and BOSS targets, requiring us to distribute the 300 APOGEE fibers among the 500 robots to maximize common coverage of the FoV by BOSS and APOGEE with minimal gaps.

- The survey teams also want to use as many of the 200 BOSS-only robots to be able to observe targets with BOSS targets when pointing at a field with mostly APOGEE targets (e.g., in the Galactic plane). This means the distribution of the 200 BOSS-only robots should endeavor to cover as much of the common FoV as possible, but the smaller number of such robots means we might have to accept more gaps in field coverage.
- Good fiber positioning metrology requires distributing the fiber-illuminated fiducials over the FoV with good radial/azimuthal sampling of the focal plane to allow for robust coordinate transformations that "fit out" optical distortions arising from the telescope and FVC optics. Fiducials outside the positioner array boundary have looser constraints and may be deployed as needed

A fiber positioner configuration satisfying these requirements is a filled hexagonal array which alternates between 2-fiber BOSS+APOGEE positioners and 1-fiber BOSS-only positioners every other concentric hexagonal ring of a 27-element wide hexagonal array, as shown in Figure 3

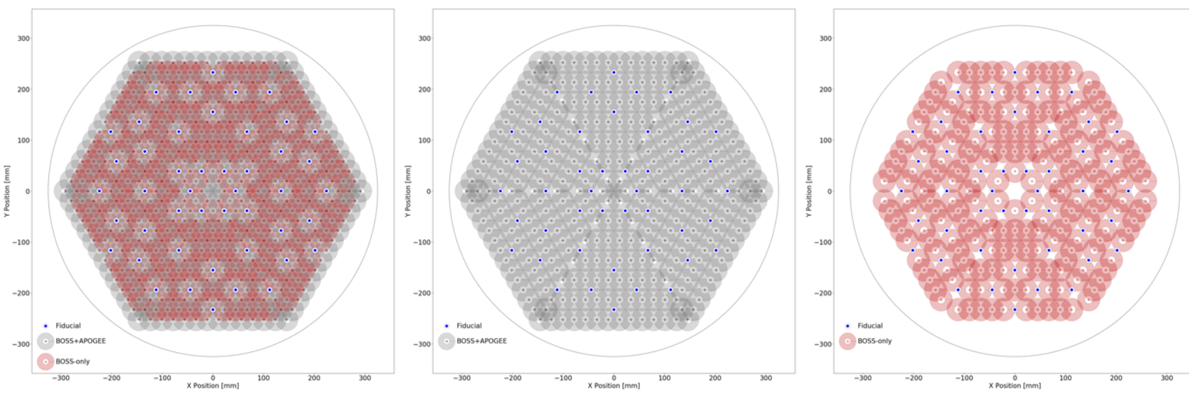

Figure 3: Arrangement of 500 positioners: 500 BOSS and 300 APOGEE fibers to cover as much of the same field of view as possible. Left: full 500 positioner array, same color scheme as Figure 2; Center: the 300 BOSS+APOGEE positioners; Right: the 200 BOSS-only positioners.

3.5 Guiding and Focus

Observing reports and telemetry gathered from the coherent fiber bundle guider systems deployed at both telescopes for the previous SDSS surveys demonstrated that when seeing is steady, neither telescope can guide to better than 0.1 arcsec, limited by the response of the telescopes to guide correction commands. While they routinely measure guide star centroids as good as 30 mas RMS in steady seeing, the telescopes cannot be guided to that precision. Guiding to within 0.1 arcsec corresponds to 5% ($1/20^{th}$) of a 120 μm fiber core diameter at Sloan, and ~$1/13^{th}$ of a 120 μm fiber core diameter at the du Pont.

For the GFAs, this means we need to be able to centroid stars to a level that the RMS guide correction computed for an ensemble of guide stars does not exceed 0.1 arcsec during conditions of nominal steady seeing. This sets requirements on the number and brightness of the guide stars. Because many SDSS-V target fields, especially for the Blackhole Mapper survey, are at high galactic latitude, as large a field of view as we can get is indicated, but we are ultimately limited by trade-offs between camera physical size and available detector formats.

The Sloan telescope is an alt-az design and so must also be guided in rotation. This sets a requirement of at least 3 (and ideally more) guide stars widely separated in angle to measure and compute rotator corrections. Rotator correction performance is anecdotally similar in steady seeing guiding performance (~0.1 arcsec) but can be worse nearer the zenith where the rotator must move faster and experiences larger accelerations. By contrast, the du Pont is an equatorial telescope and presents no requirement for guiding in rotation. However, because there was a measure of rotational flexure in the du Pont cartridge mounting system, the previous SDSS guiding system did provide for active rotation corrections on this telescope.

Archival telemetry data also establishes how well focus can be maintained by the current focus monitoring system used at both telescopes (pairs of fiber bundles stepped in focus to produce intra- and extra-focal images that are measured differentially to track and correct changes in focus). Numbers quoted by the SDSS-IV team are ±130 μm for Sloan and

±200 μm for the du Pont telescopes for minimal throughput loss (these are consistent with order-of-magnitude seeing-limited depth-of-focus estimates at visible light for f/5 and f/7.5 telescopes, respectively).

Finally, because we have a direct fiber viewing metrology system, we do not need to "guide in scale" at either telescope using stars. This was done in the current system because the aluminum plug plates were machined at room temperature and then deployed at whatever temperatures prevailed on the night of observing and there had to be a way to compensate for differential thermal expansion between the design and actual temperature. The FPS system's fiber viewing system allows measurement of this "change in scale" as a fit parameter, and so is compensated for at the time of fiber array configuration when going to a new field. Archival data shows that "guiding in scale" to account for changes in differential expansion in real-time used in the previous SDSS system was in fact very small, and for the shorter visit times (~15 minutes) for the rapid-cadence SDSS-V surveys, this is not a requirement of the system.

3.6 Mass, Envelope, and Handling

The mass of the FPS unit must not exceed 400 kg, defined by the mass limits on mounting the FPS using 3 of the current latches (300 lbs per latch times 3 latches is 900 lbs ≈ 400 kg). This weight is also within the operating limits of both telescopes for balance and moment. The current FPS system final design comes in at just under 300 kg, so we are well within that mass limit.

Finally, the FPS and all its auxiliary equipment must fit within the available space envelope and be balanced for rotation. It should be encapsulated in a thermal enclosure and use glycol coolant circulation to remove waste heat. The enclosure should be light-tight, and while it does not need to be sealed, it should limit exposure to the elements and minimize infiltration by dust, debris, and (at APO) miller moths (*Euxoa auxiliaris*)[1]. This envelope presented considerable design challenges, and it will come as no surprise that design of the cover system for the fiber patch panels was the last component of the FPS to be designed and in many ways the most difficult to get right.

Handling carts for the FPS units are based on the designs of the systems used at both observatories, though without the rapid-change requirement of the plug-plate systems.

4. FPS BASELINE CONFIGURATION

4.1 Fiber Positioner Robots

The FPS will use robotic positioners derived from a design originally developed for the ESO-MOONS spectrograph by the EPFL AstroRobotics Group. In the past year, EPFL produced in-house two series of prototypes positioners, P0 and P1, which were used by the EPFL, UW, and OSU teams to develop the FPS design. These robots are described in papers by Araujo et al.[12] and Grossen et al.[13] in these proceedings. A first-article pre-production robotic fiber positioner is shown in Figure 4.

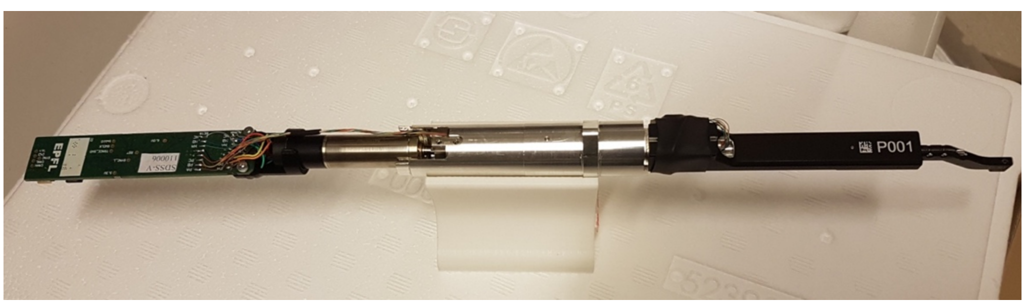

Figure 4: First-article fiber positioner robot fabricated by MPS Faulhaber in the AstroRobotics lab at EPFL.

After completion of the prototype series, the final the positioner design was issued in a public Call for Tender (CfT) issued in February 2019 to request bids to fabricate 1200 positioners: 500 plus 100 spares for each FPS unit. The contract for the fiber positioners was awarded to MPS Faulhaber in Biel, Switzerland. After production and acceptance testing of pre-series robots produced by MPS, full-rate production of robots began in early 2020. Production was

[1] Among those of us who work at observatories in the American Southwest opinion is divided as to whether trying to stop Miller moths from getting into places where we don't want them to go qualifies as a quixotic or Sisyphean task.

interrupted by the global COVID-19 pandemic but resumed in mid-2020 and all robots are expected to be delivered by December 2020. As of this writing OSU has taken delivery of about half of the 1200 production series robots and is about to start integration of the positioners with their optical fiber assemblies. Figure 5 shows production series ("flight") robots being prepared for fiber assembly integration in the labs at OSU at the time of this writing.

Figure 5: Production fiber positioner robots being prepared for optical fiber assembly integration at OSU.

4.2 Optical Fiber Assemblies (OFAs)

For the APO FPS unit, we will use 120 μm core fibers for BOSS and APOGEE-N same as are currently used by SDSS-IV. For the BOSS spectrograph remaining at APO, we will replicate the current fiber slit-head unit familiar from the plug-plate and cartridge system. For APOGEE-N we will replicate the current gang connector. We have no need to make new long fiber runs for APOGEE and will be able to be plug-and-play compatible with both systems.

For the LCO-FPS unit, we will retain the 120 μm fibers used for APOGEE-S and use the exiting gang connector for plug-and-play compatibility with APOGEE. We explored of using 180-to-120 μm core fiber tapers for the BOSS fiber runs at the du Pont, including testing production prototypes, and though a promising technology current-generation fiber tapers did not meet our specifications. See Tuttle et al.[15] (these proceedings) for the fiber taper study results.

Octagonal fibers have been adopted for APOGEE to provide a greater degree of internal scrambling and output beam uniformity to improve calibration stability and radial velocity precision for the SDSS-V surveys. The most logical location for these octagonal fibers is in the tributary fibers that runs between the patch panels with the round fibers from the robots and the female MTP gang connector that mates with the long round-fiber run into the APOGEE spectrograph.

Because of the requirement to be able to remove and replace defective robot assemblies (positioner+fiber), we have adopted fiber connectorization using ST connectors, which are well known to work for this application with minimal connector losses. Patch panels built into the FPS octagonal bases provide the transition between the fiber "robotails" mounted in the positioner robots to the fiber "tributaries" that carry science light to the BOSS and APOGEE spectrograph feeds, as well as carrying back-illumination light from on-board integrating sphere illuminators into the robot metrology fibers and fiber-illuminated fiducials used by the FVC positioner fine-metrology system. Working out the routing of the nearly 1600 fibers inside and outside of the FPS units give the very tight physical volume constraints was the most challenging design tasks faced by this instrument.

4.3 Fiber Positioner Ferrules

Each robotic fiber positioner carries three optical fibers: one BOSS, one APOGEE, and one metrology. These are mounted together in a single ferrule that is installed at the end of the positioner's beta arm. The advantages of the 3-fiber ferrule configuration are a significant reduction in the number of parts associated with the fiber assemblies, a reduction in size of the beta arm to make it possible to get positioner tips closer together without collision, and improved fiber-fiber position precision. The minimum required spacing between the science fibers is set by the requirement that light from the point-spread function wings of a bright star centered on one spectrograph's science fiber not spill over into the unused science fiber going to the other spectrograph. Accounting for typical site seeing and photometric constraints supplied by the MWM survey team resulted in a spacing of 748 μm center-to-center, corresponding to ~4.7 arcsec on the Sloan Telescope and ~8.2 arcsec on the du Pont telescope.

We explored two ferrule designs. The first design was a 3-fiber "snowflake ferrule" machined in stainless steel using wire EDM. A prototype snowflake ferrule is shown in Figure 6.

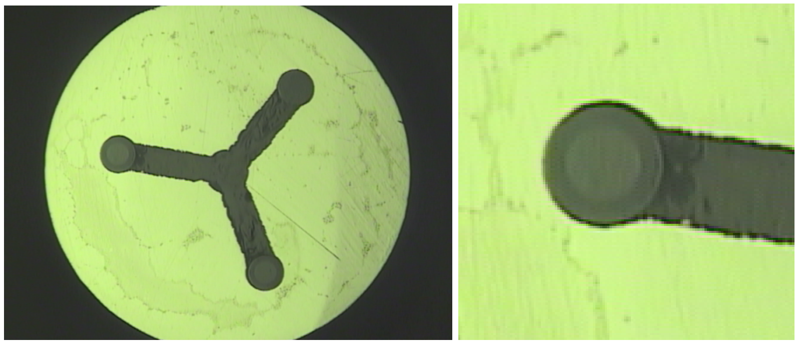

Figure 6: Left: prototype snowflake ferrule fabricated using wire EDM in the UW physics machine shop. Right: microscope image showing a mounted 120 μm fiber.

The snowflake ferrule is a 2-piece design consisting of a 10 mm-long snowflake section with exterior facets cut to match rotational keying features in the beta arm mounting hole, and a cylindrical coupler that press-fits over the base of the snowflake section to provide strain relief for fibers exiting the ferrule. The first series of robotail assemblies using the snowflake ferrules only yielded 25% with acceptable FRD measured using ring testing[16,17]; the rest failed with one or more fibers showing broad and highly structured test rings and large dispersion in ring radii and widths. The problem was isolated to the snowflake body with two probable sources: point stresses on the fibers from small EDM fabrication defects in the fiber channels, and a tendency for the optical fibers to be drawn radially towards the "arms" between the fiber channels as the epoxy cured, pressing the fibers against corners at the fiber channel/arm transition.

An alternative design proposed by FiberTech Optica reuses the already machined snowflake ferrules bodies, drilling out the snowflake features but keeping the crucial external keying facets. The three fibers are then encapsulated in drawn glass capillaries that provide the desired geometric spacing between fiber cores when bonded together and protect the fibers from stresses during mounting in the ferrule. This fiber-in-glass capillary assembly is then bonded into the bored-out snowflake section, clocked into the desired orientation relative to the external mounting facets, and then polished down to produce the fiber assembly. The output sides of the fibers are terminated with ST connectors. A microscope image of one of these fiber-in-glass ferrules from the first pilot series is shown in Figure 7.

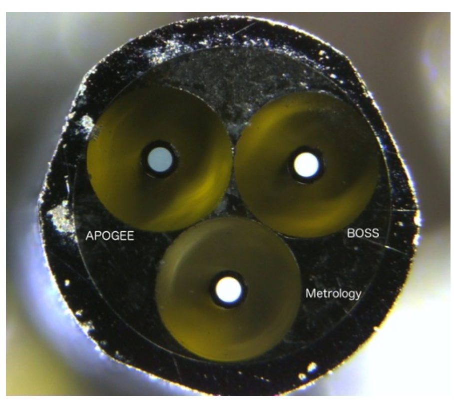

Figure 7: Fiber-in-glass capillary ferrule with the three fiber cores labeled.

This second design has consistently produced a high yield of assemblies with acceptable FRD tests for all fibers with small scatter and high repeatability. The fiber-in-glass capillary ferrules have been adopted for use in the FPS and we are about to begin full-scale production at this writing.

4.4 Guide/Focus/Acquisition (GFA) Cameras

The FPS carries six (6) Guide, Focus, and Acquisition (GFA) cameras mounted around the periphery of the positioner array (see Figure 1 right and Figure 2). The imaging camera we adopted is the Finger Lakes Instrumentation MicroLine ML4240 liquid cooled CCD camera. These use the e2v CCD42-40 2K×2K pixel sensor with a 13.5 µm pixel pitch back-side illuminated CCD with the e2V mid-band coating. The cameras are thermoelectrically cooled up to 50°C below ambient and equipped with the FLI liquid cooling package. A GFA camera in its custom mount is shown in Figure 8 with a prototype filter cell and flight Gen-2 SDSS r-band filter installed. The CCD is behind a 45 mm shutter.

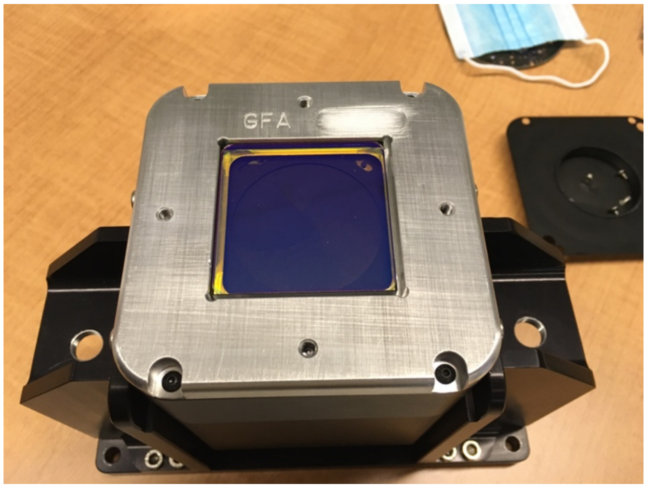

Figure 8: Guide/Focus/Acquisition (GFA) camera in its mount with a prototype filter cell and filter.

The pixel scales and fields of view of each GFA camera at the two telescopes are as follows:

Sloan 2.5m f/5: 0.2214 arcsec/pixel, FoV=7.558 arcmin

du Pont 2.5m f/7.5: 0.1476 arcsec/pixel, FoV=5.038 arcmin

The pixel size is small, so in nominal site seeing conditions we will likely operate them binned 2×2 pixels.

Each camera is equipped with a Gen-2 SDSS r band filters fabricated by Asahi Spectra Ltd., and mounted in a cell that replaces the stock front plate ahead of the 45 mm round shutters. Four (4) of the cameras, mounted at the 2-, 4-, 8-, and 10-o'clock positions around the array (Figure 2) are used for acquisition and guiding image and equipped with 5 mm thick SDSS r filters. The two (2) cameras mounted at the 12- and 6-o'clock positions are equipped with 4- and 6 mm thick filters, respectively to produce intra- and extra-focal images of stars used to monitor telescope focus (and they may also be called into service to provide additional guide correction references in sparse high-latitude fields). Each camera is operated by a dedicated small form-factor NUC computer running Linux and software written by the SDSS-V project.

4.5 Fiber-Illuminated Fiducials (FIFs)

The FIF assemblies produce an array of "artificial star" point light sources distributed throughout the FPS focal plane, providing a 2-dimensional fixed metrology reference frame when viewed by the Fiber View Camera (FVC) against which to measure the positions of the back-illuminated metrology fibers carried by all the robotic fiber positioners.

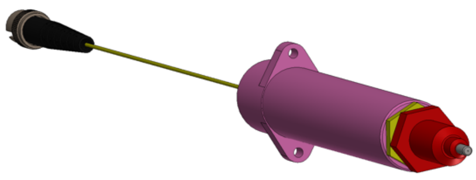

Figure 9: Fiber-Illuminated Fiducial model

Because the fiducials are being measured in the same way as the positioner metrology fibers, we opted to also use the same metrology fiber (the same Polymicro FBP120170190 120 µm core as the BOSS and Metrology fibers in the positioners), so we are measuring the FIF and positioner "spots" in the same way with the FVC system. A model of one of the FIFs units shown in Figure 9.

The FIF mounting interface to the FPS is identical to the robot interface, and we have the same requirement to place the output face of the fiber at the same 143.1 mm base-to-top offset from curved mounting plate to position the output aperture in the telescope focal plane. The design incorporates an adjustable focus feature to achieve this requirement.

The FIF assemblies have an outside diameter of 3 mm at the tips which in the zone swept the heads of the fiber positioner robots. The FIFs present a fixed obstacle for the robots, and their positions will be precisely measured using a coordinate measuring machine in the installed system so that datum is available to the path planning and collision avoidance software. The FIF fiber tilt relative to the telescope beam must be less than 0.3°, the same tilt requirement as applied to the positioner science and metrology fibers. Finally, the fivers are terminated with ST connectors and landed on the same patch panel and illuminated with the same fiber back-lighting system as the positioner metrology fibers.

The FIF fiber assemblies are being fabricated by FiberTech Optica and are being integrated in the OSU lab with FIF bodies fabricated by Southwestern Machining at this writing.

4.6 FPS Mechanical Structure & Thermal Enclosure

The FPS body consists of three structural components, shown in Figure 10.

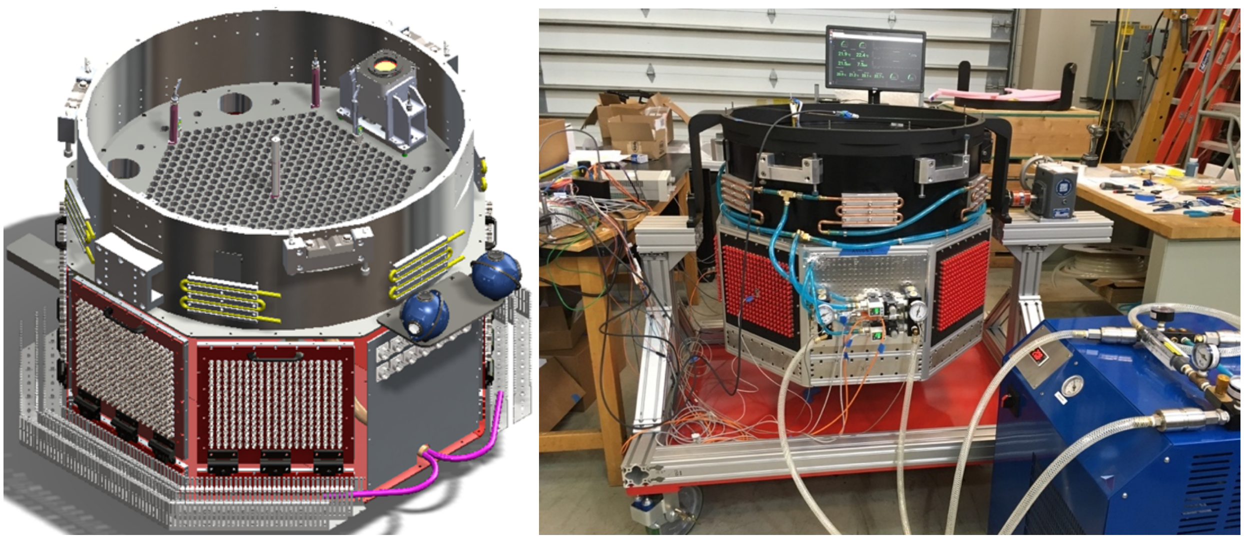

Figure 10: Left: Solidworks model of an FPS unit showing the main structural components and FBI integrating spheres (blue), but omitting the BOSS slit head, fibers, the cooling system manifold, and external plumbing. Right: photo of an FPS unit without robots or GFA cameras installed during thermal system testing in the OSU Lab in November 2020.

- The **Wok** is the large circular plate that carries the fiber positioners, fiducials, and GFA cameras. The center portion of the Wok is drilled with 547 holes in a hexagonal array to mount fiber positioners and fiducials, and there are features for mounting 6 GFA cameras at the outer edge of the Wok, along with additional fiducial holes are spaced every 15° degrees between the GFA positions at the same radius as the nominal centers of the GFA camera detectors. The Wok is 50 mm thick and made of 6061 aluminum. The curved shape of the Wok had to be machined to have a slightly aspheric surface, different for each telescope, that required a surface figure with an overall precision of 20 μm RMS to meet our fiber focus tolerances, and the mounting holes for the robots had to be very precisely perpendicular to the local curved surface to meet our tilt requirements. This made the Woks very challenging to design and fabricate, but the final parts fabricated by Tapemation have exceeded our specifications.

- The **Latch Ring** is a thick 6061 aluminum ring that carries three (3) latch assemblies equally spaced around its perimeter at 120° intervals. This is the upper body of the FPS and looks like the top cylinder of the old plug-plate cartridges. The latch rings are identical to the cartridge latches currently used at the Sloan and du Pont telescopes. The Latch Ring is the structural support for the Wok, which is bolted to an internal shoulder in the inside diameter of the Latch Ring. A cover fits over the top of the Latch Ring when the unit is off the telescope. The Latch Ring will also carry the cold plates for the liquid glycol cooling system (described below).

- The **Octagonal Base Assembly** serves as a protective structure for the fiber positioners and the fiber optic cables and is the fiber and electrical cable management volume. The Latch Ring Assembly is attached to the Octagonal Base. Removable panels on 6 sides as well as the bottom provides access to the space behind the Wok. Six of the panels carry the ST fiber connectors for the science and metrology fibers running to the 500 fiber positioner robots, one panel carries the BOSS slit head assembly, and the final panel carries the electrical connection panel, the cooling system manifold. A female APOGEE fiber gang connector (same as on the current plug-plate cartridges) is mounted at bottom dead-center of the octagonal base which mates with the long APOGEE Science fiber bundle that carries science light from IR fibers on the robots to the APOGEE spectrographs. The base is strong enough to support the entire weight of the FPS when sitting on a telescope installation lift.

The presence of the 500 robotic fiber positioners and 6 GFA cameras inside the FPS proper constitutes a significant source of internal heat that must be removed from the system. The 6 GFA cameras are thermoelectrically-cooled and can dissipate up to 50 watts per camera when running at maximum cooling (though we will operate at about 30 watts per camera). The onboard drive electronics for the robots (500 printed circuit boards) must be powered on at all time to maintain the positioning requirements (idle current to prevent cogging torque on motor power-up) which dissipates 0.4 watts per positioner, for a total steady-state power of 200 watts for the full 500-robot array. When running at maximum speed to configure, they dissipate an additional 0.1 watts per positioner, increasing total power to 250 watts. The combination of the robots and GFA cameras requires we remove about 530 watts from the system.

The FPS has two separate glycol cooling loops, one external for the FPS that uses six glycol/metal “cold plates” bolted to the exterior circumference of the Latch Ring. These cold plates remove heat from the Latch Ring and maintain the massive aluminum of the Latch Ring and Wok at a nearly constant temperature which is maintained near ambient air temperature. The robots and PCBs heat the air inside the FPS. The heat in the air is then coupled to the Latch Ring and Wok metal using circulation fans to enhance convection. This heat is then conducted through the metal to the circulating glycol in the cold plates. A second interior loop circulates glycol coolant through the six GFA cameras, each of which is equipped with a factory-installed internal heat exchanger tied to the hot side of their internal multi-stage Peltier-type thermoelectric coolers. Lab tests at OSU with the thermal test system shown in Figure 10 (right) demonstrated the ability of this exterior cold-plate configuration to meet our cooling requirements under simulated heat loads that met or exceed the expected maximum power of the interior components of the FPS.

A concern with allowing water/glycol coolant inside the FPS is the potential to expose the robotic fiber positioners to glycol in the event of a coolant leak. At risk are the motor/gearboxes on the positioners and the printed circuit boards carrying the serial communications and motor drive electronics. The motors and gearboxes are sealed, and the printed circuit boards are coated with Kontakt Chemie URETHAN 71.

To determine the effect of exposure to glycol, we tested production series printed circuit boards and fully assembled positioner robots (without optical fibers installed) by immersing them, powered and unpowered, in a 67/33 water/glycol bath. An example of one of the positioner “drowning” tests is shown in Figure 11. However scary this test looks (and it was very scary), after wiping down the positioner and allow it to air dry for 24 hours at room temperature, the positioner ran and passed all performance tests as before. We note that circuit boards without the URETHAN 71 coating failed immediately upon immersion if powered on, but every coated board tested survived repeated immersion while powered up. If a glycol leak ever occurs it will be messy but not catastrophic.

Figure 11. Fully powered-on robotic fiber positioner drowning in water/glycol coolant.

In addition to the FPS proper, we also need to remove about 200 watts from the outboard FPS instrument electronics box (IEB), and about 250 watts from the BOSS spectrograph electronics. The combined FPS+BOSS system dissipates about 1 kilowatt at maximum. The overall cooling system required at the back end of each telescopes is comprised of four separate cooling loops: the two loops described above plus separate loops for the IEB and BOSS spectrographs, respectively. These loops will be mounted on the instrument rotators and connected to the main supply and return lines from the observatory liquid cooling systems. Both observatory sites are updating their telescope cooling systems to accommodate this increased power load to ensure that we do not contaminate the observatory environments with the waste heat from the FPS+BOSS systems.

4.7 Fiber Viewing Camera (FVC) & Fiber Position Metrology

To align the science fibers with targets on the sky, we have adopted a direct fiber viewing strategy inspired by that used by DESI[18]. DESI uses a camera looking up from inside the 4-m primary mirror Cassegrain hole through the DESI corrector lenses at a "star field" composed of their 5000 science fibers back-illuminated by shutter-mounted LED strips inside each DESI spectrograph. Software measures the fiber positions relative to illuminated pinhole fiducials interspersed among the robots and applies small offsets to align them with their targets. This view-then-iterate method is required because there are no suitable small absolute encoder solutions with sufficient precision given the small robots.

For the FPS, we cannot look down into the Cassegrain focal plane in any practical way that we could find, so instead our variation on the DESI FVC uses a periscope system in which a steerable pickoff mirror is suspended looking down on the primary mirror from above using the telescope optics in reverse (light coming from the focal plane instead of to it) as part of the re-imaging optics. The optical design of the FVC for the Sloan Telescope is shown in Figure 12 and for the du Pont telescope in Figure 13. We use Finger Lakes Instrumentation ML50100 8×6k CCDs for the imaging cameras.

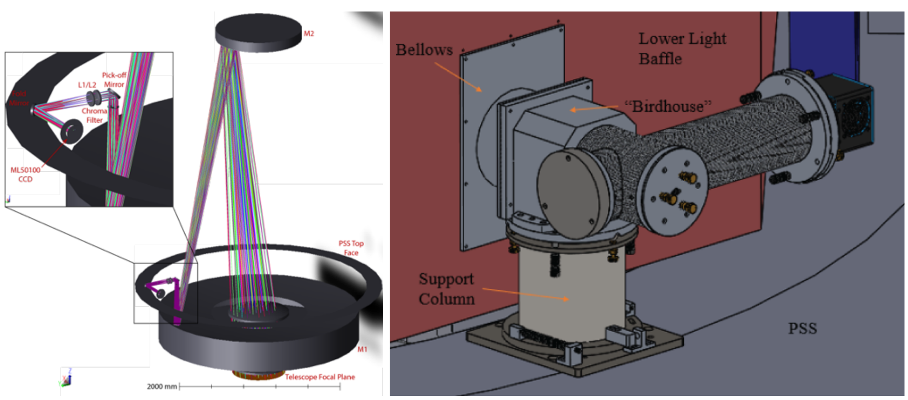

Figure 12: Sloan Telescope FVC system. Left: optical path, Right: camera optomechanical system rendering.

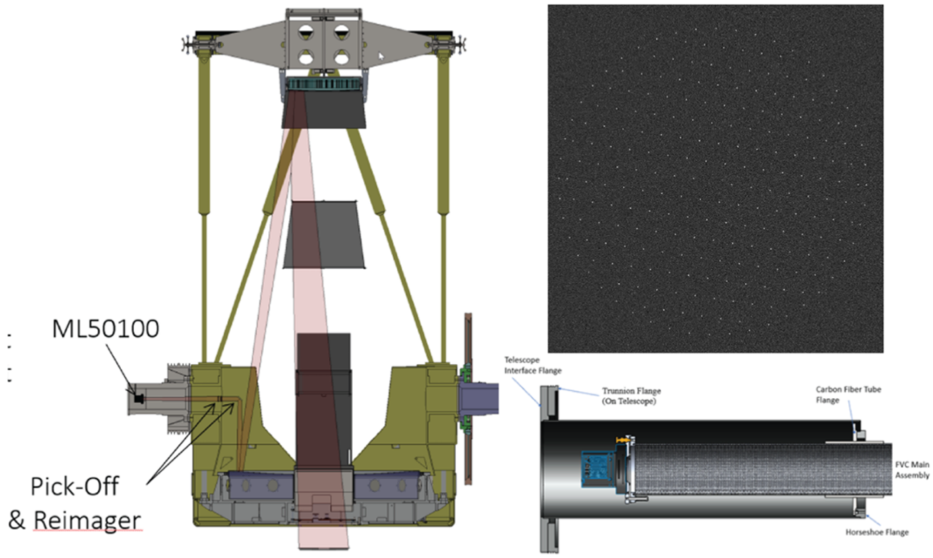

Figure 13: du Pont Telescope FVC system. Counterclockwise from left: optical path, optomechanical system rendering, spot images acquired with the FVC of a back-illuminated APOGEE test plug plate during the January 2020 engineering run.

For the FPS, we use a system of fixed FIFs and back-illuminated metrology fibers mounted on each robot that are imaged with the FVC. The use of stand-alone metrology fibers was dictated by the need to avoid potentially risky modifications to BOSS to incorporate a science fiber back-illumination system, and there was no way to incorporate a fiber back-illuminator into APOGEE. The FPS units carry integrated Fiber Back Illumination (FBI) systems to control illumination of the metrology and FIF fibers through the IEBs. The FBIs use commercial LabSphere integrating spheres and custom fiber assemblies connectorized to the Metrology/FIF patch panels.

We constructed optomechanical models of the du Pont and Sloan telescopes that combined the mechanical structures (mounting structures and baffles) with the optics of the telescope and our FVC optics to determine if the FVC systems would have an unobstructed view of the telescope focal plane. For du Pont telescope, there is significant vignetting at the field edges from the elements of the existing baffling system[4]. We have therefore designed a new baffle set for the du Pont that ensures an unvignetted view of the telescope focal plane. These are being fabricated by the Carnegie Observatory shops and will be installed on the du Pont telescope prior to the installation of the southern FPS unit. We found that the existing Sloan telescope baffling system can be used without modification.

4.8 Instrument Electronics Box (IEB)

The instrument electronics box (IEB) is mounted on the rotator near the FPS to provide for all power, ethernet, and point-of-use command and control interfaces for the positioners, fiducials, and cameras in the FPS. Features of the IEB are:

- Provides a single point of connection between observatory services (AC power and fiber ethernet) and the FPS to simplify connection and disconnection for servicing.
- Provides command & control, service distribution, and environmental monitoring functions for all FPS internal subsystems.
- Housed in a standard environmental enclosure with a removable cover for serviceability on-telescope.
- Uses industry-standard components and automation for control and environmental monitoring functions.

The IEB design represents a continuing evolution of IEB units for instruments built by OSU for a number of observatory sites over the past 15 years. These boxes have been very robust, serviceable, and designed with personnel and equipment safety as well as service ergonomics in mind. The power supplies for the 500-positioner array drives, the six GFA cameras and their computers, plus FPS sensor readout and power-controls, contribute about 200W of internal power dissipated inside the box, requiring cooling using internal Lytron heat exchangers connected to observatory-provided liquid glycol coolant to remove waste heat. The boxes will be standard NEMA enclosures, sized to fit the available space at the telescopes, and include personnel safety features and handling fixtures. Total mass is about 80 kg, and so they will be mounted opposite the BOSS spectrographs next to the FPS units, constituting part of the counterweighting needed for those spectrographs. The layout of the FPS IEBs is the same for both sites, but they will be mounted at different orientations (bottom- vs. side-mounted) to suite the available spaces at the backs of each telescope.

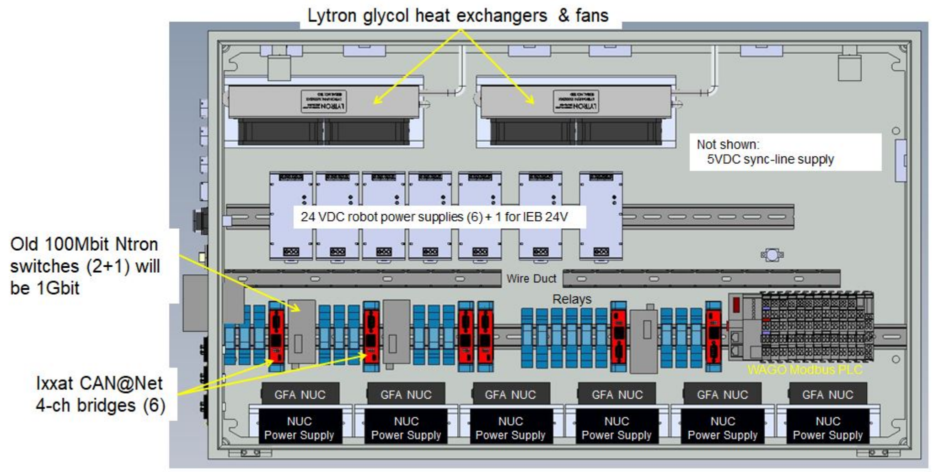

Figure 14. Diagram showing the layout of the instrument electronics box with wiring harnesses omitted for clarity.

We have already prototyped all sections of the IEB by constructing three (3) standalone "sextant controllers" that can control 1/6th of a full robot array including the 4-channel CANbus to ethernet bridge and WAGO Modbus/TCP control module that were deployed with the FPS teams at OSU, EPFL, and UW and used for robot testing, including quality testing of production robots at EPFL after delivery from MPS Faulhaber and robot collision avoidance software development by the UW team. The thermal monitoring system has been setup in a standalone breadboard configuration to evaluate all the sensors needed by the thermal management system (see Figure 10 right panel). This has put a lot of "mileage" on these critical IEB subsystem components under realistic use for over a year before assembly of the first full flight system for the first FPS unit.

5. PATH PLANNING AND COLLISION AVOIDANCE

The majority of current fiber positioner arrays (e.g., DESI, PFS) are designed such that a target in the focal plane is generally accessible to only a single positioner. In these instruments only a small amount positioner workspace overlap is required to obtain full focal plane coverage. The FPS is a densely packed fiber positioner layout with heavily overlapping workspaces; when fully extended, the beta arm of one robot embedded within the array can reach the center of the patrol field of all 6 surrounding robots. An astronomical target in the FPS focal plane will be generally accessible to 3 or 4 robots. This design is what allows the high fractional field coverage by 500 BOSS fibers and 300 APOGEE deployed on only 500 robots, increasing the options available to the survey planning software to assign targets to robots. This comes at a cost of greater risk of entanglement between positioners while moving between field configurations. This requires the FPS system be equipped with a strategy to solve for safe collision-free paths for all positioners when configuring the array for a target field. Various approaches to problems like these have been explored heavily in the distributed multi-agent robotics literature[19].

SDSS-V has developed the Kaiju software package[2] to implement collision avoidance algorithms that will enable safe FPS configuration transitions. The algorithms are described and analyzed in detail by Sayres et al.[20]. Figure 15 provides a high-level picture of the algorithmic strategy.

[2] https://github.com/sdss/kaiju

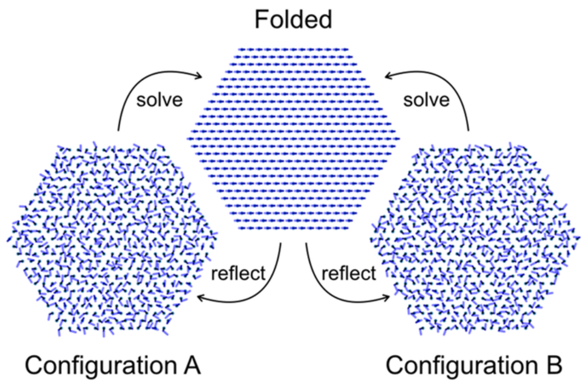

Figure 15. Positioner trajectories between configurations are solved in reverse, then the forward path is found by reversing the solved trajectory. Configuration transitions route through a common "folded" state.

The array is initialized to the desired configuration, then small perturbations are applied to each positioner such that the collective array is driven to a final "folded" lattice-like state. The forward path is then found by reversing the solved trajectory. As all paths are built between a desired configuration and common folded state, valid transitions between any two configurations are achieved. The routines compute paths in a matter of seconds, giving the FPS with the ability to perform real-time path generation. The duration of robot motion during reconfiguration is on the order of 30 seconds, comfortably within the readout time of a BOSS exposure, and able to help us satisfy our 3-minute reconfiguration time requirement. The efficiency of the routine is not perfect, but it is very high. We expect an average loss of less than one target per configuration due to collision avoidance constraints.

6. DEPLOYMENT

The first FPS unit will be deployed at the 2.5 m Sloan Telescope at Apache Point Observatory in Spring 2021. The second unit for the 2.5 m Irénée du Pont Telescope at Las Campanas Observatory in Summer 2021. Impacts on our schedule due to the global COVID-19 pandemic have been significant, limiting access to our laboratories during lockdowns, quarantined staff, delays with vendors also subject to lockdowns and quarantine, and interruptions of many of our usual supply chains. Projections of travel restrictions led us to change our original deployment plan from the du Pont to the Sloan telescopes, and we are making contingency planning to do remotely many tasks associated with training and instrument commissioning that we would normally do with site visits and larger teams.

7. ACKNOWLEDGEMENTS

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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.

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