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► **To cite this version:**

Pierre Antilogus, Éric Aubourg, Alexandre Boucaud, Patrick Breugnon, Julien Coridian, et al.. Design, assembly and validation of the Filter Exchange System of LSSTCam. SPIE Astronomical Telescopes + Instrumentation 2022, Jul 2022, Montréal, Canada. pp.121823A, 10.1117/12.2629336 . hal-03838583

**HAL Id: hal-03838583**

**<https://hal.science/hal-03838583v1>**

Submitted on 23 Mar 2023

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# Design, Assembly, and Validation of the Filter Exchange System of LSSTCam

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## ABSTRACT

The Filter Exchange System (FES) of the Legacy Survey of Space and Time camera (LSSTCam) for the Vera C. Rubin Observatory has been integrated into the camera assembly before shipping to Chile. It holds five 75-cm filters weighing 25.5 to 38 kg. The main requirement for the FES is to perform each exchange in under 90s, with 100- $\mu$ m positioning in the focal plane, while operating within the envelope of the camera body.

The FES is split into three motorized subsystems: the Carousel stores the filters and rotates the selected filter to the standby position, the Autochanger moves the filter between the standby position and the focal plane, and the Loader can be mounted on the camera body to swap filters in and out during daytime, allowing the use of the full 6-filter set of LSSTCam. The locking mechanisms are also motorized, and their designs and qualifications account for seisms up to magnitude 7. Additional design constraints come from the temperature range at the Observatory and the cleanliness requirements for the filters and lenses. Programmable Logic Controllers enforce the safety equations of the system, and the control of the FES has been integrated into the overall Camera Control System software.

After assembly of a full-scale prototype, the FES has been assembled and tested in France on a test-stand simulating telescope attitude, then integrated into the camera body at SLAC National Accelerator Laboratory. It meets its required performances, including an average exchange time of 83s.

**Keywords:** Vera C. Rubin Observatory, LSSTCam, filter, mechatronics

## 1. INTRODUCTION

The Vera C. Rubin Observatory will carry out a 10-year survey of the Southern sky with its 3.2-Gpixel CCD camera LSSTCam [1]. During the survey, data will be taken with six different filters, in the bands *ugrizy*. With its 70 cm diameter focal plane, LSSTCam is currently the largest camera in the world. The optics of the camera are also record-breaking, with a 1.55 m diameter front lens (L1). When in use, the filter will be placed between the L1-L2 lens assembly and the shutter. This sets their optical diameter to 75 cm, and adding an aluminum support frame brings their outside diameter to a maximum of 84 cm. Due to the different optical substrates and their varying thicknesses, individual filters weigh between 25.5 and 38 kg.

The telescope for the Rubin Observatory has a compact three-mirror design [1] with the camera set inside the M2 mirror, pointing down towards the M1-M3 combined mirrors. The envelope of the camera body is therefore highly constrained by the optical design. With regard to the filters, since the survey requires observations in several bands each night, this means that they have to be stored within that envelope, and there must be a fully automated system to bring them in and

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out of the focal plane position. The volume between the inner camera cryostat and the outside camera body is so constrained that the full complement of six filters cannot fit, and only five filters will be available at a given time. The Filter Exchange System (FES) must therefore include a system to swap filters in and out of the camera during daytime, to allow the use of the sixth filter. In addition, to minimize lost survey time, the requirement for the FES is to perform a full exchange between any two filters in less than 90 s. This includes moving the current filter back to storage, selecting a new filter, and positioning it in front of the focal plane ('online') with a required repeatability of 100  $\mu\text{m}$ .

There are additional constraints on the mechanical design from the risks of seisms in Chile, the requirement being that the system should hold the filter in the event of a seism up to magnitude 7, while allowing for the replacement of some parts afterwards. Another constraint, that affects mostly the motors and sensors of the system, is that the temperature of operation for the system can go down to  $-5^{\circ}\text{C}$ . To preserve the required cleanliness of the filters and optics, the design of the mechanical systems must also avoid the production of contaminants within the inner volumes of the camera, and be entirely assembled in a clean room (ISO8 level).

This paper will begin with an overview of the component subsystems of the FES, from their mechanical design to their instrumentation and control. It will present some aspects of the integration into a full system. It will also summarize the development process that took it from the early subsystem designs, to a fully-operational system integrated into the camera body, ready for shipping to Chile.

## 2. SUBSYSTEMS

### 2.1 Overview

Two hardware subsystems are integrated into the Camera Body volume: the Carousel, which stores the filters on a mobile ring around the cryostat, and the Autochanger, which moves one filter from its socket on the Carousel ('Standby' position) to the 'Online' position in front of the L3 lens. The Autochanger can be dismantled from the camera, and a second unit will be available during the survey. The third hardware component of the FES is the Loader, which can be mounted either on top of the Camera Body while it is in horizontal position (see Fig. 3), or on top of the filter storage box, in order to transfer filters between the two. Two units will also be available at the summit.

Several interfaces have been designed to hold the filter and transfer it from one subsystem to the other. On each side of the filter frame (as seen for instance in Fig.1), a complex piece is attached: it holds a pin, a slit for the Autochanger carriage, a latch to lock that interface, plus a set of three magnets for sensor identification (with a unique combination identifying each filter), and an additional magnet to detect the filter in the Autochanger carriage. At the top of the filter (in Fig. 3, bottom on Fig. 1), lodgings are cut away on both sides of the filter frame at the outer edge, to house the two 'cleats' that interface with the Loader. On the opposite side, an indentation in the frame houses the interface with the Autochanger online clamp.

### 2.2 Autochanger

The first purpose of the Autochanger is to move a filter between the Online position, the Hand-off position for exchange with the Loader, which is slightly away from the Online position, and the Standby position, for exchange with the Carousel. The available volume constrains the arc that has to be followed during this movement. It has also constrained the design of the mechanical elements of the Autochanger, and the integration of all auxiliary elements into its frame. Two motors, operating in a master-slave setup, move the support beam of the carriage along two linear rails (seen at the top of the mechanical drawing in Fig. 1), while the path of the arms that hold the filter is guided by symmetrical curved rails. Sensors detect when the carriage is at any of the three predefined positions (Online, Hand-off, and Standby). During travel, the filter is linked to the mobile arms by two pins on each side, that enter the block fixed on the filter frame. The latches that lock the filter into place are operated by independent motors, and sensors detect the 'open' and 'closed' positions.

In the online position, the repeatability of the filter positioning is ensured first by the accuracy of the motor encoders, but also by the three 'online clamps'. On each side of the filter, the X+ and X- clamps operate similarly, with the rotation of a motor transmitted through articulated arms to hooks that grab on the filter pins. At the top of the filter (on the right in Fig. 1), the Y clamp holds the filter frame by applying pressure between points on each side. Only one side of the Y clamp is mobile, and closes on the filter frame when the clamp motor rotates. Motor encoders and sensors are both used to establish whether each clamp is open or closed. Once the clamps are closed, applying additional current on the motors puts them in the 'locked' state. At this point, the filter is ready for camera operations.

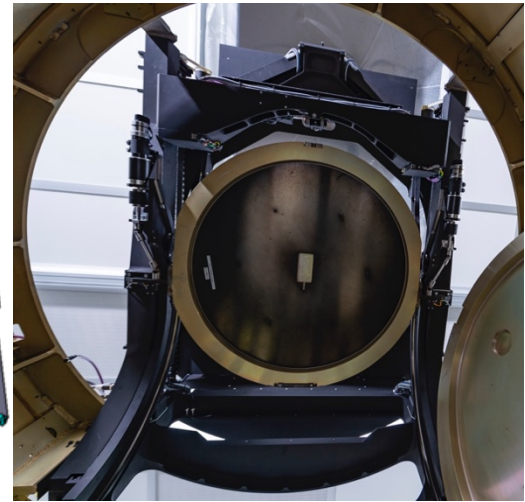
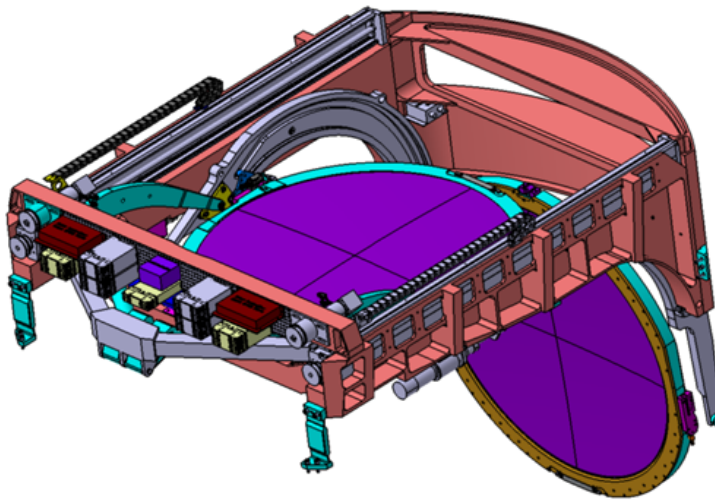


Figure 1. Left: mechanical drawing of the Autochanger. Right: Autochanger viewed from inside the fake camera body of the test-stand, with a fake filter in the hand-off position (photo credit: C. Frésillon, CNRS Photothèque). The arms of the online X+ and X- clamps are visible on each side, with the Y clamp at the top.

### 2.3 Carousel

The core of the Carousel is the rotating structure, which is assembled over an outer ring gear. Its movement is guided by a circular rail on the inner side of the fixed camera structure (the Back-flange). The rotation is powered by a motor, with three spring-operated brakes, all distributed around the gear ring. These, and other auxiliary elements are housed in outer bays of the Back-flange (Fig. 2), which created some size constraints when selecting them. The Carousel safety module, which could not fit, is housed in the Utility Trunk of the camera.

Each of the five filter sockets is bracketed by support posts, which are linked together by rods for rigidity, and on which are mounted clamp blocks. The X+ and X- clamps on each side of the filter have different designs, to hold the filter without overconstraint. Combined with the Z+ V-guide roll (see picture in Fig. 2), they must hold the filter and prevent movement along all axes. The filter pins, which are mounted on each side of the filter, are guided into position on approach by the chamfered rims of the clamps.

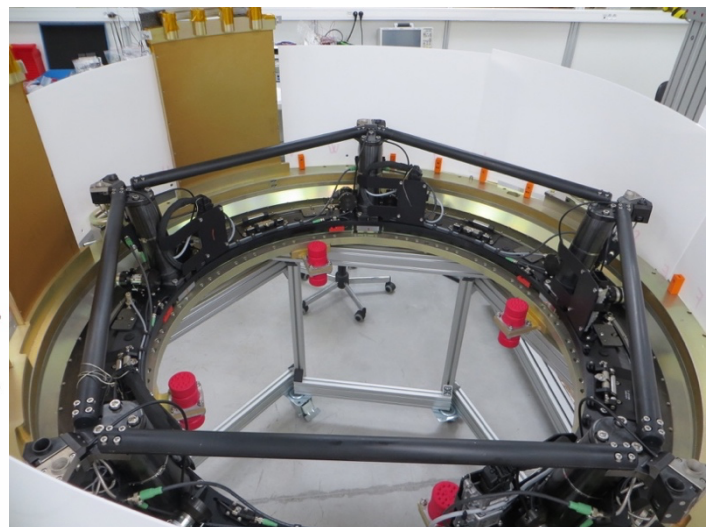
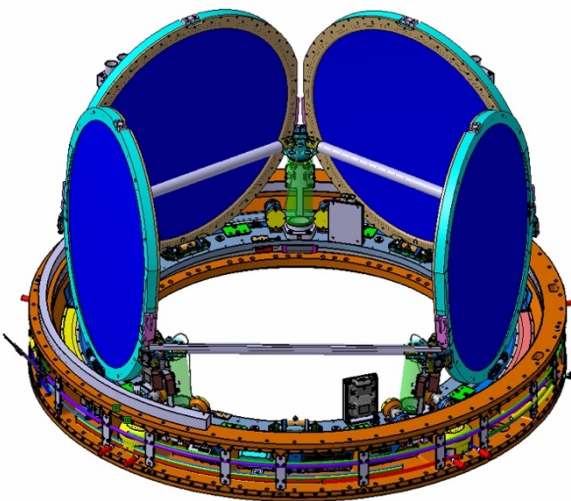


Figure 2. Left: mechanical drawing of the Carousel, loaded with four out five filters. It is integrated over the Back-flange structure (in orange). Right: picture of the empty Carousel, assembled on the final Back-flange. Each filter socket includes a filter clamp on each side, fixed to the posts of the 'pentagon' rod structure, a Z+ V-guide roll fixed in the middle at the bottom, and an I/O module for reading out the sensors.

Each clamp is instrumented with two Hall sensors, one that measures the depth of the filter pin inside the socket, one for the locked/unlocked status of the clamp. Each socket has also one contact switch sensor, which is only activated when the socket is at the Standby position, and one I/O module to read all sensors. Power and CAN bus communication for these sensor modules are transmitted to the rotating part of the Carousel through five slip ring tracks, with spring-loaded brushes to ensure contact in any orientation of the camera. The CAN bus is a dedicated Safety CAN bus, which communicates only with the Carousel safety PLC that is housed in the Utility Trunk, independently of the common CAN bus.

## 2.4 Loader

The Loader can store a single filter safely within its volume, to perform transfers between the filter storage box and the camera. It can be docked on a dedicated bench, a mobile cart, on top of the Autochanger, or on top of any slot in the filter storage box. The single axis of movement for the carriage is always vertical (Fig. 3), with rails on each side as guides. The carriage is curved to match the outer shape of the filter frame. Position sensors validate that the carriage is at either pre-defined positions, Hand-off for exchange with the Autochanger, or Storage. There is also a sensor on the Autochanger side, to detect whether the Loader is attached to the camera structure.

The cleats at the top of the filter frame on each side (in Fig. 3) are dedicated to the lifting by the Loader. Pairs of hooks, fixed at the center of the mobile carriage of the Loader, close on the cleats from the sides. To ensure that the filter is properly held, force sensors are mounted on each hook, and tuned with high sensitivity to detect anomalous behavior.

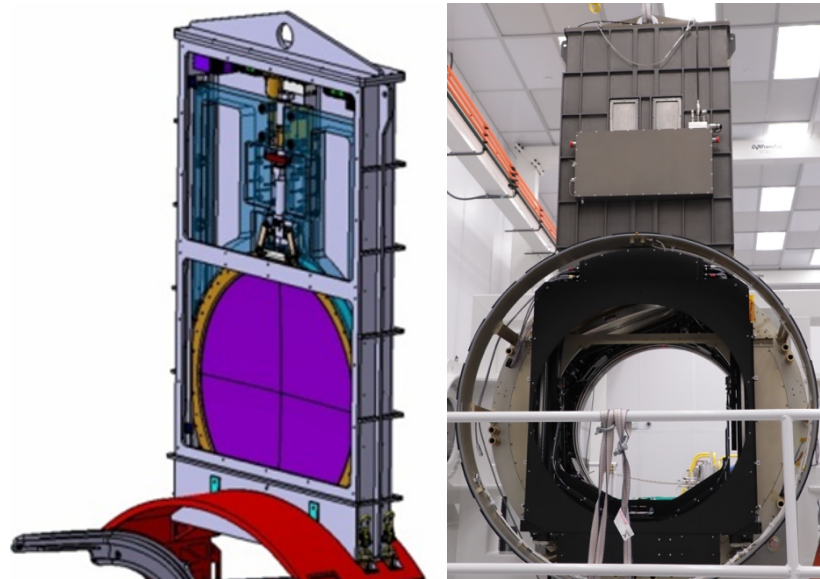


Figure 3. Left: Mechanical drawing showing the inside of the Loader, including the hooks holding the filter. Left: The Loader mounted on the Camera Body at SLAC, before integration of the focal plane cryostat.

## 2.5 Filter Control System

The Filter Control System is a software subsystem that is a fully integrated component of the control software of LSSTCam: the Camera Control System [2]. At the highest level, it can execute a full filter exchange from a single command. It also offers a graphical user interface (GUI, see Fig.4), which displays the state of the system to an observer, and a selection of high-level commands, in case manual control of the procedures becomes necessary. Lower-level commands are all accessible to qualified operators through an additional command interface.

The FCS communication with the FES subsystems relies entirely on two CAN networks, with one common network for the Carousel and Autochanger, and a separate network for the Loader (which can be either plugged in or entirely absent). Using the CANopen protocol, the FCS can query the Local Protection Modules (LPM) of the subsystems to read the subsystem statuses and sensor values. It also communicates directly with other sensor modules, and with the motor controllers which operate all components of the subsystems. In particular, managing the states of the controllers [3] is key to ensuring a smooth operation during the filter exchange.



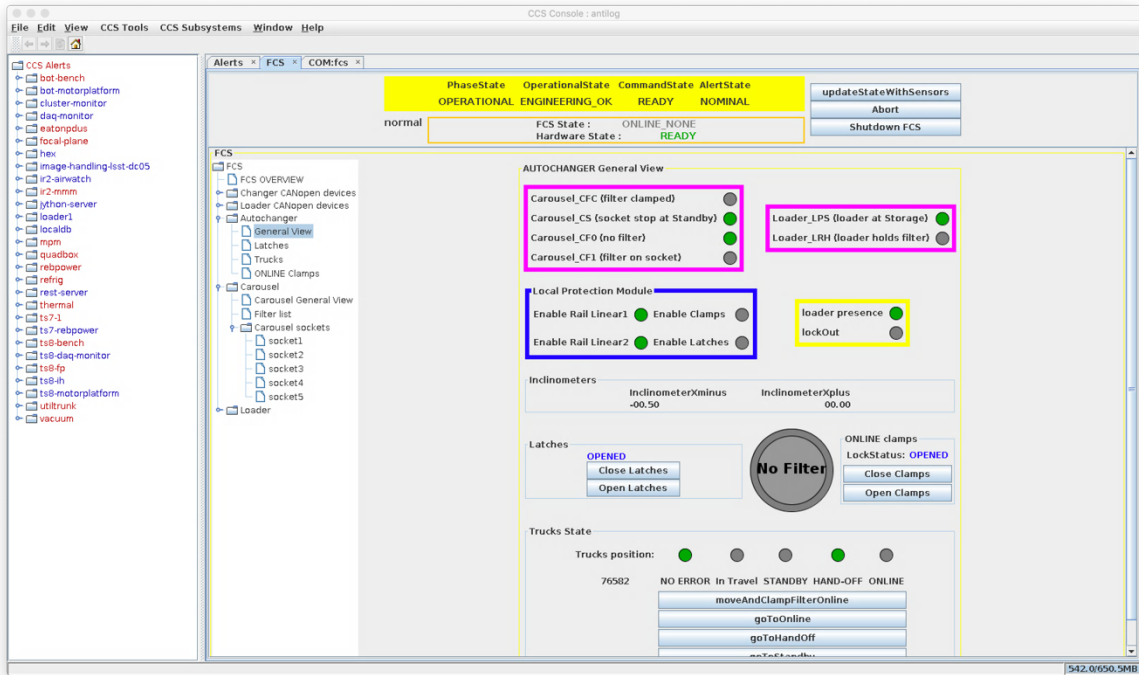


Figure 4. One view of the Filter Control System GUI. It displays inputs and outputs of the safety systems, sensor measurements, and top-level commands for the subsystem (here, the Autochanger).

With regards to hardware, the FCS only needs the two CAN buses and a network connection to the wider camera control system. It has been deployed both on a PC104 inside a dedicated crate, which has been used to test the whole system, and will be used to operate the Loader and Autochanger in standalone mode, and on the Hardware Control Unit (HCU), a PC104 located inside the Utility Trunk of the camera.

### 3. INTEGRATION

#### 3.1 Filter exchange operations

A full filter exchange operation is composed of the following steps:

1. Unlocking and opening the online clamps to release the current filter.
2. Moving the current filter from the online position to the standby position, into its socket. The speed profile is slow at the beginning of the movement, to check for anomalies, and at the end, when the filter pins enter the clamps on the Carousel. It is set to a higher speed while in travel, to save time.
3. Once the Carousel clamps on each side of the filter are closed, the Autochanger latches are unlocked and the carriage withdraws to Hand-off position, to avoid collision with the filters while the Carousel rotates (Fig. 5).
4. The Carousel rotates to put the socket that holds the desired filter in the Stand-by position.
5. The Autochanger carriage comes back to the Stand-by position, and the Autochanger latches are closed.
6. The Carousel clamps are opened, and maintained open while the Autochanger withdraws slightly, disengaging the filter pins from the Carousel clamps. The Carousel clamps are then released, ready to house the filter again when it is brought back.
7. The Autochanger carriage moves away from the Stand-by position, first at high speed, then slowly on approach to the Online position.
8. The three online clamps are closed, then locked on the filter.

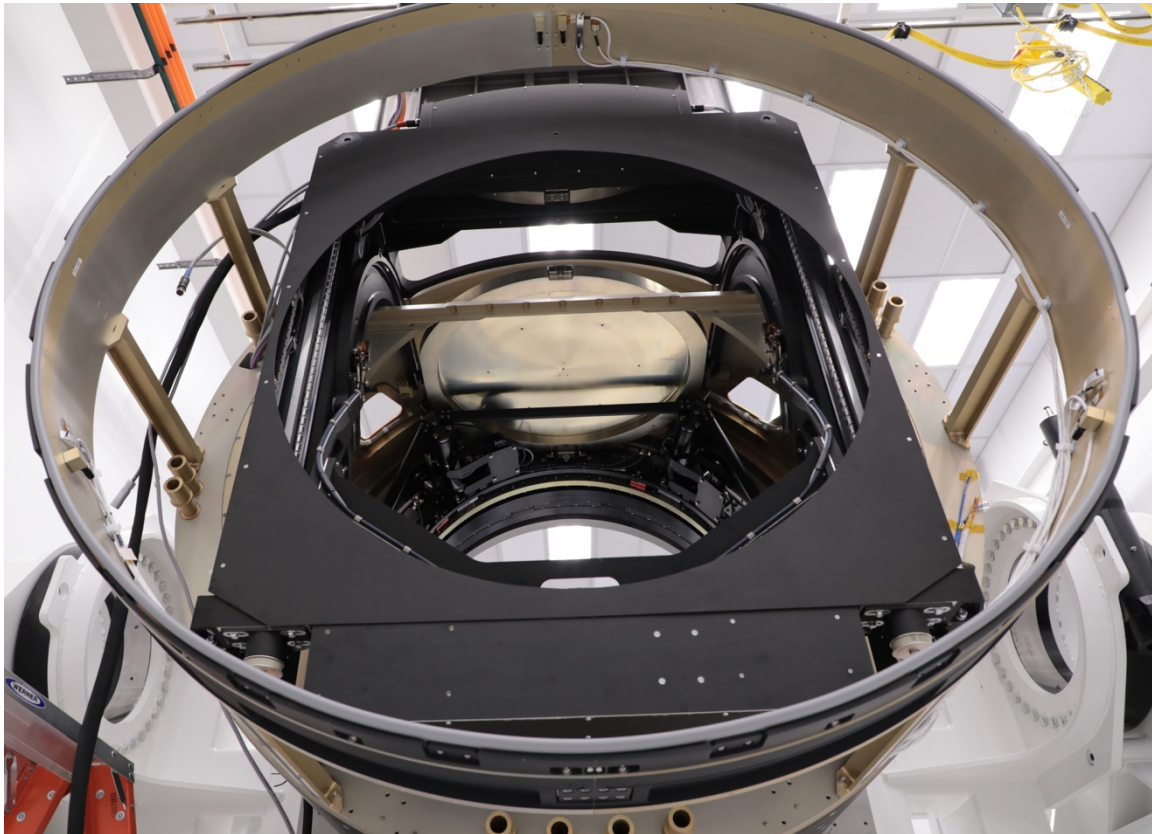


Figure 5. The Autochanger and Carousel mounted on the Camera Body in the SLAC clean room. A fake filter is on the Carousel in the Standby position. Another fake filter is housed in the Loader.

Fully-automated procedures are also defined to insert or remove a filter from the camera with the Loader. To insert a filter into an empty slot on the Carousel, the empty Autochanger grabs the filter from the Loader at the Hand-off position, the Loader releases it and withdraws, and the Autochanger finally stores the filter in the empty Carousel socket at Standby position. Unloading a filter from the camera is the reverse procedure.

### 3.2 Safety System

The goal of the Safety System is to ensure that the filters are never dropped by the FES during operation, and to avoid collisions between filters. This focus on the safety of the filters means that there are some cases when operations that are dangerous for the system itself are not forbidden by the Safety System. For instance, if both the Autochanger and the Carousel are holding the filter at standby, the carriage of the Autochanger is allowed to move by the Safety System. It is up to the FCS to check those conditions, to prevent potential damage to the FES hardware.

Each of the three hardware subsystems has its own LPM, which is a PLC (Programmable Logic Controller). These PLCs acquire sensor data, process it to compute the system states that are used in the safety equations, and take the system states from the other subsystems into account to allow or veto actions. This is done by actioning relays that cut the ‘dirty’ power supply to the motor controllers if an action is forbidden, preventing the motors from moving, and the brakes from releasing.

Each PLC communicates with the other modules of the subsystem on its own CAN network, separately from the CAN buses common to the HCU and non-safety modules. The PLCs also have an interface towards the HCU, but they can only be queried to read the system states and sensor data, not sent commands or re-programmed. Communicating system states between PLCs, which is critical for safe operations, is done through dedicated lines, where each signal is paired with its opposite.

### 3.3 Mechanical interfaces

The success of the exchange procedure relies on several conditions, some of which are verified at the time of the mechanical assembly, and others that set constraints on the movements during operation. Mechanical adjustments are not always one-off: for instance, the Autochanger can be extracted and mounted back into the camera. The Carousel clamps can also be replaced. The main safety-related concern when operating the FES inside the assembled camera was the clearance of the filter movement around the cryostat. This has now been checked several times with fake filters, after dismantling and remounting the Autochanger, and the safety margins offered by the design are satisfactory.

In practice, interfacing with the filters, and operating the different parts of the system that hold them, has required a number of adjustments during the development process. For instance, the process to clamp a filter in the Online position, that is currently encoded as a single FCS command, is a complex combination of commands to the linear rails and online clamp motors, that has to be executed in a precise order to achieve the required positioning.

The mechanical interface between the Carousel and Autochanger, to ensure that a filter brought by the Autochanger can be properly clamped into the Carousel, is also an example of combined mechanical and movement conditions. The orientation of the filter is critical for successfully clamping it in both clamps. A dedicated tool had to be developed to ensure the proper positioning of the Z+ guide on the Carousel. The required repeatability for the mounting of the Autochanger, on positioning the Autochanger rails relatively to the Carousel sockets at Standby, is 1 mm. But there is also a precision requirement on the Carousel rotation of 100  $\mu\text{m}$ , to ensure alignment. This has direct consequences on the duration of the exchange, since the rotation controller needs more time to stabilize the position of the Carousel.

## 4. DEVELOPMENT PROCESS

### 4.1 Towards the full-scale prototype

Discussions of the involvement of laboratories from IN2P3 (Institut de Physique Nucléaire et de Physique des Particules) in the LSST project started in 2006. The Preliminary Design Review was held in November 2013, with the workload already split into subsystems, and distributed between engineering teams in several laboratories. At that time, in addition to the overall designs, single-element prototypes had already been designed to address the most critical design risks that were identified. Full subsystem prototypes were next, along with several reviews.



Figure 6. The test-stand holding the full assembly of fake camera body, Carousel and Autochanger, with an angle of  $-45^\circ$  on the horizontal axis. The test-stand can rotate along this axis from  $-90^\circ$  (pointed vertically, downwards), simulating the camera when the telescope would be pointed at zenith, to  $+90^\circ$ , which is not possible for the telescope, but is convenient to perform mechanical work. The whole prototype is additionally mounted over a ring gear, for rotation along the camera axis.



Finally, in March 2018, the prototype subsystems were integrated into a full scale-1 prototype on a test-stand that could simulate all telescope attitudes (Fig. 6), from zenith (camera looking down), down to the horizontal in order to load filters. This step was key to delivering a working FES, due to the mechanical constraints discussed in the previous section.

Obviously, the development and validation of the FES required the use of fake filters (seen in Fig.1, 2, 5, 6), which replicate the weight distribution and the mechanical interfaces of the real filters. While the 38-kg u filter is the heaviest of the LSSTCam set, the fake filters were designed to simulate the weights of all filters and higher, up to a factor of 1.6 above the u filter. Filters with added weight were used to validate all operations with an additional safety margin. Having a varied set of weights was also necessary to test the rotation of the Carousel under various conditions, including when loading filters into a partially-filled Carousel, which maximizes the imbalance.

After testing of the final model on the same test-stand, and shipping to SLAC National Accelerator Laboratory for integration into the camera, the prototype was actually re-assembled on the test-stand. This was originally planned for a year-long test that would simulate the lifetime of the system, and to validate the second units of the Autochanger and Loader. It also turned out to be a highly useful tool to keep working on optimizing the system while access to the US was impossible due to the Covid-19 pandemic.

#### **4.2 Additional validation tests**

In parallel to the progressive build-up of the prototype, and then of the final model of the FES, tests were carried out on individual elements of the design. The schedule for these tests was set up based on the risk level that was associated with each item. For instance, one major test for the safety of the filters is the measurement of the tensile strength of the filter pins, whose diameter is only 5 mm at the thinnest point. These tests were carried out on dedicated test pieces, which were produced along each batch of filter pins that were manufactured.

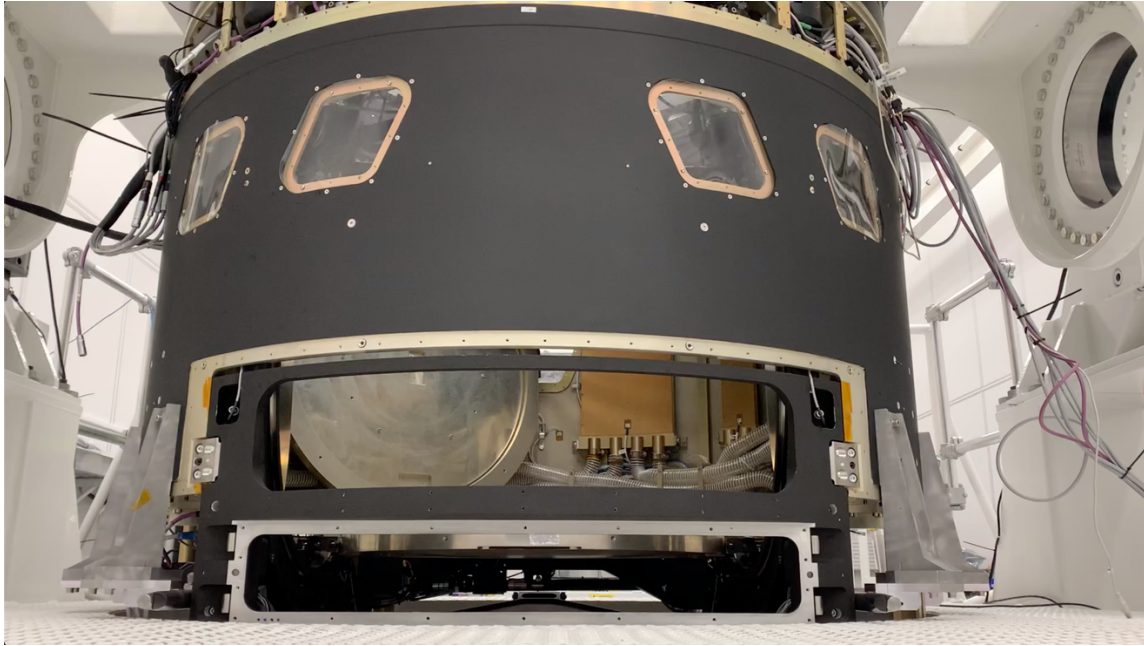
Validation tests at observatory temperatures have been carried out on the subsystems in climatized chambers, at several stages of the FES development. As expected, the operation of some motors is affected, and some sensor values shift, but the final design has taken those constraints correctly into account. As for the cleanliness requirement, it has impacted the design and procurement of the FES, and a check on potential contaminants has been carried out. In addition, a measurement of dust generation by the FES has been scheduled for the long-term test.

#### **4.3 Tests of the final model**

While tests were carried out on the prototype system, the final models for the subsystems were already in the assembly phase. A number of design elements were modified following the lessons learned from the prototypes, so it was necessary to have another full system test on the test-stand before shipping to SLAC. This phase started in June 2019, and ended with a demonstration of the functionality of the system with fully-automated filter exchanges. The system was then dismantled and shipped to SLAC in October 2019. Re-assembling and testing, which showed some minor shipping damage, took up to January 2020, at which point the access to SLAC was interrupted until July 2021 for the French team.

Once access was re-established, the FES was put back into service at SLAC. Through a number of optimizations in the software, communications, safety system reactivity, and motor configuration, the nominal operating time was reached in October 2021. The filter exchange time between any two sockets depends on whether the new filter is one or two sockets over from the current one, but it is now always under 89 s, and averages to 83 s (Video 1).

The last step to fully integrate the FES in the camera was to operate it from the camera Utility Trunk, instead of the dedicated auxiliary crate. The Utility Trunk houses the FES modules that could not fit into the available volume: the Carousel PLC, the HCU for the FCS, and temperature sensor modules for the Autochanger. This step was completed in April 2022, after the LSSTCam cryostat was finally integrated with the outer Camera Body.



Video 1. Full filter exchange at nominal time, with the camera in the vertical position. The filter at the Online position at the start of the video can be seen through the bottom window. <http://dx.doi.org/doi.number.goes.here>

## 5. CONCLUSION

The development of the FES covered not only every mechanical element of the system, but also motorization for all mobile components, instrumentation by multiple sensors to verify the system state at every point, communications, and software to execute all operations as designed. The requirements and constraints combined to make this a challenging enterprise, demanding attention to all details to ensure proper operation. This paper could only touch on some aspects of this work, and a more complete paper will follow.

The LSST Filter Exchange System has mobilized the work of many personnel over the years, not all of whom are authors of this article, and whom we want to acknowledge here.

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