The Industrialization of Astronomical Instrumentation: An Industrial Systems and Process Engineering Perspective

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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. Collaboratively, organizations across both academia and industry have partnered to overcome technical challenges and execute operational directives associated with commissioning the various mechanical, electrical, and software subsystems of SDSS-V. While this type of collaboration is not unique, the scale and complexity of next generation astronomical instruments is an emerging challenge that requires industrial systems and process engineering practices at a quasi-industrial scale. Driven by the success of multiplexed spectroscopic surveys, instrumentation is evolving to include systems with hundreds to thousands of components and sub-assemblies procured or produced from various sources. This trend requires the adoption of new and existing processes and best practices in the design, integration, and test of next generation astronomical instruments. The following discussion outlines those industrial systems and process engineering processes, methods, and practices, currently in the operational phase, for the design, integration, and test of the SDSS-V Focal Plane System (FPS). An emphasis is placed on processes, methods, and practices related to coordination of multiple contract manufacturing vendors and operational execution of small batch manufacturing.

Keywords: SDSS, massively multiplexed spectroscopy, systems engineering, robotic fiber positioners

1. INTRODUCTION

The design and build of astronomical instrumentation continues to expand in size and complexity requiring new and existing processes and best practices to meet schedule, budget, performance, and reliability requirements. Massively multiplexed spectroscopic surveys, such as SDSS-V[1], have introduced instrumentation with thousands of distinct serialized and common-off-the-shelf (COTS) components at small batch industrial scales. Small batch industrial manufacturing relies heavily on process design and implementation to deliver high-quality products over large quantities of components, assemblies, and end items. This is accomplished, in-part, by employing processes engineered to produce predictable results across a range of specifications at scale. Similarly, evolving astronomical instrumentation requires stringent specifications be maintained over thousands of similar or identical components and assemblies while ensuring reliable performance, low cost operation, and shorter design-to-sky development cycles.

The SDSS-V Focal Plane System (FPS), currently entering the lab assembly, integration, and test (Lab-AIT) phase, has adopted a series of small batch industrial manufacturing processes and best practices to address the challenges presented by producing components and assemblies that consistently meet specification at higher quantities. A few themes arise when considering the transferability of industrial manufacturing systems to astronomical instrumentation; 1) process design prior to implementation, and process control during implementation, are critical factors in consistently meeting product specifications across large component quantities; 2) design (i.e., specification) is an up-stream process that is a direct input into small batch manufacturing processes; 3) specifications are interrelated whereas failure to consistently meet one may impact others at scale; and 4) large component quantities have the effect of scaling benefits and shortcomings of processes design in direct proportion to the quantity of components manufactured.

Putting the FPS[2] in context, a single FPS unit is comprised of five hundred (500) fiber positioner robot (FPR[3]) assemblies integrated across two similar but distinct FPS units totaling one thousand distinct FPR units. FPRs are assembled to holes perforating a precision machined focal plane surface. Each FPR assembly is composed of a mechanical alpha and beta arm and primary housing, electrical printed circuit board (PCB), and Optical Fiber Assembly (OFA). The PCB is assembled to the lower FPR housing, aptly named the PCB holder, using two M3 screws. The optical fiber assembly (OFA) is comprised of three individual fiber strands with independent ST connector terminations on one end and a single custom ferrule termination at the opposite end. The OFA is routed through the FPR along an axial channel that extends from just above the PCB to an opening just below the beta arm. The OFA is fixated at one end to the beta arm and at the opposite end to an exit strain relief (ESR). Three OFA fiber strands extend beyond the FPR and PCB to interface with an external connector panel. FPRs, PCBs, and OFAs are manufactured by external contract manufacturers. FPR, PCB, and OFA assembly occurs within the FPS project team.

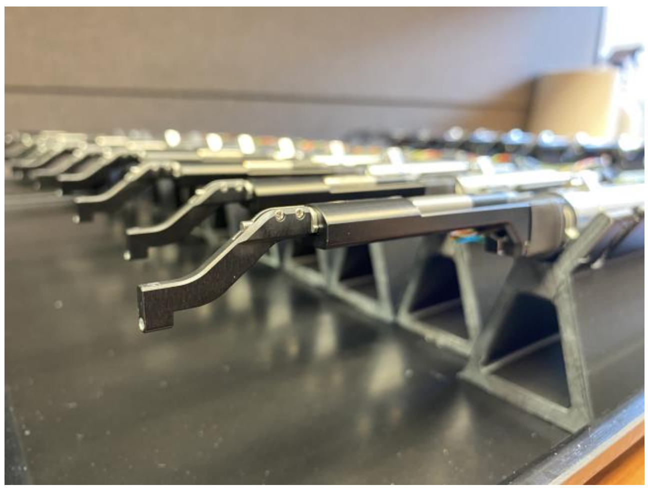

Figure 1. Fiber positioner robots with beta arm shown at the furthest extent and alpha arm extending just below two screws fixing the beta arm to alpha arm.

The remaining discussion details industrial processes, methods and practices, planned or operational, utilized during SDSS-V FPS Lab_AIT. Topics include operational workflow planning, functional work cells, quality management processes, a simplified manufacturing resource planning (MRP) system, and the use of contract manufacturing (CM).

2. FPS INDUSTRIALIZED PROCESSESING

2.1 Operational Workflow

Prior to launching operations for FPS Lab-AIT, comprehensive operational planning outlined inputs, outputs, processes and resources required to setup an industrial small batch manufacturing environment. An operational workflow consisting of Operations (Ops) defined the interaction of components, procedures, equipment, fixtures, and quality measures that, once applied, produce consistent component and assemblies for use in downstream Ops or work cells. Ops were conducted within functional work cells described in the following sections. Multiple operational workflows were needed to support convergent sub-systems including the FPR-OFA assembly, Field Illuminated Fiducial (FIF) assembly, and system-level integration workflow. The FPR-OFA assembly is described in more detail to illustrate implementation of industrialized process control.

The FPR-OFA assembly operational workflow is central to producing FPR-OFA assemblies that consistently meet system-level performance requirements for every assembly. Twelve hundred (1200) serialized FPRs and twelve hundred (1200) serialized OFAs move through the FPR-OFA assembly operational workflow. The workflow is initiated with Op

10, a rework step for securing the printed circuit board (PCB) to the FPR due to loosening PCB screws during shipping. Subsequent Ops are described in Table 1.

Table 1. Detailed Ops for the FPR-OFA assembly operational workflow.

Ops	Description	Activities
10	PCB and ESR base fixation with thread lock	Thread lock is applied to PCB screws to secure the PCB to the FPR PCB holder component. Thread lock is applied to ESR screws to secure the ESR base to the FPR PCB holder.
20	IPQC: pre-dress motion test	An in-process quality control measure to validate FPR performance prior to assembly of the OFA.
30	OFA dressing and ferrule fixation	Assembly of the OFA to the FPR by threading through the FPR body. The OFA custom ferrule end is loosely fixated to the FPR beta-arm end prior to metrology and final fixation.
40	ESR dressing; ESR cover fixation	The OFA is threaded through the ESR channels; the ESR cover is fixated using two screws clamping the OFA and PCB wire bundles in place within the ESR.
50	IPQC: post-dress motion test	An in-process quality control measure to validate FPR performance after assembly of the OFA and final fixation to the ESR.
60	Ferrule metrology and fixation	Final height of the custom ferrule end is set to 143.1 mm relative to the FPR flange datum.
70	IPQC: light transmission and fiber tip imaging	An in-process quality control measure to validate OFA light transmission after OFA handling. This measure does not verify OFA performance requirements but rather confirms no overt damage was caused during OFA handling. The fiber-tip is imaged for independent coordinate analysis post system-level integration.
80	Pre-integration inventory	Confirmation the completed assembly is placed in inventory and ready for system-level integration.

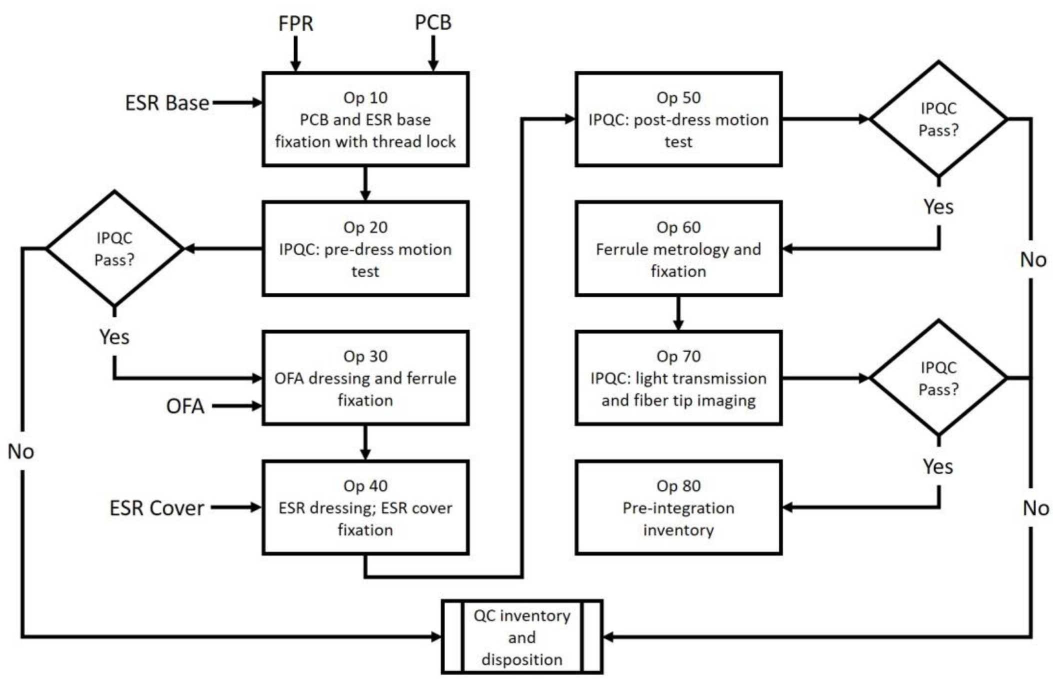

Figure 2. FPR-OFA assembly operational workflow. Inputs are designated by incoming arrows for the relevant Ops.

2.2 Production Travelers

Production travelers are implemented to facilitate Ops within and across functional work cells. Production travelers are physical cards that, for a given end-item, capture completed and outstanding Ops, the date when an Op is completed, and who completed it. Travelers always accompany the work in process (WIP) serialized component or assembly within and across work cells and throughout the operational workflow providing current status information. Once the component is integrated into the FPS system-level assembly the traveler is logged to provide end-to-end traceability.

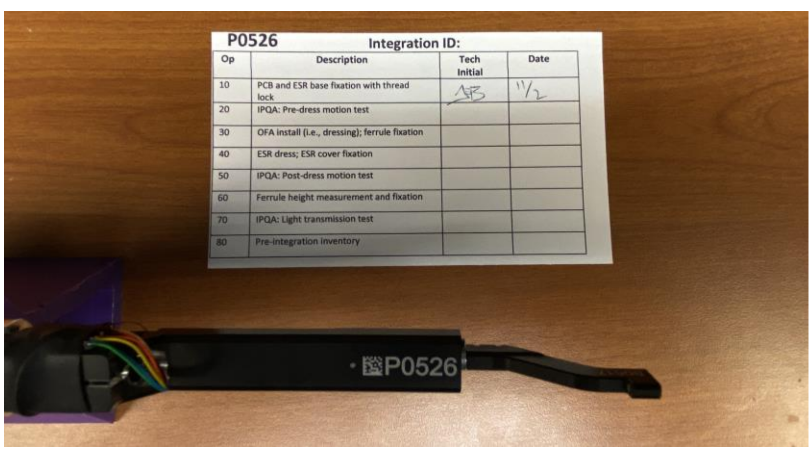

Figure 3. Production traveler example shown for WIP serialized component P0526. From left to right, Ops are listed in the first column, Op description in the second column, technician initial in the third column, and the date of Op completion in the third column.

2.3 Work Cells and Material Handling

Functional work cells consisting of technicians, processes, and specialized equipment are setup to conduct Ops based on end-item requirements and workflow planning. Work cells include FPR-OFA assembly, FIF assembly, and system-level integration. Planning for each work cell included consideration for component throughput, material handling within and between work cells, in-process quality control, inventory management, and technician interchangeability. All aspects of work cell planning converged to maximize product consistency and production rate while minimizing product damage, non-conformance, and rework. Additional requirements and constraints placed upon work cell planning included technician health and safety, available space, infrastructure, and work cell proximity.

During FPS Lab-AIT site health and safety restrictions constrained work cell operation to a single technician per work cell or manufacturing area for any given period. The added constraint placed a greater emphasis on throughput planning to maintain upstream production in the system-level integration work cell.

Specialized handling carts and fixtures were designed and built to move WIP components within and across work cells. Material handling is a key consideration to reduce component damage and maintain production throughput. Furthermore, fixtures allow for rapid processing and transition between Ops and while reducing component handling. For example, FPRs are elevated on the fixture base and secured with a top clip to provide access from all sides while avoiding damage during Op activities.

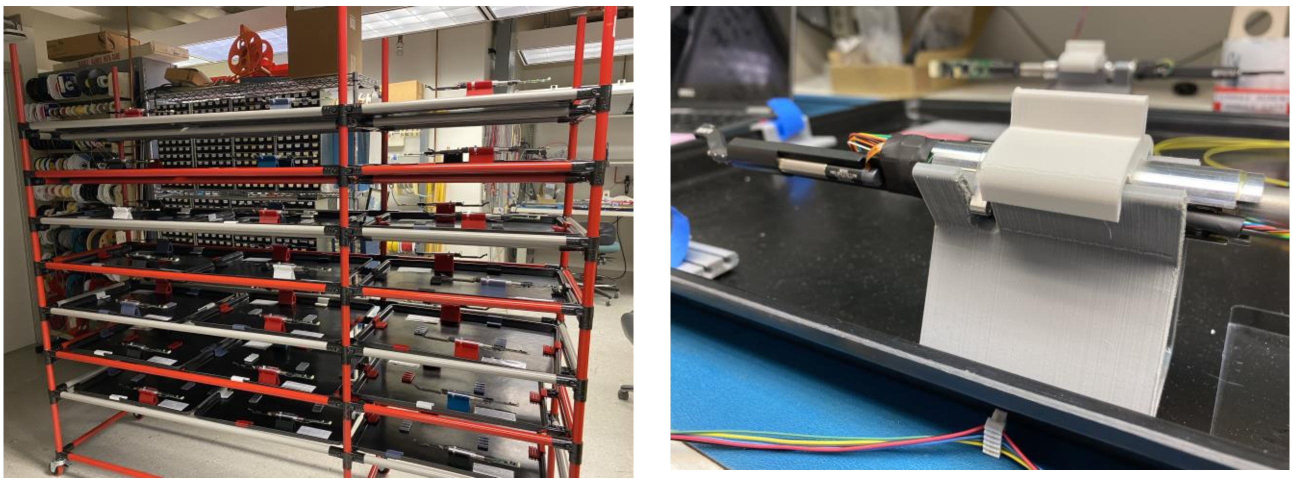

Figure 4. Specialized handling carts and fixtures. Left: FPR-OFA assembly WIP inventory cart used to move completed assemblies between work cells. Right: FPR fixture with base and clip used during FPR-OFA assembly and fixation.

2.4 FPR-OFA Assembly Functional Work Cell

The FPR-OFA assembly functional work cell is organized to facilitate assembly of FPR, ESR, and OFA components. The work cell consists of two primary stations, 1) FPR and OFA assembly and fixation; and 2) ferrule metrology and fixation. Between stations FPR-OFA assemblies are maintained at WIP staging areas to facilitate the next Op. Completed assemblies are placed on WIP handling carts for transport to the system-level integration functional work cell.

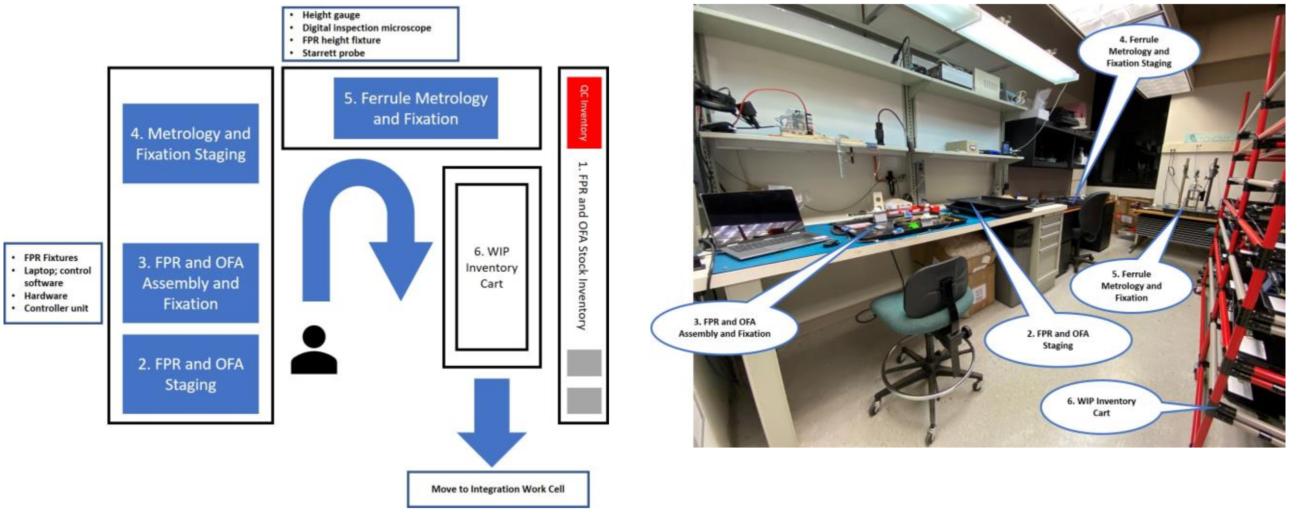

Figure 5. FPR-OFA functional work cell. Left: Schematic layout showing sequenced Ops and required equipment and fixtures. Right: Completed work cell cross-referencing elements shown in the schematic layout. FPR and OFA Stock Assembly Inventory not shown.

2.5 FIF Assembly Functional Work Cell

Like the FPR-OFA assembly functional work cell, the FIF assembly functional work cell is organized to facilitate assembly of FIF fiber bundles and FIF mechanical bodies. The work cell consists of two primary stations, 1) ferrule fixation; and 2) FIF metrology. Between stations FIF assemblies are maintained at WIP staging areas to facilitate the next Op.

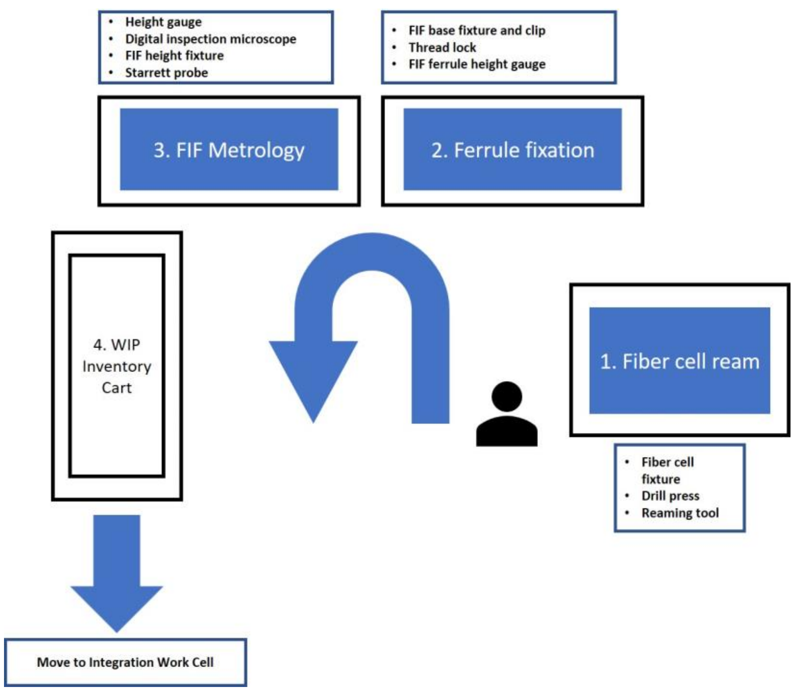

Figure 6. .FIF functional work cell. Schematic layout showing sequenced Ops and required equipment and fixtures.

2.6 System-level Integration Functional Work Cell

Components and assemblies converge to the system-level integration functional work cell. Unlike the FPR-OFA and FIF functional work cells, the system-level integration functional work cell is not sequenced by Op but rather by configuration. The FPS sextant configuration determines the order of integration activities. Like the FPR-OFA and FIF functional work cells, tools, procedures, and technicians are employed to facilitate production of FPR-OFA assembly integration into the FPS structure. Other FPS subsystems as discussed in Pogge R. and Collaboration[1] are also integrated in this functional work cell.

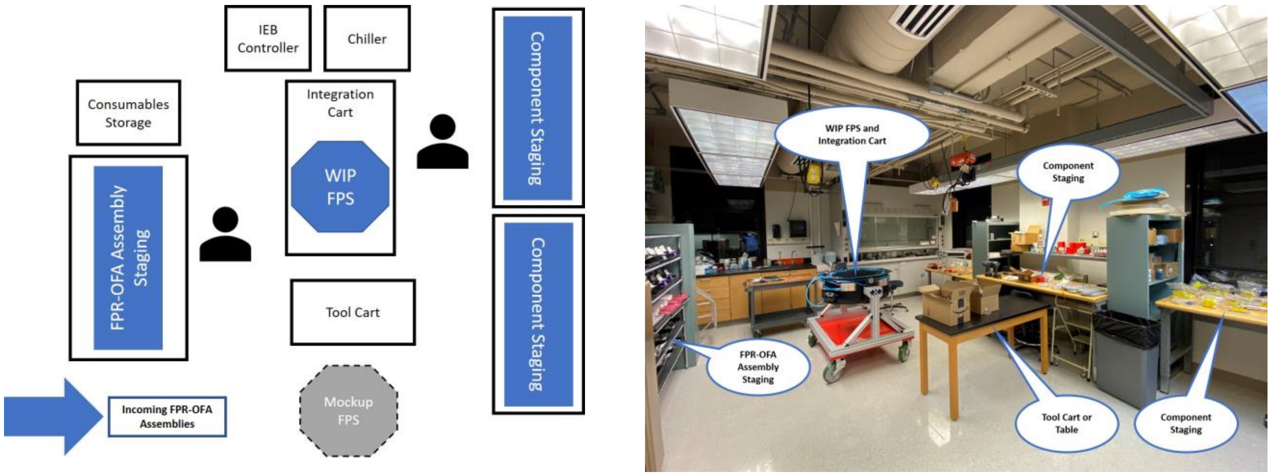

Figure 7. System-level integration functional work cell. Left: Schematic layout showing work cell elements. Right: Completed work cell cross-referencing elements shown in the schematic layout. Mockup FPS, IEB Controller, and Chiller not shown.

2.7 Quality Management Processes

Quality management procedures are implemented at several stages of the operational workflow to mitigate risk and improve consistency; hallmarks of successful manufacturing at any level. Quality management procedures within FPS Lab AIT include documented procedures, incoming quality control (IQC), in-process quality control (IPQC), process validation, and non-conformance tracking. At the time of this writing system-level verification and validation planning is underway to identify testing methods and procedures to verify system requirements and validate end-item functionality prior to shipping and onsite commissioning.

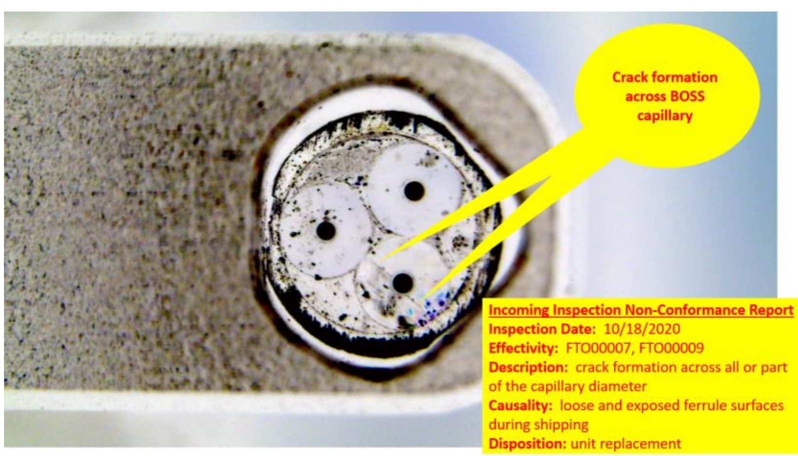

Figure 8. Example non-conformance report generated during IQC showing damaged capillary face. Inspection date, effectivity, causality, and final disposition.

3. MANUFACTURING RESOURCE PLANNING (MRP) SYSTEM

Manufacturing Resource Planning (MRP) systems are used extensively in industry to manage operational workflows, component tracking, configuration management, load balancing, and WIP activities. While current FPS component quantities are small in-comparison, the need for a rudimentary MRP system was driven by over three thousand (3000) serialized components and thousands of COTS components and bulk items used across two (2) FPS instruments. A simplified MRP system was deployed using MS Excel data modeling tools. Data tables capturing serialized components, component non-conformance, configurations, operational workflows, transfer transactions, and item custodians were created to capture manufacturing data. Relationships were created between tables to drive rudimentary reporting for inventory, traceability, quality control, configuration management, and production planning.

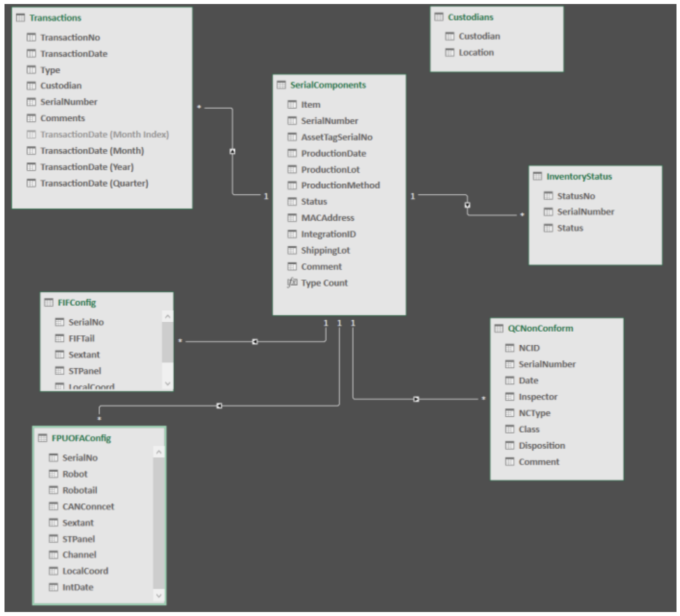

Figure 9. Simplified MRP data model using MS Excel data modeling tools. Tables and relationships are created to manage inventory, configuration, and quality data items and provide traceability for serialized components.

4. CONTRACT MANUFACTURING

Contract manufacturing vendors are used extensively to provide components and assemblies for FPS small batch manufacturing processes. FPR, custom ferrules, OFAs, FIF fiber assemblies, FIF bodies, and fiber tributary assemblies are all produced by contract manufacturing vendors. Procedures within the broader quality management plan regulated incoming components and assemblies as measured against documented requirements. Regular status meetings with vendors addressed technical challenges, production schedule, updated requirements, and quality issues. As with industrial manufacturing, management of vendor relationships for small batch manufacturing operations has significant impact in downstream activities. For example, the FPS team experienced FPR and OFA delivery delays due to vendor supply chain concerns and shipping complications impacting schedule and budget. Coordination with reliable vendors resulted in overcoming these issues while difficulties with unreliable vendors had a greater impact on schedule and budget. In retrospect, a more comprehensive vendor management plan, commonly adopted in industrial manufacturing, was needed earlier in the project planning phase.

5. CONCLUSIONS

Ongoing FPS Lab-AIT activities leveraging industrial manufacturing processes and best practices are evidence of the growing influence of industrialization in astronomical instrumentation. The need for industrial systems and process engineering capabilities is evident as the size and complexity of instrumentation continues to grow. The use of contract manufacturing is also driving higher demand for industrialized processes, quality management, and simplified MPR systems to manage small batch manufacturing. Massively multiplexed spectroscopic surveys like DESI[4] and now SDSS-V will continue to push astronomical instrumentation toward adopting industrial processes and best practices in the years ahead.

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