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Mechanical design evolution of the VIRUS instrument for volume production and deployment

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ABSTRACT

The Visible Integral-Field Replicable Unit Spectrograph (VIRUS) is an integral field spectrograph to support observations for the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX). The VIRUS instrument is fed by more than 33,000 optical fibers and consists of 150 spectrographs in 75 individual, identical units. This paper discusses the evolution in mechanical design of the VIRUS unit spectrographs to maximize the cost benefit from volume production. Design features which enable volume manufacture and assembly are discussed. Strategies for reducing part count while enabling precision alignment are detailed. Design considerations for deployment, operation, and maintenance en mass at the Hobby-Eberly Telescope are also made. In addition, several enabling technologies are described including the use of cast aluminum in vacuum housings, use of cast Invar, and processing cast parts for precision tolerances.

Keywords: Telescopes: Hobby-Eberly, Astronomical instrumentation: Spectrographs, VIRUS, Spectrographs: Integral Field, Spectrographs: mechanical design

1. INTRODUCTION

The Visible Integral-field Replicable Unit Spectrograph (VIRUS[1]) consists of a baseline build of 150 identical spectrographs (arrayed as 75 unit pairs) fed by 33,600 fibers, each 1.5 arcsec diameter, deployed over the 22 arcminute field of the upgraded 10 m Hobby-Eberly Telescope (HET[2][†]). The goal is to deploy 96 unit pairs. VIRUS has a fixed bandpass of 350-550 nm and resolving power R~700. VIRUS is the first example of industrial-scale replication applied to optical astronomy and is capable of spectral surveys of large areas of sky. The method of industrial replication, in which a relatively simple, inexpensive, unit spectrograph is copied in large numbers, offers significant savings of engineering effort, cost, and schedule when compared to traditional instruments.

The main motivator for VIRUS is to map the evolution of dark energy for the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX[3][‡]) using 0.8M Lyman-α emitting galaxies as tracers. The full VIRUS array is due to be deployed in late 2011 and will provide a powerful new facility instrument for the HET, well suited to the survey niche of the telescope. VIRUS and HET will open up wide field surveys of the emission-line universe for the first time.

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[†] The Hobby – Eberly Telescope is operated by McDonald Observatory on behalf of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximillians-Universität München, and Georg-August-Universität, Göttingen

[‡] http://hetdex.org/

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VIRUS was conceived as an astronomical instrument which could be deployed in quantity, offering scalable on-sky coverage while leveraging mass-manufacturing principles to reduce cost. The VIRUS-P instrument served as a functional prototype, proving the performance and cost, and its design and use is well documented [4-10]. Recent design efforts have focused on reducing the cost and complexity of the instrument. Cost savings in fabrication, assembly, and operation were considered.

2. "PAIRING" OF SPECTROGRAPHS

One of the most significant departures of the VIRUS design from that of VIRUS-P was the "pairing" of two operationally independent spectrographs into one mechanical package. This change had significant implications not only to the instruments' mechanical design but also the detector readout electronics, integral field unit (IFU), and telescope focal surface layout.

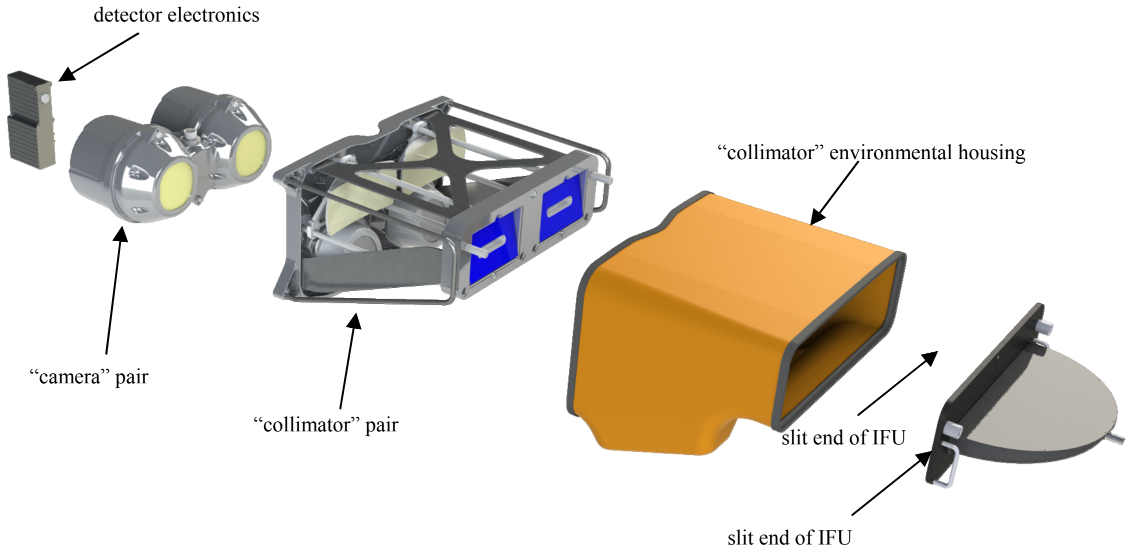

Figure 1. Basic components of the VIRUS spectrograph

Pairing the spectrographs enabled reduction of mechanical structure to support optics by eliminating the redundant structure of two spectrographs placed side-by-side. The housing to provide environmental protection to the collimator section of the spectrograph could also be shared amongst two spectrographs which reduces the material needed for that function. The complexity of the superstructure to house the 150+ spectrographs could also be reduced by pairing the instruments because fewer interfacial features between instrument and superstructure are required. More detailed information on the VIRUS support structure can be found elsewhere [8].

The camera cryostat vacuum is also shared between a pair of spectrographs. This modification effectively halves the number of ancillary vacuum components such as valves and vacuum gauges. This saves not only the expense of these components but reduces the number of sealing surfaces which contribute to long-term vacuum degradation and are a point of failure. Similarly, the cryogenic cooling system is shared between pairs. This reduces the part count of the instrument cryogenic system and also simplifies the cryogenic distribution system and loses associated with fittings and valves. The instruments cryogenic system development and testing is described in greater detail elsewhere [9].

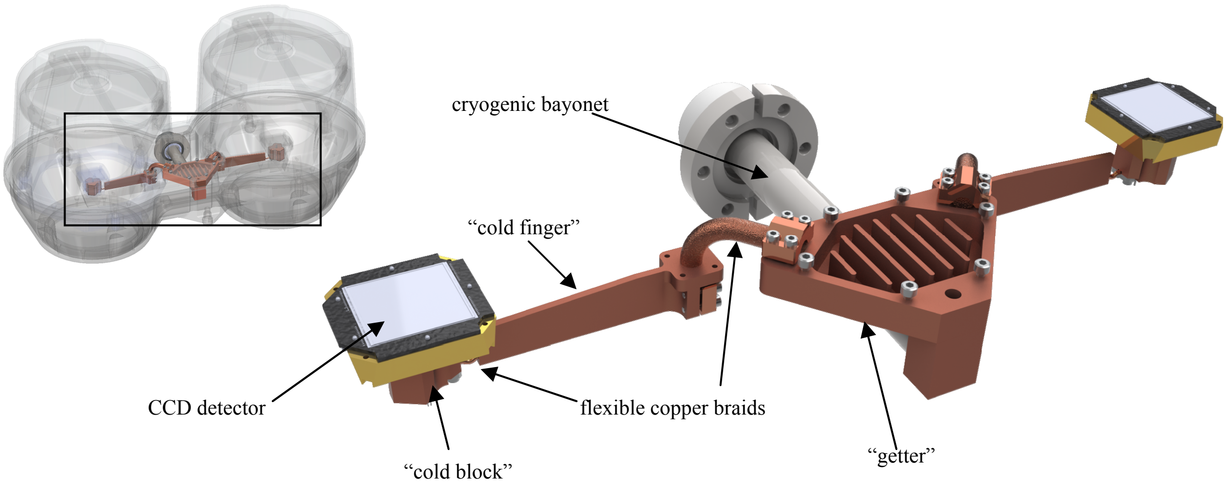

Figure 2. Camera cryogenic cooling system

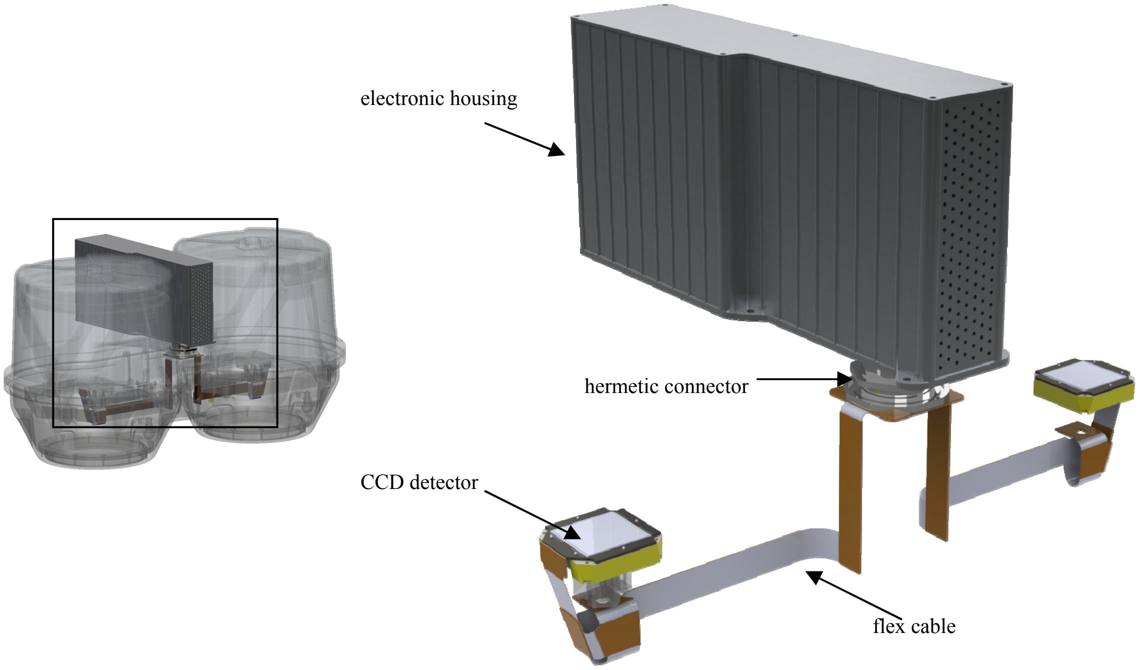

Figure 3. Camera electronics system

The detector read-out electronics mechanical design also incorporated the pairing of spectrographs. The flex cable internal to the camera cryostat connects two CCD detectors to a single hermetic bulkhead connector. Again, by two spectrographs sharing one hermetic connector, the total number of connectors is reduced as is the number of sealing surfaces. The detector readout electronics manufacturer, Astronomical Research Cameras Inc. was able to design a single compact electronics package capable of reading and controlling two detectors along with handling detector temperature control for both detectors. The mechanical envelope of the electronics module was designed to fit between the spherical mirrors of the camera pair, allowing the electronics module to be connected directly to the hermetic connector on the exterior wall of the camera cryostat. Connecting the electronics directly to the camera eliminated expensive external cabling and a point of failure which can contribute to signal degradation and can allow the introduction of electronic noise.

Combining the fibers of two IFU's into one mechanical package had significant benefits to the design of the upgraded HET Prime Focus Instrument Package (PFIP). Much of the IFU mass carried by the HET tracker is the conduit which serves to protect the IFU optical fibers. This mass is reduced by combining the fibers of two spectrographs into one conduit. The complexity of equipment which guides the fibers from telescope focus to the instruments is also reduced by the reduction in number of conduits. The IFU production, handling and testing are written about in greater detail elsewhere [11,12]. The input head of the VIRUS IFU is an array of 224 fibers contributing to two spectrographs. This allows up to 96 IFU's (supporting 192 spectrographs) to be packed into a 16x16 arcminute square at the telescopes focal surface with one-quarter fill and provide sufficient mechanical features for a robust, secure, and precise interface between IFU input head and telescope.

3. ADAPTATION FOR INDUSTRIAL REPLICATION

The fabrication of large numbers of identical instruments creates an opportunity for cost savings inherent to purchases in bulk. Just as the price of off-the-shelf items is reduced for purchases of large quantity, the price of custom fabricated parts are typically lower when ordered in large quantities. This is often due to savings by machine shops through ammortization of non-recurring engineering charges (NRE) such as fixturing and end-loading which is the natural improvement and speed a technician or laborer gains through repetition. However, some fabrication processes and some design features better leverage the cost-benefit of volume production than others. Likewise, the quality control and tolerance range of large quantity production is dependent on the processes used and the design of the parts. Considerable engineering effort was placed on exploring fabrication techniques which maximized these cost benefits.

3.1 Metal castings as structural parts

Casting is often characterized by its lack of precision and repeatability which does not lend itself well to producing instrumentation. In addition, casting processes traditionally require high up-front costs for fabricating the molds making them uneconomical for low-quantity production and risky for design efforts where prototyping is required. However, the recent proliferation of stereo lithography and other rapid prototyping devices has significantly decreased the cost of producing prototype castings. Complex part shapes can be quickly and economically "printed" in 3D using stereo lithography equipment or machined from plastic foam. Those parts can then be used to imprint sand molds or in the case of investment casting, coated with refractory material and melted out through a sprue. Several companies offer fast turnaround, low cost prototype casting services and can accept CAD models online without need for mechanical drawings. Prototype Casting, Inc. and Ultracast, Inc. have been used for the aluminum prototype castings while Wisconsin Investcast was used for Invar castings.

Figure 4. Collimator "baseplate" casting

Castings offer the ability to produce part shapes which would otherwise be impossible or prohibitively expensive to machine from a solid billet of material. Consider the "collimator baseplate" (Figure 4); a bulkhead which serves as a mechanical interface for the camera, VPH gratings, and collimator spherical mirrors. This part weighs 4.6kg, however if it were machined from a solid piece of aluminum it would require an aluminum slab weighing over 66kg. When produced in quantity, the price of the raw casting can approach $500USD: less than the cost of the stock material needed to produce this part through traditional machining.

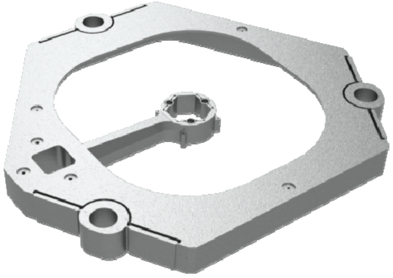

Figure 5. Camera "spider" casting

Cast material is often characterized as having low internal stress when compared to raw materials which are produced through cold-work, such as sheet and plate stock. This is an important advantage for castings when precision machining is required. For example, the "spider" (figure 5) is a cast Invar 36 part which supports the detector head module within the camera body. The part has several surfaces which are machined in a secondary operation. The relative tolerance between surfaces which register the detector at the center of the part relative to the camera at the periphery have a precision on order of 50microns. If this part were to be machined from a plate significant internal stress would be released when the large amount of material was removed around the central feature. Work-holding clamps would restrain the part during machining, but when released, the imbalance of internal stress would potentially result in out of tolerance deflection between the precision surfaces. Strategies such as stress-relieving heat treatment between machining steps are possible to reduce this effect, however the advantage of low internal stress in cast parts is clear. The low internal stress is also important to maximizing long term dimensional stability (creep) and thermal stability of the part.

3.2 Metal castings as vacuum housings

The advantage of using castings as structural components is clear as they enable designs which would otherwise be impractical if fabricated with other methods and are inexpensive when produced in large quantity. However, castings of aluminum in particular can often contain metallurgical defects such as voids and inclusions of foreign material such as the sand comprising the mold. These artifacts are usually not significant enough to effect mechanical performance of a part. However, vacuum housings of traditional cryostats are crafted with careful attention to avoid sources of virtual leaks and foreign material. For this reason, cast aluminum is not often used for vacuum housings even though few examples exist to validate that logic. At the design stage, the VIRUS team decided the fabrication advantages of cast aluminum were worth pursuing possible solutions to the vacuum integrity issues. The camera crysostats were designed as a pair of aluminum castings with the intention of contracting a foundry to produce a prototype set for the purpose of testing actual vacuum integrity. MKS Instruments suggested the vacuum impregnation of Locktite Resinol into the castings to fill and seal voids and inclusions. MKS Instruments and its subcontractor General Foundry Services produced 5 prototype camera cryostats for testing as well as providing design guidance for the vacuum components. Testing of these units so far have yielded encouraging results, with vacuums as low as 1e-7torr achievable and millitorr vacuums sustained for weeks. The operational camera will incorporate a "getter" for cryogenic pumping and initial testing has demonstrated microtorr vacuums sustained for extended periods.

Another concern raised about the use of castings in vacuum housings was the surface roughness of the housing interior wall. Traditional cryostats are constructed with very low surface roughness in order to decrease the overall surface area with potential to carry containments that out-gas in vacuum. Aluminum castings have a relatively rough surface, often being sand-blasted at the foundry to hide imperfections and remove "burrs" or "slag". Tests performed so far have not indicated any problems due to the surface roughness and it is unclear if the Locktite Resinol treatment plays a factor.

3.3 Use of cast Invar

Invar 36 is well known amongst instrument designers for its low coefficient of thermal expansion (CTE). The nickel-iron alloy is indispensable for producing parts which maintain precise dimensions over extended temperature ranges. Another advantage is that it closely matches the CTE of fused silica commonly used in optics. However, the material is expensive and available stock sizes are limited. By casting Invar, the material use is maximized and part designs are not limited to stock material availability.

Invar used in welded structures is usually heat-treated after welding with the understanding that the welds and heat affected zone would not maintain the low-CTE properties upon solidification. By extension, one might assume the same applied for castings and that cast Invar must be heat-treated to regain the low-CTE property. This assumption has not been borne out in our measurements. The "spider" part described in section 3.1 was produced with no heat treatment. The part’s CTE was tested over the instruments’ operating temperature range a found to be within 10% of published values.

Many machinists believe cast metals to be difficult to cut and the relative infrequency of Invar use adds to that trepidation. However, cast Invar has proven to be as freely machined as mild steel. Some caution must be taken due to the “gummyness” associated with high Nickel content, but very fine surface quality is achievable with adequate coolant flow during machining. Cast Invar is also readily cut using electron deposition machining (EDM), however it must be noted that we have experienced some issues with inclusions in the cast material interrupting EDM wire operations.

3.4 Design considerations for cast parts

The geometric tolerance of raw cast parts is generally not sufficient for registration of precision components, optics in particular. Deviations of up to 0.5mm from nominal are considered normal. Thus, secondary machining processes are required for precision surfaces. Part designs must incorporate this requirement, with additional material added to regions requiring secondary machining operations. It is often useful to produce CAD models with multiple configurations. One configuration should contain the geometry of the raw casting and be supplied to the foundry. A second configuration should contain the final machined geometry and be supplied to the machinist.

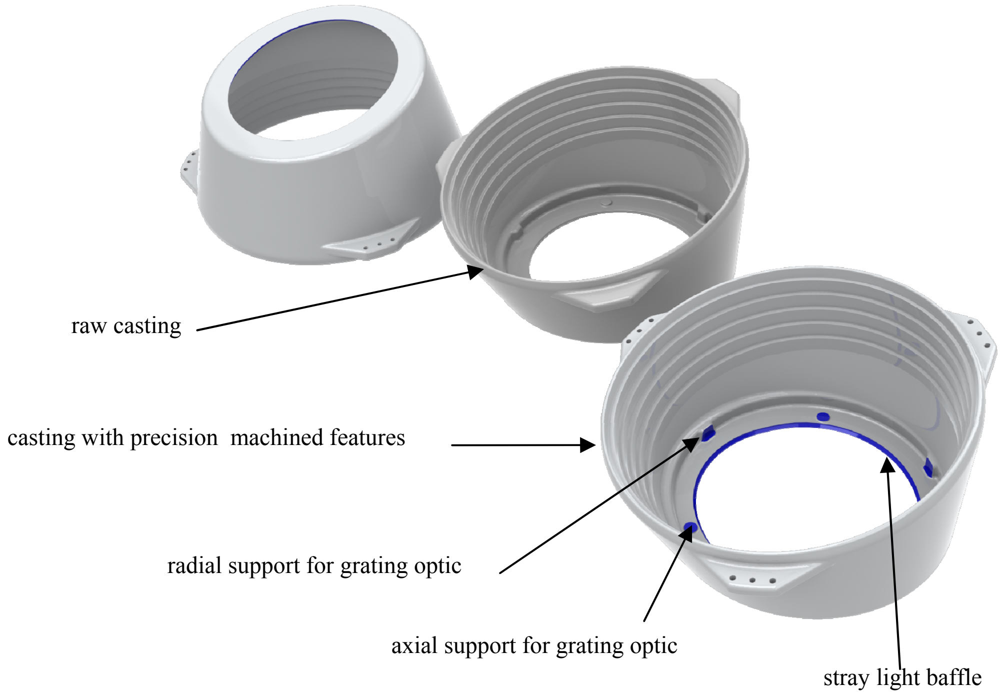

Figure 6. VPH grating mount casting

Take for example the "VPH grating mount" depicted in figure 6. The spectrograph volume phase holographic (VPH) grating is secured to this part using room temperature vulcanizing (RTV) adhesive and the assembly is mounted to the spectrograph's "collimator baseplate" via a kinematic mount. The alignment of the grating relative to the spectrograph is achieved through tolerances of machined surfaces. The raw casting has 6 raised features which are subsequently machined to provide radial and axial support to the grating. Proper sizing of the raised features will ensure sufficient material exists for removal during secondary machining thus revealing a precision surface. However, it is important to limit the amount of material to be removed since this reduces machine time and allows light cuts to be taken which minimizes the forces subjected to the part by the cutting tool. Such "skin" cuts improve the machined surface quality and precision.

Castings which use two-part sand molds are typically the most economical to produce. Certain design limitations are inherent to the process; most notably the requirement of draft and prohibition of undercut. The sand castings produced so far have had a 1-degree draft requirement which is relatively easy to achieve for most parts. Investment castings are often used as a means to avoid draft and undercut requirements however the designer must consider how the blank is produced. While stereo lithography can produce blanks of arbitrary geometry for prototype castings, production of investment cast parts in large numbers using stereo lithographic blanks would be quite expensive. Moving from prototype to production requires fabrication of a hard tool for making wax blanks. The hard tool will have the same draft and undercut requirements as a sand mold unless inserts are used which again increases cost.

Wall thickness variation is another design consideration which must be made for cast parts. The solidification rate of the cast material has some effect on the material properties. Therefore, large wall thickness variations would lead to variations in cooling and solidification rate and subsequently lead to inhomogeneous material properties. Wall thickness variations can also present difficulties relating to the dynamics of pouring molten material. If the molten material is to be poured into a mold through only one sprue, sufficient area must be present to allow flow throughout the part prior to solidification. The presence of thin walls can restrict flow and are often the first regions to solidify. If those regions are passages to other areas, they can prevent complete filling of the mold. This is especially true for gravity-fed casting processes.

3.5 Design considerations for precison features in volume production

One of the challenges with producing instruments in quantity is controlling the geometric tolerances of the individual parts so that the critical dimensions of the complete assembly will fall within specification. While careful measurement and rework is acceptable for parts produced in one-off fashion, economic mass-manufacturing must be executed so that each part is consistently produced within its acceptable tolerance range consistently. We have adopted several design strategies which leverage the precision of modern manufacturing equipment while minimizing susceptibility to common sources of error.

The 3-axis vertical CNC milling machine is perhaps the most common machine tool available for production scale fabrication. The ubiquity of these machines makes their ownership and operation relatively inexpensive and that is reflected in the price of parts fabricated by such. It is therefore advantageous to design parts which can be fabricated in these machines. The inherent precision of the CNC milling machine lies in the control of its three axes. The sources of error occur through wear of the cutting tool and setup of the part in the machine by the technician. A part which can be fabricated with a consistently high level of precision should minimize the number of setups in a machine and not rely on the precise dimension of the cutting tool.

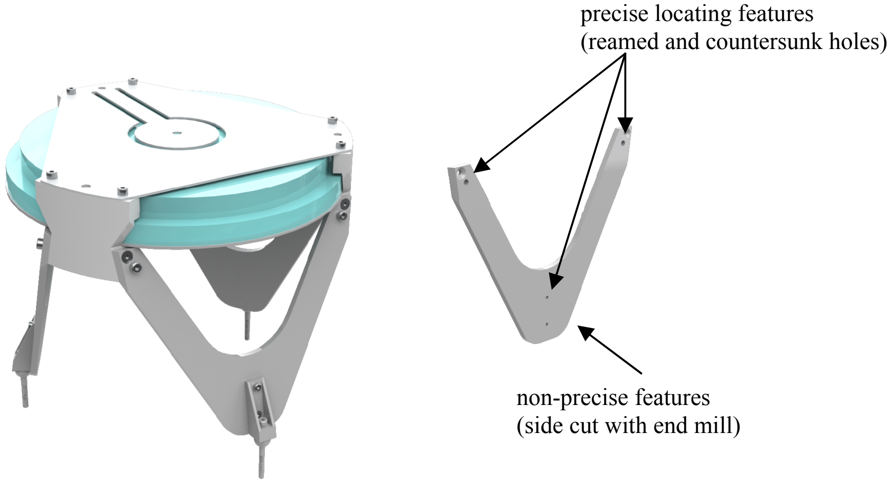

Figure 7. Camera mirror support assembly

As an example, consider the “camera mirror support legs” depicted in figure 7. These parts are machined from flat plate and have only features which are machined from one side of the plate. The stock material can be clamped to the machine work surface and the entire part is cut in one setup. Additionally, the features which require precision are located only by the X and Y axes of the machine. The precise cutting tool diameter has little effect on concentricity of a holes location. Conversely, the location of a side-cut surface is highly dependent on the tool diameter. Side cuts should be reserved for features with relaxed tolerances such as the part profile of the camera mirror support leg. Surfaces cut with the end face of a cutting tool can achieve a higher level of precision than side cuts because the actual end face location of the cutting tool is more readily measured. Surface locations determined by depth-of-cut are therefore favorable for tightly toleranced features.

Milling machines with 4 or 5 axes can produce more complex parts with minimal setups, however there is often a premium to pay for such services particularly for large part envelopes. Part designs requiring multiple setups are often inevitable for complex assemblies. The errors resulting from multiple setups are usually attributed to transferring the part coordinate system to the machine coordinate system between setups. Such errors can be reduced by incorporating datum features which are easily referenced at each of the parts setup orientation. In some cases, features must be added to a part so that they create a datum which can be accurately measured in each setup.

3.6 The use of kinematic mounts in fabrication and integration

"Kinematic mount" refers to a mechanical coupling which is minimally constrained, such as a rigid body with three spherical surfaces coupled to a rigid body with three vee-grooves. The kinematic mount enables highly repeatable registration between components and their use is prevalent in precision optical assemblies. The VIRUS spectrograph relies on kinematic mounts between sub-assemblies which need to be precisely coupled to each other. The optical and mechanical tolerances of the instrument are arranged such that parts of a particular type are interchangeable. For example, the "camera" couples to the "collimator" through a kinematic mount. It is required that any camera could be used with any collimator and perform within specification. Similarly, the VPH gratings are connected to the collimator, as are the detector sub-assemblies to the camera body. The kinematic mounting features can also serve as reference datums during fabrication.

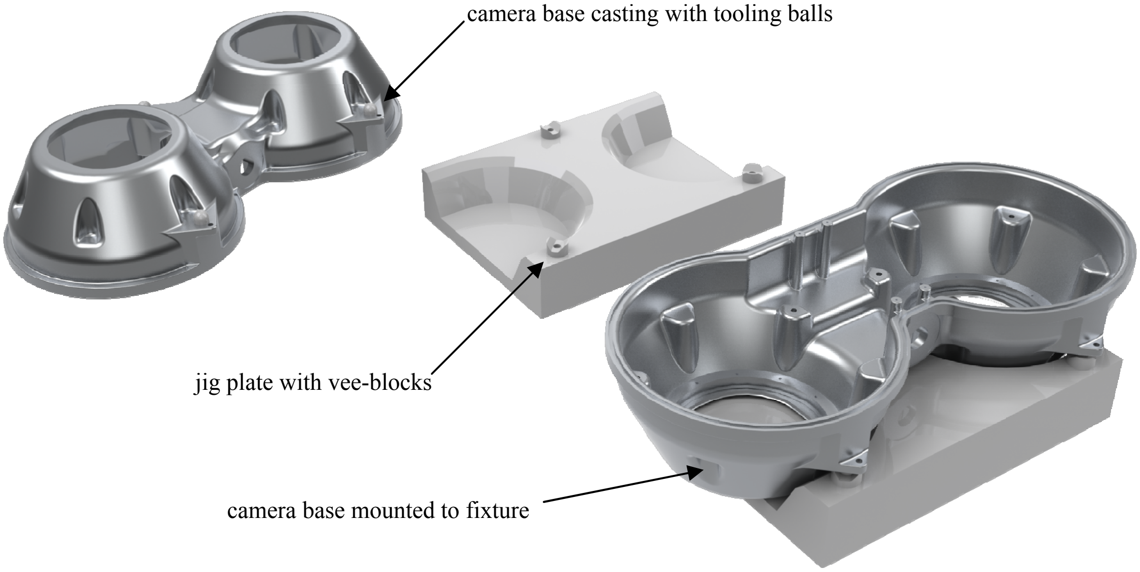

Figure 8. Camera base casting and fixture for secondary machining

Consider the "camera base" casting (figure 8). The raw casting has no easily-measured reference datums. The first machining step is to create three holes where tooling balls are then press-fit. The tooling balls serve as the spherical surfaces which define the part's coordinate system. The camera base, with tooling balls, can then be placed in a fixture who's mating kinematic mount acts as a surrogate for the collimator. The fixture is simply machined aluminum jig plate outfitted with the same off-the-shelf vee-blocks used on the collimator “baseplate”. Subsequent machining operations on the camera base are thus relative to the kinematic mount. This method is particularly well suited for large quantity production. The fixture is fabricated with high precision, but only needs to be fabricated once. Once mounted in a three-axis milling machine, the fixture provides a simple yet precise interface for raw castings to be registered. Each casting to be machined is bolted to the fixture and processed without need for time-consuming and error-prone measurement.

3.7 Design of adjustment mechanisms

While proper design can ensure machined parts are precise and consistant, the alignment tolerance of the VIRUS optics exceed the capabilities of most CNC machine capabilities. While additional alignment steps are inevitable, VIRUS incorporates features which reduce the number and cost of these alignments. Two strategies were taken. The first was to relax the alignment tolerance of the majority of the components and incorporate a “compensator”. Both the camera module and the collimator module each have optical compensators. The optical performance degradation resulting from errors in the position and manufacture of all the optical components are compensated for through the mechanical adjustment of one optic. The optical tolerance budget and compensator scheme is discussed in greater detail elsewhere [11].

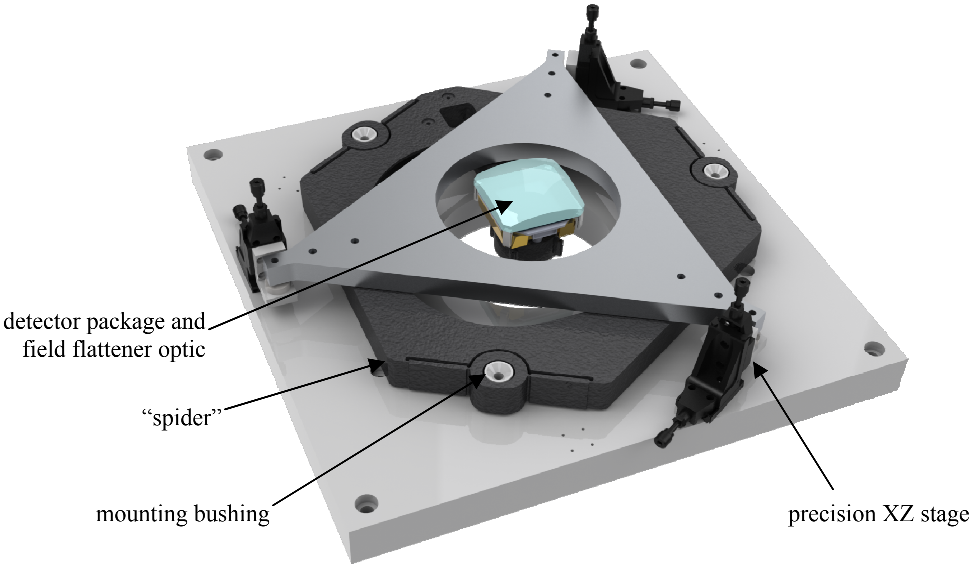

Figure 9. Detector head alignment mechanism

The second strategy for reducing cost of alignment is by designing the precision adjustment and metrology mechanisms as external equipment independent of the instrument. The detector head alignment mechanism (figure 9) consists of 6 precision stages and an optical metrology system (not shown). This mechanism is temporarily mounted to an unaligned detector head and adjusted with feedback from the optical metrology system. When the detector head is aligned to within specification, epoxy is injected between the spider and three mounting bushings at its periphery, locking the alignment in place. Once cured, the detector head is removed from the alignment mechanism and mounted into the camera using the bushings as the mechanical interface. The precision stages would be prohibitively expensive to incorporate into each instrument (and would take up valuable space), but their function is essential. Since the detector head is only aligned once, the precision stages can be designed as an external component and the relatively inexpensive epoxy used in each instrument instead. Additional alignment mechanisms used during VIRUS assembly are discussed elsewhere [16].

4. SUMMARY AND STATUS

The recent VIRUS design efforts have focused on reducing cost and complexity of the instrument. The use of castings has been adopted where possible due to their inherent cost savings when produced in large quantity. Castings are also used to produce part geometries which would otherwise require multiple parts and additional assembly. The machining requirements of the individual components have been evaluated to minimize setup steps and rely on the precision capabilities of modern CNC machines. The parts and subassemblies were designed to reduce tolerance stack-up be reducing complexity and part count.

Production prototypes of most components have been produced in small quantities thus far. All of the castings were prototyped and fixtures for secondary machining were used to simulate the production environment. Refinements to designs have resulted from this exercise. Design progress and prototyping of the CCD detector and electronics, IFU, and support structure have also driven changes to the instruments mechanical design. Final designs are nearly complete and production parts will begin fabrication in the coming months with the first operational units expected by the start of 2011. A production line is being set up at TAMU for VIRUS assembly [17].

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