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A novel approach to small form-factor spacecraft structures for usage in precision optical payloads

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ABSTRACT

Precision optical payloads will soon experience a boom in manufacturing scale with the onset of proliferated satellite constellation concepts. Presently, the cost of assembly for a single unit can reach upwards of $500,000. Reduction in recurring engineering and assembly complexity can reduce this figure by up to two orders of magnitude. This paper discusses one potential solution which relies on consistent structural components that are easily manufactured in bulk quantities to facilitate general uses while also enabling high-precision mounting in designated payload slots. This proposed approach combines standardized struts and panels able to be connected and stacked in a variety of ways to form a modular structure from 1U subsections. For the subsections in need of higher precision, slots are milled and reamed from the same standard panel. Within these slots, card-like brackets are mounted to within 10 micrometer precision with the use of low-tolerance gauge spheres. A technique called "screw-pulling" secures these brackets such that the gauge spheres act as nearly single-point-of-contact datums. This approach allows payloads to be tested externally with minimal alignment shifts when re-integrated into the structure and is demonstrated with a 2.2 µm pixel size CMOS sensor and a 23 mm focal length lens.

INTRODUCTION

Precision optical payloads have a variety of uses on orbit such as high-speed communications, navigation, and high-resolution imaging. Due to the directionality of optical operational concepts, misalignments between the payload and spacecraft bus may greatly affect mission performance. These misalignments cause errors in attitude knowledge and reduce the signal-to-noise ratio. While on-orbit calibration techniques exist to reduce errors in alignment knowledge, this paper focuses on reduction of the initial misalignments to reduce manufacturing cost of precision optical payloads.

Optical links include both closed-loop and open-loop tracking. For some multi-payload systems such as laser communication constellations, the optical terminals often have closed-loop acquisition schemes to ensure alignment between spacecraft and increase signal. Misalignments between the terminal and spacecraft bus could increase the acquisition time of such systems. Open-loop systems are less robust to alignment error, requiring technical procedures to measure the alignment prior to launch. In some open-loop systems, there may be no method of calibration on orbit such as single star tracker attitude systems.

Highly Manufacturable General Structure

Novel structural components and processes are major factors in precision optical payload cost. To increase the simplicity of the structural design and conform to the general principles of manufacturability, the generalized structural components stem from two major pieces[1]. These pieces, shown in Figure 1, are the side panels and the connecting support struts, which create the generalized shape of the system.

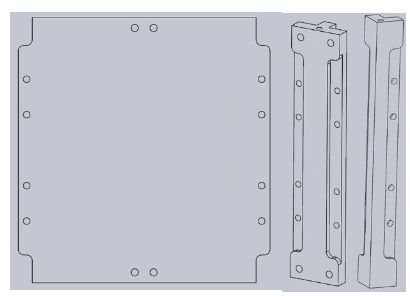

Figure 1: Standardized Structural Components

Using readily acquired aluminum, the raw material may be procured in bulk quantities and easily machined "blanks" manufactured for storage until a payload or mission establishes the cutout requirements during production. The blank panels have a depth of 1 cm to support a variety of potential mounts required, while the strut blanks are a 2 cm by 1 cm by 9.5 cm rectangular prism. This approach creates general 10 cm by 10 cm by 10 cm (1U) subsections to start as the basis for printed circuit board (PCB) layout and optomechanical design. Additionally, by selecting readily available materials and pre-machining the blank templates the procurement time for the payload structure is dramatically reduced during the development phase of a mission[1]. Figure 2 shows some example panel configurations, such as an azimuth-elevation mount panel, a lightweight structural design, and precision payload slots that will be discussed later in this paper.

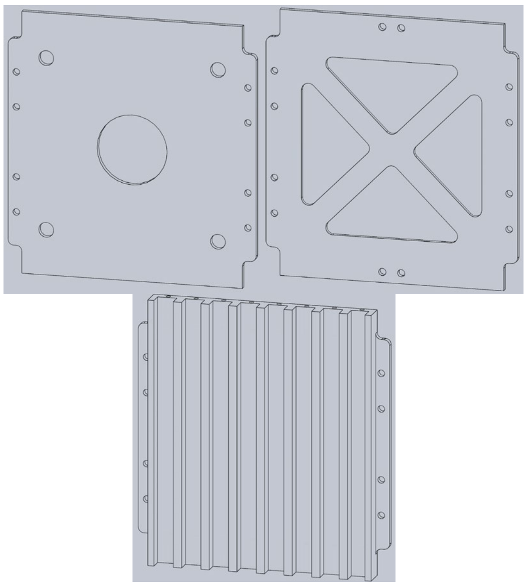

Figure 2: Example Panel Templates

These panels and struts are designed such that the 1U subsections may be extended in any direction to fit a desired bus layout while maintaining consistent rigidity. For example, a primary payload may require a largely hollow 1U or larger space, while a larger quantity of supporting electronics or secondary payloads may be housed in the precision-reamed slot style subsection. Figure 3 is a block diagram showing an example of how the 1U formfactor may be expanded to fulfill specific bus volume requirements. Figure 4 provides an example layout with the previous templates forming a 2U structure with the front-plate removed for visibility.

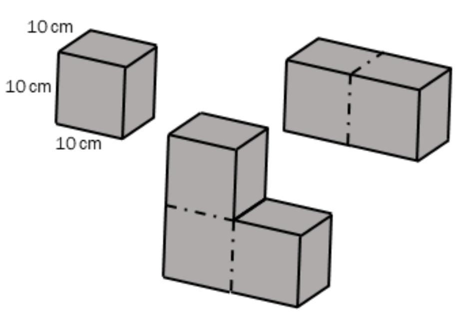

Figure 3: Example Potential 1U Expansions

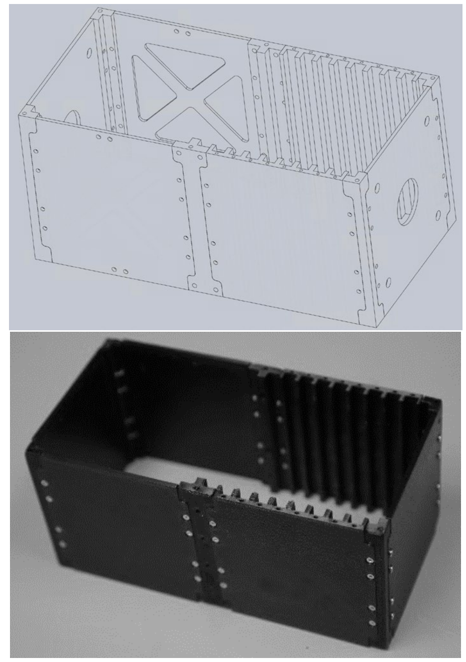

Figure 4: 2U Structural Layout

The dimensions of the blank templates are near to convenient commercial off-the-shelf (COTS) raw sheet and bar stock from various United States distributors. As such, the estimated cost of each 1U subsection is on the order of $50 for the raw materials and fasteners, with the cost of machining and staking being dependent on a manufacturer's resources.

Establishing Datums

Datums define the coordinate system of a structure and affect the interfaces between mating structures. In practice, a datum is a plane, line, point, or axis from which part features are referenced. Datuming is critical for precision placement of hardware due to surface imperfections on one or both interfacing surfaces[2]. Foregoing extremely costly processing methods, surfaces that are designed to be flat will have surface imperfections that impact how one structure is mated with another. For planar faces with surface imperfections, a datum is defined to be the theoretical plane established by the surface's tallest imperfections. Each theoretical datum surface is associated with a physical surface on the structure; this is the datum feature. For rectangular prisms with six degrees of freedom (DOFs), the datums are typically three mutually perpendicular planes. As subsequent datums are defined on a given structure, the number of points required to define this hypothetical plane decreases. For the primary datum, which is the first-defined surface, the hypothetical plane is independent of any other datum references. Therefore, it is defined by the three highest imperfections on the surface, which themselves establish a plane. The next plane, or secondary datum, is restricted by being perpendicular to the primary datum plane and requires only two surface points to form the plane. The tertiary datum requires one surface point and is perpendicular to both earlier datum planes. As such the primary datum restricts motion in three DOFs (one translational and two rotational), the secondary datum restricts motion in two DOFs (one translational and one rotational), and the tertiary datum restricts the remaining one translational DOF. Thus, the structure's position is fully defined in all six DOFs from these datums[2]. Figure 5 provides an example of establishing datums for a structure.

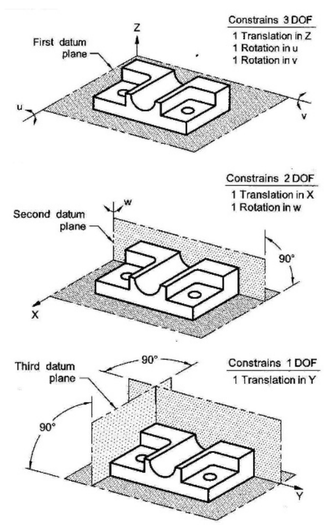

Figure 5: Three perpendicular datum planes[2]

For assemblies that rely on the contact of planar surfaces, consistent ordering of these surfaces is necessary to achieve repeatably precise mates. Due to the imperfect nature of surfaces, the order in which datums are defined affects how one structure mates with another. Datums are named alphabetically, starting with, "A." For complex structures and assemblies, any number of datums may be defined for reference during design, manufacturing, and assembly.

Figure 6 demonstrates the importance of defining datums in a particular order, which must be observed to obtain consistent positioning of a structure in an assembly. Figure 6 can also be interpreted as showing the important of the order of surface contacts between an imperfectly surfaced part and a part with perfectly planar surfaces. This concept extends also to the interfacing of two imperfect surfaces, as the combinations of interfacing surface imperfections can compound to allow for even greater positional variance of the mated structures if a specified order of surface contacts is not considered.

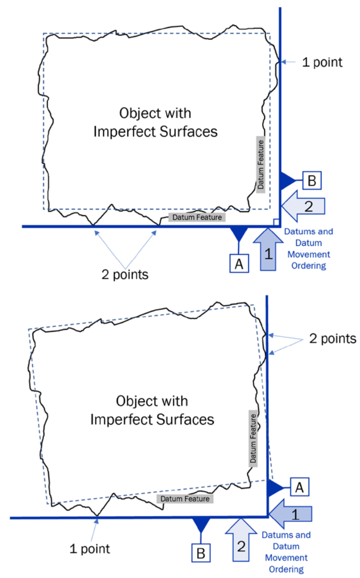

Figure 6: Datum order and part placement effects

Screw-Pulling

The necessity to regulate and maintain the order of surface interactions between two mated structures poses a novel problem for achieving precision placement of one structure that is inserted into another with a tight fit. The insertion scenario forces simultaneous contacts of multiple surfaces and therefore makes the order of surface contact ambiguous. To enforce primary, secondary, and tertiary surface interactions as defined by datuming above, it is conceived that contact order is to be replaced by the enforced strength of surface contacts. This is done by a process developed for this research called "screw-pulling."

Screw-pulling is the process by which specific surface interfaces are reinforced using a screw or screws that pass through one of the contact surfaces and into another. By tightening the screws, the two features are forced to experience stronger interaction with each other. When this is done on multiple locations across a plane, the enforced contact simulates the interaction of datum A by forcing the maximum amount of contact points between the given surfaces. This can then be done on a second pair of surfaces to simulate the datum B, and again with a third pair of surfaces to simulate the datum C, and so on for as many datums as necessary. For a motion-restricted case of three mutually perpendicular pairs of planes, such as insertion of one rectangular prism to similarly shaped cavity, screw-pulling is theoretically only required for datums A and B, as the interactions between the tertiary datum features are already fully defined.

Mechanical Alignment Techniques

Placement of one structure in a secure position relative to another structure has historically been well studied. Many methods exist for affixing two structures, but the reliability with which components may be repeatably removed and replaced with micron precision—by hand—remains to be fully investigated[3].

The field of wood working is rich with methods for sturdy joinery. Of these, "mortise and tenon" joints, "domino" joinery, and "biscuit" joinery were worth superficial investigation. Mortise and tenon joints are mechanical connections between two structures in which a segment of one structure, referred to as the tenon, is inserted into a snugly fitting cavity in the second piece, the mortise[4]. For electrical work or plumbing, these features are analogous to a pair of male and female connectors. These connections are typically held in place by the materials' friction and are supplemented with an adhesive. Figure 7 shows the structure of a mortise-tenon joint.

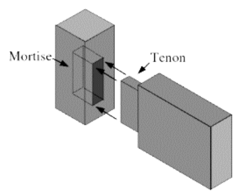

Figure 7: Mortise-tenon joint structure[4]

Occasionally, pins are inserted through the mortise-tenon joint to increase joint cohesion[5]. For remove-and-replace capabilities, adhesives are not allowable, therefore all strength must come from the friction from the tight fit. Unfortunately, this very same joint-enforcing friction will likely cause wear between metal parts, changing the features of the fit after each placement and removal. Additionally, the large contacting surface areas allow for inconsistencies in how the imperfect surfaces mate to each other each time, further lowering placement precision. Figure 8 shows how a pin may be included into a mortise-tenon system.

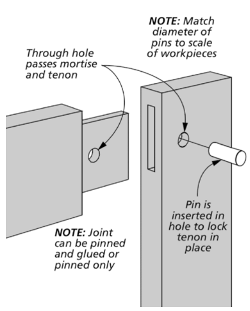

Figure 8: Pin inserted into a mortise-tenon joint structure[5]

Another method, domino joinery, uses a similar concept to mortise and tenon joinery[6]. Where in the previous method the tenon is an extension of one of the bodies to be joined, dominos act as a tenon that connects two mortise structures. This method suffers the same constraints as the mortise and tenon joints: large contact surfaces that allow for placement inconsistencies, and the strength of the connection is largely friction-based.

Biscuit joinery employs the same concept to the same downfalls[7]. What is differentiates this method from the previous two is the shape of the insertion component and the circumstances in which they excel. Biscuits are typically oblong in shape and thinner than the insertion components of the above methods. This means that they excel for thin parts or on angled connections through narrow material. Figure 8 provides a comparison of domino and biscuit joinery on the left and right, respectively.

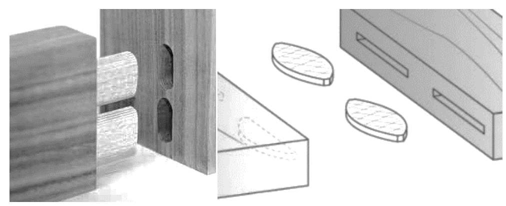

Figure 9: A visual comparison of domino and biscuit joinery[6,7]

In any of these methods, joints are structurally sound, but may be difficult to replicate with precision. Also, these methods may be straightforward to implement on a single face of a structure but are more complicated for a structure that is to be inserted into another structure. Implementation of any of these methods on the faces that slide past each other would require slots to be cut out to allow the sliding motion for installation. These slots would eliminate the restriction of motion in the slide-direction, further reducing placement precision.

Screws or pins alone can also serve to fasten and align a joint between components. Such a technique is called "pocket hole joinery" in woodworking and involves the fasteners passing through one structure and into the other[8]. These joints are common in mass produced items and are considered strong and inexpensive. However, the precision of alignment relies both on the precision of the pockets cut into the materials and the alignment of the pockets at the time of screw insertion. As with all other previous methods, it too has large contact surfaces whose imperfections can interfere with micron-level placement precision.

Based on research done by Daniel Hillsberry, applying a constant force onto a structure that is supported by spherical ball bearings in all three axes allows for repeatable precision placement of the supported structure[3]. Due to the nature of their application, these spherical ball bearings are referred to as "gauge spheres." The support from gauge spheres allows for theoretical single-point contact locations between the support structure and the part being placed, which eliminate imprecisions in placement from surface imperfection interactions. Hillsberry shows that a structure can repeatably be removed and replaced by hand with placement consistency more precise than was detectable by the 7 µm measurement precision capability available for that study. Hillsberry's research outlines using gravity as the constant force and employed this method for structures being placed in stationary mounts that resemble the interior corner of a cube, with his test setup shown in Figure 10. As such, this current research is needed for adapting the system to more fully enveloped structures for application in dynamic environments.

Figure 10: The UF Remove and Replace Dynamic Optical Bench[3]

Analysis of Alignment Methodologies

The precision of surface interfaces in assemblies is affected by two primary factors: area of surface contact and the quality of the interfacing surfaces[2].

Surface roughness average (Ra) of the assembly components will affect the possible repeatability of precise placement. The number of possible states for relative positioning between components are reduced when surface interface areas are reduced, or the interfacing surfaces are smoother. Since, surface finishing cannot feasibly achieve perfect planarity, the reduction of contact areas should be the primary method for reducing the allowable states as much as possible. Even still, surface finishing can make a significant difference in the precision of a surface. Figure 11 illustrates the typical surface qualities yielded from different surface finishing methods. In any case, to achieve repeatable precision placement, efforts should be made to both increase surface smoothness and decrease surface contact areas.

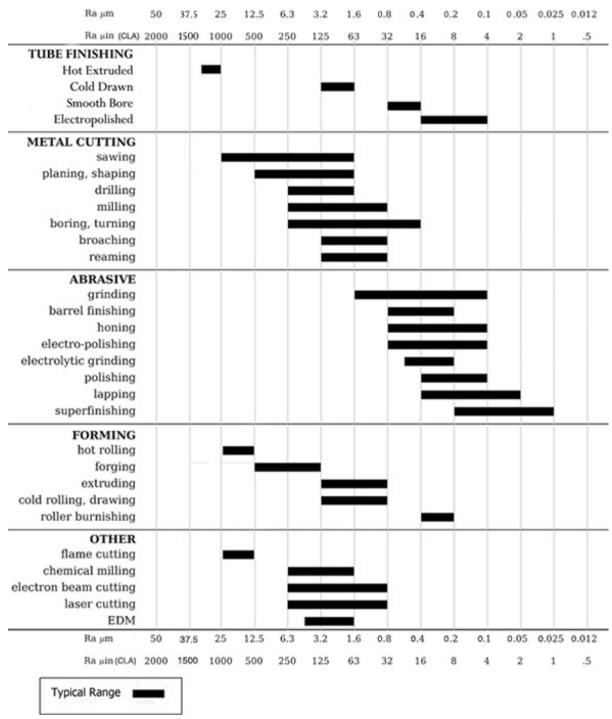

Figure 11: Indicative surface roughness comparisons[9]

Gauge spheres manufactured to varying degrees of precision are readily available for purchase. McMaster-Carr sells gauge spheres in steel, stainless steel, aluminum, ceramic, and glass, each in multiple variants and diameter tolerances. The listed tolerances in Table 1 are what may be procured for spheres of imperial sizes reasonable for the application relevant to this research[10].

The tolerances of these products range from as low as ±0.254 µm for the Acid-Resistant Silicon-Carbide Ceramic Balls to as high as ±254 µm for the Hollow Corrosion-Resistant 3003 Aluminum Balls. For integration in space applications, the focus will be put on Steel, Stainless Steel, and Aluminum components. With tolerances at the larger limits of the range, the aluminum products are not likely to be chosen for micron-level precision applications. Steel and stainless steel products both have candidate products with tolerances on the order of ±3 µm or better and therefore can be considered for this application[10]. In addition to dimension tolerances, sphericity is also a relevant tolerance. For a perfectly spherical gauge sphere and a perfectly planar surface where neither deform, there will be exactly one point of contact. This would mean perfectly replicable mates given proper installation. Realistically, a sphere is the prime candidate for achieving minimized contact area between two structures, even when the sphere and plane are both imperfectly manufactured surfaces.

Table 1: Example Gauge Sphere Materials and Their Diameter Tolerance[10]

Gauge Sphere Material	Diameter Tolerance
Steel	±0.00005" to ±0.005"
Stainless Steel	±0.0001" to ±0.001"
Aluminum	±0.001" to ±0.010"
Ceramic	±0.00001" to ±0.0002"
Glass	±0.0002"

The theoretical single point of contact that occurs when a sphere is pressed against a plane creates a small area of contact. Pressures over small areas of contact experience Hertzian Contact Stress which are extremely high material stresses due to interface geometry of single-line or single-point contact; common examples including wheel-and-rail interfaces and the mating of gear teeth[11]. The resulting stresses cause deformations in the surfaces wherein the spherical surface generates a dent in the planar surface, enlarging contact area until stresses are lessened to levels not sufficient for material deformation. The depth of these dents (δ) is dependent on modulus of elasticity (E), interface diameters (d), and the force binding the structures together (F). For metals with high elastic moduli, deformations are typically small. Equation 1 is used to calculate the deformation due to Hertzian Contact Stress[11].

$$\delta = 0.77\left(2F^2\left[\frac{1}{E_1}+\frac{1}{E_2}\right]^2\left[\frac{1}{d_1}+\frac{1}{d_2}\right]\right)^{\frac{1}{3}} \qquad (1)$$

Biscuits are typically manufactured out of a wood byproduct for use in joining wooden components; they are not engineered for precision tolerances[7]. Moreover, any COTS wood biscuits would likely be too large for use in small satellite applications; standard sizes for biscuits are shown in Table 2. Therefore, any application of biscuit joinery in small satellite applications would likely require machining of precise biscuits of a custom size, further increasing cost of manufacturing.

Table 2: Standard Biscuit Sizes[7]

Trade Size	Length	Width	Thickness
FF	0.5"	1.375"	0.15625"
0	1.75"	0.625"	0.15625"
10	2.125"	0.75"	0.15625"
20	2.375"	1"	0.15625"

Dominos face a similar problem as biscuits: any COTS products would be too large and too imprecise for this small satellite application. The smallest standard size is 4 x 17 x 20 mm. A general rule of thumb for both dominos and mortise and tenon joints is that the width of the inserted material should be about one third the width of the two surfaces being joined. This means the joining faces should be at least 12 mm, or nearly half an inch wide. Custom dominos would have to be designed and manufactured, increasing production costs and lead times[1].

A mortise and tenon system may be integrated into the design of structures and would therefore achieve appropriate sizing. The presence of protruding surfaces as tenons may complicate manufacturing, however.

Even with appropriately adapted sizing for biscuits, dominos, or mortise and tenon joints, the reliance of these methods on large contact areas between imperfect surfaces is a source of imprecision[2]. Repeatedly precise placements are not guaranteed when imperfect surfaces mate. To aid in this issue, surfaces can by highly treated to reduce roughness. These processes can be costly and time consuming and reduce imprecision, but do not eliminate it[1]. Surface contact should be minimized wherever possible, and these methods rely on surface contact and the resulting friction.

Pocket hole joinery with pins or screws requires large contact surfaces between the joining structures but relies primarily on the pins or screws for alignment precision[8]. This alignment would be subject to the precision of the hole diameter and screw or pin diameter. Use of pins to secure one structure to another would require interference fits which, due to the nature of the interface, would alter the pins' and holes' surfaces with each placement and removal. This means the precision of repeated placements is not guaranteed and limits the number of fastenings allowed to meet a required tolerance. Fixture by use of screws relies on interactions of highly complex helical surfaces on the screw and structure, which are not guaranteed any appreciable amount of precision and further increase manufacturing costs[1]. It is the conclusion of this analysis that repeatable micron-level precision alignment for small satellite applications should be explored with gauge spheres; which is done in the design discussed below.

DISCUSSION

This paper primarily discusses a method which facilitates repeatable precision placement of one component into another: a bracket into a slot. Although multiple units of each structure are to be manufactured and implemented, the goal of the design is to ensure repeatable precision placement of one given bracket into one given slot. So, a bracket 'a' is to sit in slot 'A' to a micron-level precision, repeatably. Additionally, bracket 'a' is to do the same if placed into slot 'B.' However, the a-A fit position is not guaranteed to be the same as the a-B fit position. The same can be said for two different brackets in the same slot: a-A is micron precise; b-A is micron precise; but the a-A and b-A positionings are not guaranteed to be the same. Thus, each bracket-and-slot pair can be thought of as a unique system, all of which individually attain unique repeatable micron-level precision. Therefore, the similarity of component parts between units, such as the manufacturing variability of the gauge spheres, is not of significant concern provided each component is within specified manufacturing tolerances.

The size and shape of each bracket is manufactured to conform to a pre-designed slot structure that is built into a CubeSat form factor. The slot structure fits within a 1U form factor and each bracket is contained by a single slot. A 'slot' is defined as the pair of trough structures—one on each side of the bracket—into which a bracket is inserted. The troughs are flanked by the teeth that brace the bracket on either side. A 2U CubeSat design and slot structure are shown in Figure 4; the slots exist within the 1U portion of the spacecraft on right half of the design.

Gauge Sphere Retention and Affixation

Designing a bracket to fit precisely into a predetermined CubeSat form factor using gauge sphere-based alignment methods requires intentional selection of how the spheres are to be retained. Design concepts are considered for their ease of manufacturability, implementation, and expected precision. Slots cut out of material blanks, materials with recessed edges sandwiched between two overhanging tabs, flat-bottomed drilled holes, holes with vents from adjacent faces, and drill-bit formed holes with parallel vent holes are conceived: the latter design being chosen. Figure 12 shows the final selected design while Figure 13 illustrates the four previous design concepts.

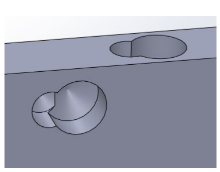

Figure 12: Selected Gauge Sphere Retention Method

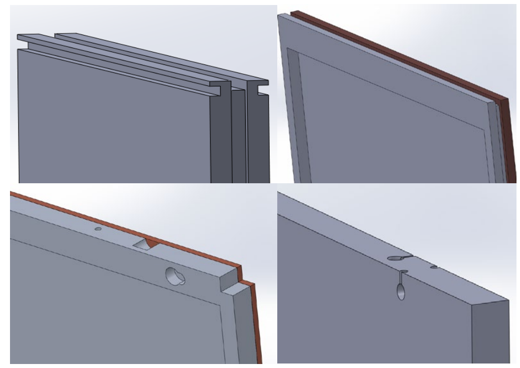

Figure 13: Iterations of Gauge Sphere Retention Concepts

The sphere affixation methods that are considered are retention via a shim that was to be screwed into the bracket, or an adhesive inserted directly into the drilled hole of the bracket. The shim is to have a circular cutout through which the slot-interfacing contact surface of the gauge sphere extended. The retention of a sphere in a cylindrical recess by a shim requires at least half of the diameter of the sphere to exist within the recess. To secure the sphere to the bracket, the shim must make contact between the equator and the exterior pole of the sphere. This affixation technique is shown in Figure 14.

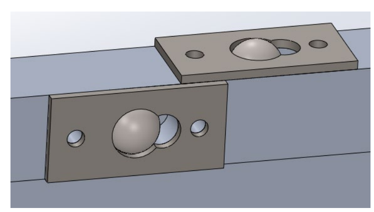

Figure 14: Retention of Gauge Spheres via Shims

The shim method is eliminated due to the scales required for such a mechanism to be manufactured. The shim would require a thickness that allowed the exterior pole of the sphere to protrude over the edge of the shim, meaning the shim must be less than the radius of the sphere. However, the allotted size for each bracket restricts the allowable gauge sphere diameter. Preliminary investigation demonstrated that the gauge spheres are to be on the order of 0.125 inches. Therefore, shim thickness could be no more than 0.0625 inches, and likely should be significantly thinner to ensure no shim-slot interference at different fit positions. Additionally, this same clearance is to be allotted for any adhesive or fastener that holds the shim to the bracket. This would require the thickness of the shim to be on the order of 0.03125 inches and the use of fasteners with ultra low-profile heads. The required thinness of the materials, and the number of additional parts: at least one shim and two fasteners per gauge sphere, make this design undesirable due to the added complexity and increased manufacturing costs[1].

Thus, the alternative adhesive-in-hole affixation method shown in Figure 12 is selected. The secondary shafts drilled into the bracket serve as both a vent for air release, and as a reservoir for adhesives forced from the sphere's hole upon insertion. This reservoir allows the sphere to be pushed fully into the drilled hole without concern that the presence of the adhesive would prevent full insertion. This method is plausible, even at the small scales required by the design objectives.

Manufacturing of Precision Mounting Holes

The nature of the drill-bit used in creating the gauge sphere recesses affects how deeply the sphere sits into the mounting hole. How a sphere sits in recesses cut by each of the three most common drill bit tip angles is shown in Figure 15. Because the sphere is to sit in the conic drill-tip feature, there is a ring of sphere-feature contact; the more obtuse the angle of the bit, the lower that contact ring is on the sphere, causing that sphere to sit deeper into the shaft relative to the cylindrical portion of the recess.

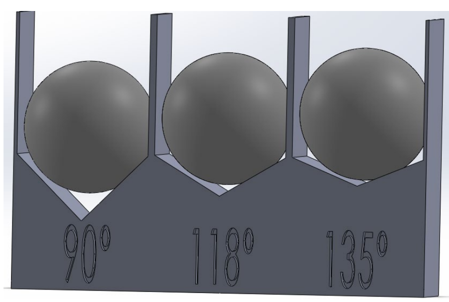

Figure 15: Effect of Drill Bit Geometry on Gauge Sphere Insertion

After application of all relevant concepts discussed, an initial design is conceived. This design is bare-bones and serves as a concept qualification prototype for the one-slot bracket. By adding generalized design features, a variety of payloads may be mounted to the simplified bracket design[1]. Bolt patterns through the middle of the large face of the bracket and cutouts for wide component clearance near the sides are added as an example layout for printed circuit boards (PCBs) with larger components in Figure 16. This prototype has proven preliminary ability to hold equipment of interest and mate successfully with the slot. Further, the bracket design has been adapted into a multi-slot bracket which can hold larger components such as star trackers, baffles, and other precision optical payloads.

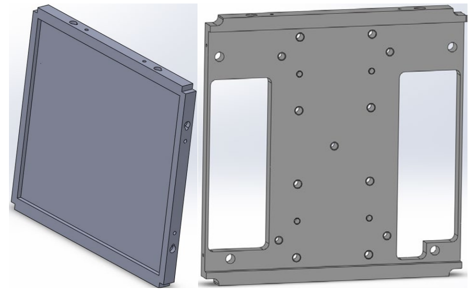

Figure 16: Blank Bracket Template and Example Mounting Bracket

Preliminary examination has concluded that this design concept is extendible to any scale of small satellite. As the current design is built for fitting within a 1U subsection of a CubeSat, investigation into enlarging the design is ongoing. The design concepts underlying the achievable repeatable precision are irrespective of scale. A sphere on a plane will be in contact at a single point, no matter the size of the sphere or plane. In fact, due to surface imperfections and the nature of Hertzian Contact Stresses, use of larger spheres will reduce surface deformations of interfacing structures that result from a given screw-pulling force[11]. However, preliminary data shows that any Hertzian Contact Stress deformations that would exist with the intended screw-pulling force and chosen materials are not of significant concern. Additionally, an increase in manufacturing cost is directly related to maintaining equivalent precision over a larger surface area[1]. Even without scaling the current design of the interfacing components, this exact design of gauge sphere, hole, and slot can be used in larger systems for which the body of the bracket is enlarged as necessary. Preliminary investigation shows that the current design can withstand the thermal and vibrational environment that are expected for the proposed use of the design.

CONCLUSION

Manufacturing optical payloads at scale will require precise, repeatable, low-cost assembly solutions while maintaining high-performance mission requirements. This paper presents a novel approach to high-precision mounting of optical payloads that could reduce cost of component installation by up to two orders of magnitude while also facilitating lower precision, general-use volumes. This method is adapted from test assembly techniques used in the Laser Interferometer Space Antenna (LISA) mission research. The precision of the system is preliminarily demonstrated to be within desired values, even when optical payloads are installed by hand due to novel use of gauge spheres, datuming, and screw pulling.

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