A Novel Hemispherical Anti-Twist Tracking System (HATTS) for CubeSats

Eli Bashevkin, Joseph Kenahan, Brian Manning, Brian Mahlstedt, Andrew Kalman
Space & Systems Development Laboratory, Stanford University
496 Lomita Mall, Stanford, CA; (650) 723-2849
ebashevkin@stanford.edu, jkenahan@stanford.edu, manningb@stanford.edu, bmahl@stanford.edu,
aek@stanford.edu

ABSTRACT

Satellites must often point a device continuously at an object while the satellite and/or object move through space. With these devices, connections are typically made between the articulated device and a fixed base around which the device rotates in one or more axes while tracking. Implementing these connections can be a challenge in size-constrained applications or when uninterrupted tracking is required. Within the small satellite realm, some new solutions (e.g., Canfield joint) have recently been developed to address this problem. Given the mass and volume constraints imposed upon CubeSats, the authors feel that none of the existing solutions solve the problem elegantly or efficiently. A new, simple two degree-of-freedom (2-DOF) joint - the Hemispherical Anti-Twist Tracking System (HATTS) - is proposed that allows continuous tracking through a hemisphere with continuous rotation while avoiding any twist in the connection(s) from the device to the base. This design is notable for its simplicity and its ability to continuously rotate. The HATTS joint has a reduced component count and fewer interfaces between moving parts than other solutions, thereby potentially increasing pointing accuracy while lowering cost, mass and complexity. In the CubeSat-specific implementation (CubeHATTS), two identical motors are rigidly affixed to the chassis of the satellite and provide the two DOFs via a jointed elevation arm and dual coaxial gears operated either synchronously or differentially. CubeHATTS is able to track continuously through a hemisphere and when stowed, the entire system fits in a volume of approximately ¼ U (10cm x 10cm x 2.8cm).

NOMENCLATURE

r : *radial distance from origin in spherical coordinate system*

ϕ : *polar angle measured from zenith direction in spherical coordinate system*

θ : *azimuth angle in spherical coordinate system*

INTRODUCTION

Many applications require the ability to continuously point a device (payload) at an object as that object moves through space. With active devices, connections (electrical, fluid, etc.) are typically made between the moving payload and a fixed base, around which the payload rotates in one or more axes while tracking. To prevent twisting of these connections, existing systems either use electrical slip rings or rotary fluid couplings for uninterrupted motion. Systems that do not require continuous tracking may use an unwinding operational procedure after a certain number of revolutions. A few designs have been proposed to allow continuous tracking without the use of slip rings or rotary fluid couplings. Potential applications include satellites, solar arrays, telescopes, cameras, turrets, antennas, wind turbines, radar, and satellite dishes.

Detailed design work has been completed on a HATTS implementation suitable for pointing a CubeSat's solar array, but this is only one of many possible applications for the HATTS joint. For example, the pointing system for "The Dish" radio antenna at Stanford University is only able to rotate twice about its azimuth direction before it must unwind to prevent damage to the antenna cables. Implemented with the HATTS joint, antennas such as this would be able to continually track an overhead object. Similarly, more terrestrial devices such as camera mounts and gun turrets would have the ability to continually track their target of interest regardless of their motion when implemented with a HATTS joint. Further discussion in this paper is limited to satellite applications, but the applications for the HATTS joint are not.

With CubeSats continuing to gain popularity in both educational and commercial satellite markets, the capabilities and requirements of these satellites are growing as well. The fixed solar panels that could handle the power requirements of earlier CubeSats are inadequate for emerging high-power CubeSats. Given the volume and mass constraints of the CubeSat Design Specification (CDS), simply adding more solar panels is often not an option, thus designs must maximize the efficiency of the panels that fit within the permissible stowed volume envelope.

The power that a solar panel can generate is proportional to the projected area along the vector towards the Sun, so it is vital to orient the panels directly at the Sun for maximum efficiency. This presents a major challenge not only in CubeSats but also in larger satellites. Most satellites in a geosynchronous orbit (GEO) use a simple 1 DOF solar tracking system that provides adequate performance. However, in low earth orbit (LEO), 2 DOF or higher DOF systems are needed to efficiently track the sun throughout an entire orbit. It is therefore highly desirable to produce a system that can rotate an array through an entire hemisphere by varying both a rotation and elevation angle from the satellite while minimizing system complexity. For a CubeSat application, the system should also take up no more than ~0.5U (10cm x 10cm x 5cm) when stowed, as tracking systems larger than this would greatly limit the available remaining payload volume.

In the stowed configuration, the CubeSat HATTS (CubeHATTS) implementation takes up approximately 10cm x 10cm x 2.8cm. The unit is designed with many commercial off-the-shelf (COTS) parts so as to leverage economies of scale for increased reliability and lower cost. The joint addresses the requirements of controlling 2 DOFs in a very small volume by using a jointed elevation arm and two identical, radially-mounted motors driving coaxial gears to vary the elevation and rotation. The wire twist issue is solved by the HATTS joint, which uses a gear linkage between the solar array and satellite body to prevent relative rotation. This gear is implemented as a ball gear that is engaged at relative angles varying from 0° to 180° to keep the panels from spinning with respect to the satellite body.

BACKGROUND

Problem Definition

An analysis was conducted to identify all the stakeholders in a CubeSat tracking joint and their respective values. These stakeholders were then ranked on a 1-10 scale according to their relative importance to the success of such a joint. The results are summarized in Table 1.

A Quality Function Deployment (QFD) was used to translate the stakeholders' values into design requirements. The four most important requirements were:

- Full hemispherical pointing
- Continuous tracking capability
- Volume < ½ U (10cm x 10cm x 5cm)
- Surface area consumed < 25% of 3U CubeSat

Table 1: Key Stakeholders and Values

Weight	Stakeholder	Values
10	Satellite Owner/Operator	• Affordability • Power generation capabilities • Interference • Regulatory compliance • Novelty • Ease of operability • Mission risk • Satellite development time
10	CubeSat Bus Manufacturer	• Return on investment • Marketability • Project risk • Ease of subsystem integration
10	Launch Provider	• Regulatory compliance (mass and volume)
10	Standardization Regulator	• Regulatory compliance (mass and volume)
10	Investors	• ROI • Project Risk • Company Image
8	Payload Designer	• Power generation capabilities • Reliability • Interference
6	Insurer	• Unit Affordability • Mission Risk
1	Part Suppliers	• Production Volume

HATTS CONCEPT

The HATTS joint was developed specifically to solve the tracking problem. It is a 2-DOF joint, the minimum required for a tracking system, and is able to continuously rotate about its zenith direction. Internally, the HATTS joint can be viewed as having three distinct motions: rotation about its zenith direction (θ), rotation of the polar angle down from its zenith direction (ϕ), and twist about the joint's pointing direction. The twisting motion is coupled 1:1 to the rotation direction θ such that for each complete revolution in the θ direction the joint also rotates once about its pointing direction. This coupling eliminates relative twist between the joint's payload and the base of the joint while preserving the desired two degrees of freedom.

Fundamentally there are only four different components to the HATTS joint, each corresponding to a specific motion of the joint. These components are presented in Figure 1. Part 1 is the fixed portion of the joint and includes the joint's base and the fixed ball gears, which are described in more depth below. Part 2 is the rotation platform and sets the θ angle. Part 3 is the elevation platform. This component is mounted on the rotation platform, and so moves with it in the θ direction, and

also sets the φ angle. Part 4 is the anti-twist segment of the joint. This component moves with part 3 but is allowed to twist relative to it. The ball gears on part 4 interface with those in part 1, coupling their respective orientations to prevent relative twist between them.
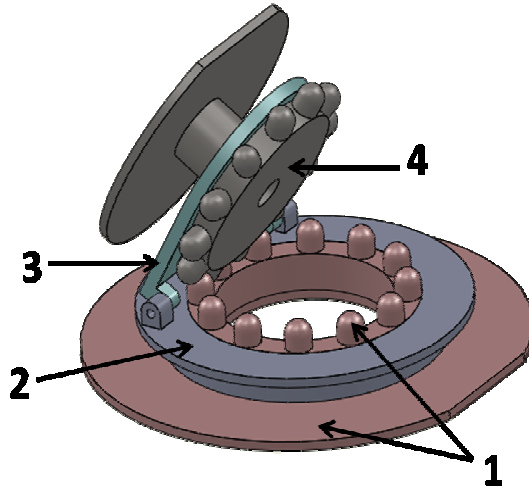

Figure 1: The HATTS Joint

In the current iteration, ball gears are used to couple the θ and twisting motions, though other coupling mechanisms are being considered. Ball gears are well-suited for this use because they are able to engage through a large range of angles. The current ball gear system imposes a constraint that the axis about which the joint rotates in the φ direction must pass through the ball gear contact point. This allows for the same contact point of the gears regardless of their engagement angle. Coupling schemes other than ball gears may not require this constraint on the location of the φ rotation axis.

CUBEHATTS JOINT

We designed an implementation of the HATTS joint for use on CubeSats, which we refer to as CubeHATTS. CubeHATTS as presented in this paper was designed to be the gimbal joint for a CubeSat solar array, and design decisions were made with this application in mind. This application was picked as a most common usage scenario, however with little to no modification CubeHATTS as presented could be adapted for other payloads, including antennas and sensors. In order to comply with our university's export control policies, we limited CubeHATTS development to TRL 4, which influenced a number of design decisions and led to the use of COTS (i.e., not uniquely space-grade) components wherever possible.

We built a complete model of CubeHATTS in SolidWorks with all components, including the nuts, bolts, and selected motors. In its current revision

CubeHATTS measures 10cm x 10cm x 2.8cm when stowed and has a mass of 250g. It is expected that with future revisions the height will be reduced to 2.5cm and the mass will be significantly reduced. A number of innovations were used to pack the HATTS joint into this small volume, and are described below.
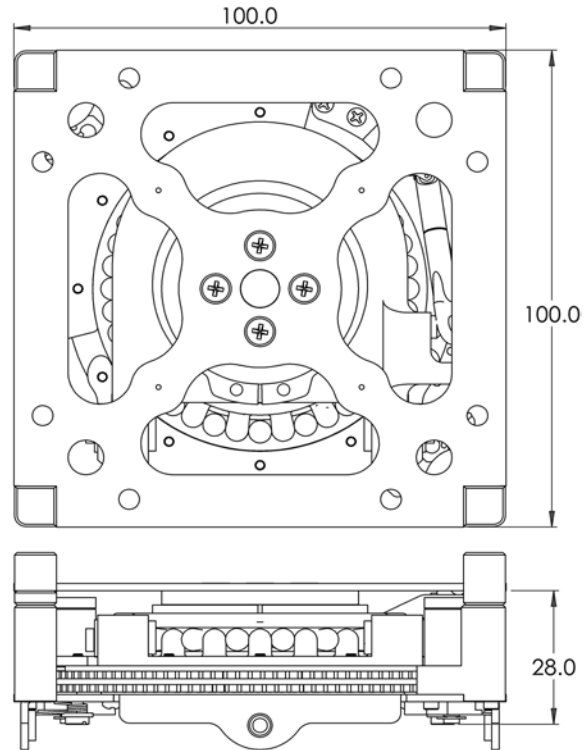

Figure 2: Engineering Drawing of CubeHATTS in Stowed Configuration, Top and Side Views

Telescoping Arm

Due to the comparatively large size of CubeSat solar panels, the joint needs to be able to extend the solar panels out past the sides of the CubeSat structure in order to be able to rotate a solar array through a full hemisphere. We included a telescoping arm in CubeHATTS to allow it to reach over the side of a CubeSat but still stow into a small volume (see Figure 5). A burn wire releases the arm that is then extended by a spring to its full length. After it has been deployed, the arm remains extended for the duration of the life of the satellite, held in place by the internal spring. The telescoping arm can be seen deployed in Figure 3. Throughout its entire hemisphere of operation, the plane of the top of the telescoping arm never intersects the CubeSat structure (not shown) below it.

In its solar panel application, CubeHATTS has one deployment event: the extension of the telescoping arm. This extension action can be combined with the deployment of the solar array and used to

simultaneously deploy CubeHATTS and a number of solar panels. In HATTS applications that do not require extension over the edge of the satellite for clearance reasons, the telescoping arm would be unnecessary and no deployment events would be required.
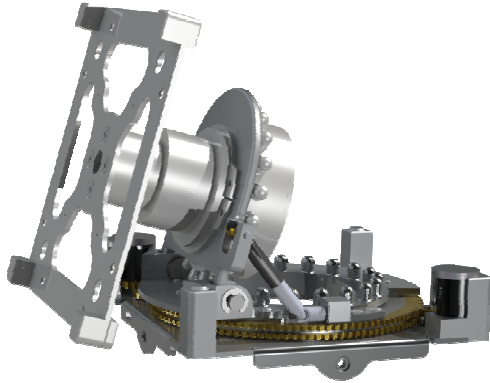
Figure 3: CAD Rendering of CubeHATTS with Telescoping Arm Deployed

Dual Coaxial Gears

We developed a system using two coaxially mounted gears to control the two degrees of freedom. The two coaxial gears can be seen in Figure 3 and Figure 4, located vertically between the joint's base plate and the bottom ball gears. Two identical motors drive each of the gears separately.

The lower coaxial gear is affixed to the rotating platform of the joint (part 2 in Figure 1). Driving this gear moves the joint in the θ direction. The upper coaxial gear floats on the rotating platform, and therefore can move relative to it. A linkage, referred to as the elevation arm, connects this gear to the elevation platform (part 3 in Figure 1) and is discussed in greater detail below.

The ϕ angle of the joint can be set by moving the upper coaxial gear relative to the lower gear (i.e., by changing the phase difference between them). When the phase difference is increased the upper coaxial gear moves the base of the elevation arm towards the ϕ rotation axis, "pushing" up the elevation platform and increasing ϕ. Conversely, decreasing the phase moves the base of the elevation arm away from the ϕ rotation axis, "pulling" the elevation platform down to a smaller ϕ angle. Thus, to remain at a fixed ϕ the upper and lower coaxial gears are driven in phase and to change ϕ the phase difference between the gears is changed. As long as the necessary angular velocity is below the maximum speed of the motors ϕ can be controlled independent of θ.

A detail of the elevation arm as implemented on the CubeHATTS prototype can be seen in Figure 4. In this implementation, the elevation arm is composed of a COTS rod end attached to a COTS U-joint. The U-joint is pinned to an aluminum bracket, which is then attached to the top of the upper coaxial gear. The rod end is attached to an appropriate fitting on the elevation plate. Therefore, the elevation arm in the CubeHATTS prototype adds four joints to the HATTS design. We believe that a ring-and-pinion approach along the ball gear contact point axis may be able to replace the elevation arm, thereby eliminating these joints; this remains a topic for further investigation.


Figure 4: Elevation Arm in CubeHATTS Prototype

We investigated several different designs to drive the elevation angle. Of these designs, the dual coaxial gears with an elevation arm was most efficiently able to make use of the excess volume in the stowed configuration of the joint, and so was deemed best suited for the volume-constrained environment of a CubeSat.

CubeHATTS Advantages

CubeHATTS uses two identical motors rigidly affixed to the base of the joint. Only one motor type must be qualified for use, and neither the motors nor their wiring ever move while operating the joint. Additionally, these motors can be located anywhere radially with respect to the two coaxial gears. On CubeHATTS we mounted the motors in opposite corners of the satellite to best utilize the existing available volume.

The unique coupling between the ϕ and θ directions from the dual coaxial gear system can be leveraged to help restore functionality if the joint suffers from a single motor failure. If either motor fails and locks up, the other motor can still be used to change the phase difference between the coaxial gears and adjust the elevation angle. The joint can either be returned to a known "home" or $\phi = 0°$ position or can remain operating in 1-DOF mode to allow a satellite to continue limited operations.
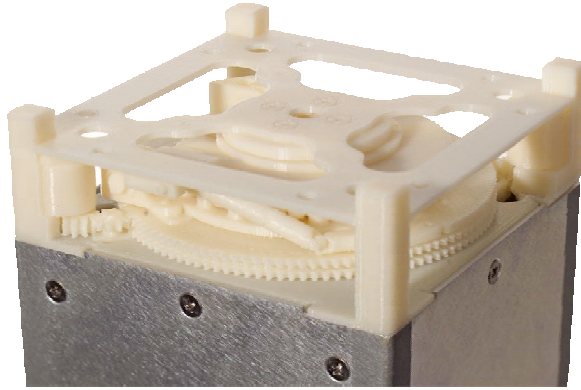
Figure 5: 3D-printed Mockup of Stowed CubeHATTS Affixed to CubeSat Chassis

Table 2: Summary of CubeHATTS Characteristics

Metric	CubeHATTS
DOF	2
Internal Joints	4(+4)
Motors / Actuators	2
Relative Twist	No
Sprung Motor Mass	None
Mass & Volume	250g, ¼ U
Manufacturing Sensitivity	Low
Susceptibility to Gimbal Lock	None
Single motor failure mode	-Retains elevation DOF -Return to home position
Motor Location	Radial, rigidly fixed to chassis
Torque Profile	Varies with position

HATTS Limitations

HATTS has some specific limitations and as such is not ideal for all applications. There exists a singularity at the $\phi = 0°$ position, where the θ rotation axis aligns with the pointing direction of the joint. In this position a degree of freedom is lost as only changing the ϕ direction will alter the pointing direction of the joint. This singularity only presents a response-time problem; all positions can be reached from this position, but certain positions will be slower to reach than others as a less-than-optimal path must be taken. This singularity also prevents uninterrupted slewing from $\phi = -90°$ to $\phi = 90°$. As the joint reaches $\phi = 0°$ in this operation, an infinite-speed rotation by 180° in the θ direction is required to continue slewing uninterrupted. Due to real motor limitations a small perturbation off the desired path near $\phi = 0°$ is required to complete this slew operation.

ALTERNATIVE SOLUTIONS

We identified two alternative joints for a CubeSat tracking system: a conventional 2-DOF gimbal and a Canfield Joint. These joints are described below, and a comparison is presented in Table 2.

Conventional 2-DOF Gimbal

Conventional 2-DOF gimbals are widely used and can be seen in applications such as ground-based tracking antennas or gun turrets. This type of joint operates like HATTS with the anti-twist segment removed. Traditionally, one motor drives the rotation of the joint in the θ (i.e., azimuth) direction while a separate motor mounted on this rotating portion drives the rotation in the ϕ (i.e., elevation) direction. The elevation motor typically moves with changes in azimuth.

These joints exhibit relative twist between the payload and the base of the joint. Two solutions are used to prevent this relative twist from damaging components: slip rings or operational untwisting. Slip rings enable an electrical connection to be maintained between two bodies rotating relative to each other. Disadvantages of slip rings include their complexity, size and the additional failure modes they introduce. An alternative to slip rings is to use operational procedures to prevent the joint from twisting cables too far. In practice, this consists of allowing the joint to rotate a fixed number of revolutions in either direction before it must reverse its direction and untwist any connections.

Canfield Joint

One novel solution that was considered was the patented Canfield joint, which utilizes three independently driven arms arranged in a triangle to connect the platform of the joint with its base. Each arm includes three hinges and two twist joints, and by controlling each of the arms independently it is possible to orient the platform within a hemisphere. The Canfield Joint is an inherently 3-DOF joint; in addition to pointing through a hemisphere it can independently control r. As such, it requires three motors to operate. A model of a Canfield Joint can be seen in Figure 6.
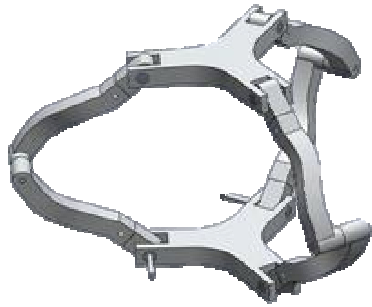
Figure 6: A Canfield Joint

We consider the Canfield joint's need for three motors to operate to be a drawback, asthe additional motor over a 2-DOF joint consumes additional space and power and adds an additional failure point to the joint. The large number of hinges and joints also gives us pause.

Table 3: Comparison of Gimbal Joints

Metric	HATTS	Conventional 2-DOF	Canfield
DOF	2	2	3
Internal Joints	4(+4)	2	15
Motors / Actuators	2	2	3
Relative Twist	No	Yes	No
Sprung Motor Mass	None	Yes	None
Mass & Volume	250g, ¼ U	Unknown	Unknown
Single Motor Failure Mode	• Retains elevation DOF • Returns to home position	• Retains control of remaining DOF	• Limited motion, dependent on joint position at time of failure
Motor Location	Anywhere outside of joint	At each internal joint	Triangle at base of joint
Torque Profile	Varies with position	Constant	Varies with position

DEVELOPMENT PROGRESS

Development work within SSDL has been ongoing to confirm the feasibility of some of the key aspects of CubeHATTS as well as to characterize the behavior of the HATTS joint. In less than two months, we designed, built, and tested a CubeHATTS prototype to verify key performance parameters.

Risk Assessment

We conducted an analysis to select the aspects of CubeHATTS that presented the greatest programmatic risks and were best suited for early risk reduction. The areas selected were the motor sizing and bearings, coaxial gears and elevation arm, and ball gear arrangement. CubeHATTS uses all plain bearings, and we decided to study the friction in these joints and the motor torque required to drive the joint at the desired speeds. We selected the coaxial gear and elevation arm arrangement for study to investigate how precisely this allowed us to control φ. While we had conducted extensive CAD analysis to check for interference problems with the ball gears, we wanted to physically test the backlash and friction in the gears as well as their sensitivity to manufacturing defects.

CubeHATTS Prototype

We created a prototype in order to test the areas selected for risk reduction. The prototype was designed to be representative of CubeHATTS but we intentionally chose to exclude the tensioned idler gears between the motors and coaxial gears, as well as the telescoping arm, to speed up development. The testing unit fits within the 10cm x 10cm CubeSat footprint. We used a university machine shop to modify COTS components where necessary and used an online machine shop to manufacture all custom components. This constrained us to design all custom parts for a three-axis CNC with ±0.005" (0.13mm) tolerance, but in exchange provided less than one week turnaround from part submission to part delivery. All machined parts were made of 7075-T6 aluminum, left in its natural state (i.e., not anodized). Critical plastic parts were made via an online service from a material extensively tested at NASA Ames Research Center.

We designed each set of ball gears to be manufactured as one piece on a three-axis CNC mill. We requested a light bead blast to smooth defects from the surface milling process used to create the individual balls, and subsequently tumbled the parts as well. Designing one-piece gears rather than individually manufacturing each ball and fastening them to a central unit reduced manufacturing time and cost and also allowed us to test the impact of loose manufacturing tolerances on the ball gears.

Figure 7: CubeHATTS Prototype

To simplify the system, we mounted the motors underneath the joint and rapid-prototyped an elevated base upon which we mounted the base of the joint, creating room for the motors. In place of the telescoping arm we manufactured a fixed arm of similar dimensions on SSDL's 3D printer. We placed 0.002" (0.05mm) thick Kapton® sliders between metal-on-metal and metal-on-plastic interfaces to minimize friction within the associated joints.

We installed four LEDs at the end of arm and powered them from a nine-volt battery in the base of the joint to demonstrate the untwist ability of HATTS. The actual, working prototype is shown in Figure 7.

Testing Results

Testing with the prototype has been extremely successful and all initial testing goals have been met. We have effectively demonstrated the ability of the motors to move the joint and have characterized the internal friction. The coaxial gear system has worked as designed with no issues. Similarly, we have been pleased with the effectiveness of the ball gears. The ball gears operate smoothly through the full range of φ angles from 0° to 90°.

Additionally, the HATTS joint is very strong, with large bearing diameters contributing to its load-carrying capability.

We have been pleased that despite the direct-from-CAD manufacturing processes, the joint as assembled exhibits very little slop. The ball gears mesh very cleanly and have limited backlash.

FURTHER WORK

The current prototype has validated the concept of HATTS, but with further revision we believe the design can be improved. The most obvious improvement that we want to make is weight reduction. Many of the parts in the current model are solid parts designed to be easy to manufacture. We plan to skeletonize some of the components, which should result in significant weight reduction.

We will conduct tests to demonstrate that the joint is both capable of surviving the launch into orbit and that it is able to operate successfully in the space environment. This will require system-level tests such as putting the joint through a shake-test and testing that the joint operates within a vacuum chamber that simulates the sun's thermal loading. Additionally, we will need to conduct part-level tests to ensure that all moving components, including motors and bearings, are capable of long-term operation in the space environment. We would like to conduct a full lifetime analysis to determine how the joint and motors react to fatigue.

Additionally, further work will include developing a robust control algorithm for the joint. We will develop and implement a full kinematic model of the joint as well as a simple software interface to the satellite that allows the satellite's primary computer to fully control the joint and recover from hardware or software interrupts.

CONCLUSION

The innovative HATTS joint allows for orientation control through a hemisphere while avoiding cable twist and consuming minimal volume when stowed. The proposed design, using an elevation arm, dual coaxial gears and radially mounted motors to control elevation and rotation, makes for a very simple and easy-to-manufacture layout that packs efficiently into a small volume. Compared to competing designs, such as the Canfield joint, the HATTS joint is smaller and stronger, has fewer parts, is less complex to control and can be more efficiently adapted to the CubeSat chassis. When fielded, the innovative HATTS joint design has the potential to allow for a new generation of CubeSats with more available power and payload volume than has previously been possible.

The HATTS joint is currently patent pending.

REFERENCES

1. Canfield, S. L., "Development of the Carpal Wrist; a Symmetric, Parallel-Architecture Robotic Wrist". Ph.D. dissertation, Virginia Polytechnic Institute and State University, 1997.

2. "CubeSat Design Specification," at http://www.cubesat.org/images/developers/cds_rev12.pdf

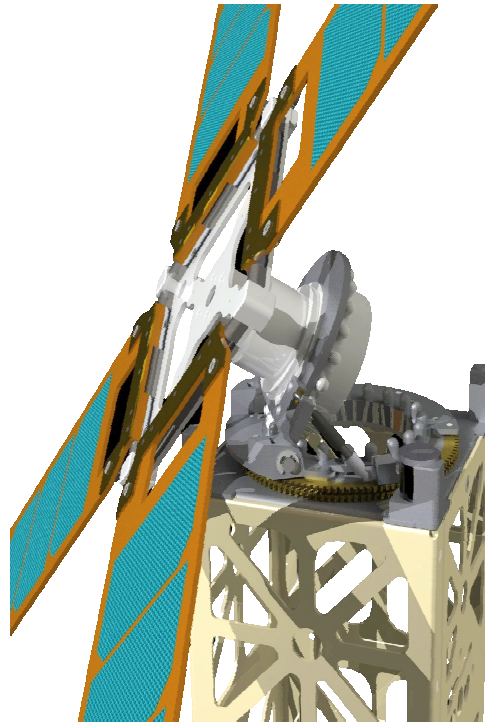3. Canfield Joint Image at http://roboticcanfieldjoint.webstarts.com/index.html

Figure 8: CAD Rendering of a 28W Solar Array Articulated via CubeHATTS on a CubeSat Chassis