Solar Cube: A Heliogyro Propulsion System for CubeSats

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The Solar Cube heliogyro is a 2U CubeSat propulsion system that utilizes reflected solar pressure as its only means of propulsion and attitude control. As Solar Cube spins, collective and cyclic pitch of four helicopter-like sail blades vectors thrust and precesses the spin axis on demand to provide complete control authority. Each solar reflecting blade measures 152 meters long, is up to 0.28 meters wide, and is constructed from aluminized polyimide film. During operation, centripetal tension and chord-wise battens provide stiffness. The system weighs approximately 2.5 kilograms and, when fully deployed, has a characteristic thrust of 0.12 mN or greater. Three high-fidelity blade system prototypes with distinctly different blade widths have been fabricated to prove its design. The prototypes have undergone component- and system-level testing to demonstrate stowage, deployment and pitch actuation in a laboratory environment. To completely validate the system before flight, the blade assembly will also undergo ground testing in a vacuum, thereby demonstrating deployment, blade pitch and blade damping in a flight-relevant environment. Photogrammetric measurements from the test will confirm flexible blade models. The test is intended to occur in the Plum Brook Station solar simulator at the NASA Glenn Research Center which, at 30.5 meters in diameter, has sufficient room to test 13 meter-long blades spinning about a vertical axis situated at the center of the chamber. The test will provide conditions as close to flight as can be obtained on Earth. This paper describes Solar Cube design, development, and test procedures. The path to flight, from ground testing up through protoflight development is described.

Key Words: Heliogyro, Solar Sail, CubeSat, Developmental Testing

1. Introduction

The Solar Cube heliogyro is a CubeSat propulsion system that utilizes reflected solar pressure as its only means of propulsion and attitude control. Collective and cyclic pitch of the windmill-like sail blades vectors thrust and precesses the spin axis as needed to provide complete control authority. Compact stowage of its four 152 meter-long blades allows Solar Cube to fit within a 2.5U CubeSat volume, yet deploy over 150 square meters of total sail area. Heliogyro miniaturization provides CubeSats the possibility of undertaking exotic missions once reserved for large spacecraft.

Solar Cube is the culmination of a series of design studies dating back to 1967 when Richard MacNeal conceived of the heliogyro. His company’s papers on mission design, performance, control behavior, deployment, orbital maneuvers, and structural dynamics proved conceptual feasibility.1,2 Experimental testing of a blade in a spinning room demonstrated controlled pitch, as well as repeated unrolling and stowing of the blade.3 In 1977-78 MacNeal, along with JPL, Ames Research Center, and Langley Research Center, progressed past conceptualization to design quantification as they conducted a comprehensive design study for implementation in a 1981 Halley’s comet rendezvous mission. In their design, two tiers of 6 blades at opposite ends of a cylindrical structure counterrotated, to eliminate gyroscopic stiffness and thus allow the sail to more rapidly precess its spin vector. This scheme also removed nutation and other disturbances that rotate the spacecraft.

To sufficiently drive the 3800 kg non-sail mass, each of the 12 blades was 7500 meters long and 8 meters wide. In bench tests, axial stress caused the blades to develop deep, longitudinally-oriented deformations. A framework to keep the blades taut and relatively flat was considered essential. Quad-redundant edge stiffeners not only improved uniform cyclic pitch and off-loaded the excessive blade stress, but they also worked together with parabolic tendons, constant tension springs, and battens to pull the blade material taut. However, such a complex design choice decreased the reliability of deployment and drove the weight up. A significantly smaller payload could have led to a simpler design without the parabolic tendons and tension springs. In the end, development halted due to perceived risk.3) The heliogyro for the comet rendezvous showed the fundamental flaw with sail designs at the time. The payloads were so heavy that the sails to drive them were impractical.

A decade later, a different design tack emerged, focusing on relatively tiny heliogyros for low-risk demonstration missions. A team from MIT, touting a heliogyro with 8 blades, each 100 meters long and 1.5 meter wide, petitioned for entry in a race to Mars.4) With blades 100 m long, no extra support such as edge stiffeners or battens appeared in the design. Novel contributions included:5) a solid-state blade actuation system consisting of two strips of piezoelectric material deflecting in
opposite directions to pitch the blade root; a blade deployment analysis with simulated blade behavior showing the tradeoffs between blade rolls situated at the root versus attaching them at the tip; and a heuristic design study for the purpose of determining an optimal heliogyro configuration for Earth-orbit escape.

Following another decade hiatus, the effort begun at MIT came to life again at Carnegie Mellon University in the form of Solar Blade, a four-blade heliogyro microsat technology demonstration project.\(^6,7\) The Solar Blade team designed and built a mechanical prototype and created a preliminary technology baseline document for the mission.\(^8\) They also conducted blade deployment and pitch tests in an 8 ft square spinning room, which provided valuable insight into the importance of constraining blade behavior at the root during deployment and pitch actuation. Without the constraint, the deployed portion of the blade will hang to the side when the blade pitches, and will not pitch appropriately.

A dissertation associated with Solar Blade\(^9\) contained a complete stiff-blade heliogyro spacecraft model that showed that the spin vector is controllable via blade pitch alone. The work also illustrated flexible blade behavior through a cloth-like particle model and a modal model using Kane’s equations. With the cloth model, blades with aspect ratios of 1000:1 were shown to operate stably. Results from the dissertation also showed the smoothing effect that battens have on the blade surface.

Over the last half dozen years, a team primarily from NASA Langley Research Center and the University of Colorado have also conducted heliogyro and pitch control studies.\(^10-12\) They have presented HELIOS, a six-blade ESPA-class concept used to advance research and prepare for a tech demo in the future; conducted structural and stability analysis; and conducted small-scale vacuum chamber tests.\(^13\) They also have worked to develop control laws that overpower motor friction and dampen modes.\(^14\) To further study blade behavior, they propose an in-flight test of a two-blade heliogyro test stand mounted inside a 6U frame.\(^15\) Updated flutter analysis has revealed regions of operation to avoid flutter.\(^16\)

This paper discusses recent research efforts dedicated to the development of Solar Cube, a heliogyro for CubeSats and a successor to Solar Blade. Design iterations, driven toward miniaturization, have resulted in a heliogyro system approximately 2.5U in size, with some important benefits; relatively short blades avoid the blade stress problem that drove the Halley’s comet heliogyro to a complex design; the smaller spacecraft precesses quicker; and the CubeSat size enables nanosats to reach far-out locations that are otherwise unattainable.

2. Solar Cube

Solar Cube has the appearance of a Dutch windmill and employs sail control akin to a helicopter. Four solar reflecting blades attach to a central bus via extendable struts. Each blade measures 152 meters long, is up to 0.28 meters wide, and is constructed from aluminized, flight-qualified 5μm Kapton polyimide film. During operation, centripetal tension and chord-wise battens provide stiffness. The system uses collective and cyclic pitch of the blades to control attitude and thrust, and an onboard supervised autonomous GNC system to generate short-term trajectory-following command sequences. Actuators pitch and actively dampen the blade from the root. The heliogyro propulsion system weighs approximately 2.5 kilograms. When fully deployed, characteristic thrust, or the thrust achieved by Solar Cube with its sail normal to the Sun at 1 AU, is 0.12 mN.

2.1. Stowage and deployment

For stowage, each blade is rolled onto a spool adjacent to its pitch actuator. The blade roll assemblies and struts stow along opposite sides of the bus (see Fig. 1). Deployment follows the sequence shown in Fig. 2. After release from the launch vehicle, the blade assemblies release, the struts deploy, and propulsion units on the struts detumble the spacecraft and point it toward the Sun (steps 1 and 2, Fig. 2, top right). While maintaining a lock on the Sun, the propulsion unit spins up the spacecraft to 60 revolutions per minute. Then, the blades feed out in a controlled, balanced manner (Step 3, Fig. 2, bottom). The feed rate is sufficiently slow to maintain a positive trailing edge stress in the blade, thus guaranteeing a smooth, radial deployment. During deployment, Solar Cube slows to its operating spin rate of 1 rpm, at which time the blades collectively pitch. For the rest of the deployment, solar pressure on the blades boosts the angular momentum while the blades feed out at a speed sufficiently slow to maintain a constant spin rate.

![Stowage of blade assemblies](image-url)
Fig. 2. Deployment sequence. Top left, Solar Cube stored inside 6U CubeSat; top right, solar panel releases, blade assemblies separate; bottom, struts extend, blades pitch 90°, spacecraft points toward Sun, spacecraft spins up, and blades unroll.

Each blade assembly consists of a pitch motor, a blade roll and spool, a damping system, a deployment motor, a roll support yoke, deployment sensors, and a pitch sensor (see Fig. 3). Attached to the assembly is a STEM boom, which is itself rolled up for stowage. Two of the assemblies that are opposite each other have a micro-propulsion system attached for sun acquisition and spin-up. The four STEM booms attach to a ring that is part of the CubeSat structure.

The 6U form factor is not ideal for the heliogyro. A circular form factor is more efficient, as it allows blade assemblies to stow in a circular pattern. Four blades were chosen for the 6U CubeSat due to blade packing efficiency. Four rolls can be larger in diameter than six. As a result, more sail material fits within the envelope.

2.2. Operation

The four blade control maneuvers used in steering the craft are cyclic pitch, collective-cyclic pitch, collective pitch, and half-p pitch (see Fig. 4). Each maneuver results in a net force and/or torque being applied to the spacecraft. Using these maneuvers, the GNC system accepts desired force and torque values and pitches the blades using the appropriate parameter settings to execute the maneuvers.

An innovation included with the heliogyro is a proprietary GNC system that autonomously provides supervised autonomy as it makes short-term trajectory decisions and course corrections. Using cyclic pitch, collective-cyclic pitch, collective pitch, and half-p pitch, the GNC system accepts desired force and torque values and pitches the blades using the appropriate parameter settings to execute maneuvers. Included in the control system are active in-plane and out-of-plane blade dampers, located where the blade assembly struts attach to the central bus.

Fig. 3. Solar Cube blade assembly.

Fig. 4. Blade pitch maneuvers. From left to right, top to bottom: cyclic pitch provides an in-plane thrust; collective-cyclic pitch changes the spin rate and precesses the spin vector; collective pitch changes the spin rate; and half-p pitch precesses the spin vector.

3. Development Path

One of the biggest obstacles to flight is accurately modeling and controlling the blades. Therefore, much of the design work that has gone into Solar Cube has been geared toward a flight-relevant terrestrial test that will demonstrate deployment and pitch actuation of blades with length-to-width aspect ratios as high as 170. This aspect ratio is approximately a third of the design for flight. The test will validate blade models, as well as control algorithms, through actual operations. Within the Space Power Facility at NASA’s Plum Brook Station, the envisioned test setup will consist of three blade deployment/pitch assemblies of varying width attached to a rotating platform. Cameras atop the platform film deployment and pitch from the root. With the vacuum chamber at $10^{-5}$ Torr and the platform spinning at 180 rpm,
the blades unroll slowly, maintaining a positive trailing edge stress, and thus, a straight blade. With a diameter of approximately 30 meters, Plum Brook provides the space necessary to conduct meaningful tests on blades as long as 13 meters.

Once the blades are deployed and the spin rate has slowed to 90 rpm, the pitch mechanisms follow a series of flight-like pitch profiles. A spin rate of 90 rpm is sufficient to limit the out-of-plane coning, or droop, to ~1°. The response along the blade is captured through photogrammetry by two overhead cameras imaging retro-reflective targets spaced along the length of each blade. Comparison of the resulting dynamic blade shape with blade simulations will verify blade models.

Control algorithms will be used to maintain as flat a blade shape as possible by actively damping at least the first twist mode. The effectiveness of the algorithms will be verified through the Plum Brook Test.

After successful blade model and control algorithm verification, the heliogyro concept will reach NASA’s Technology Readiness Level (TRL) 6, and protolight development of a Solar Cube technology demonstration vehicle will commence. At this point, the spacecraft design could change, depending on funding available for launch. Although a 6U, four-blade configuration is viable and less expensive, a cylindrical 12 blade version in a space slightly larger than 12U is preferred. Either way, the ultimate aim is to carry the design through to an in-space technology demonstration that not only establishes heliogyro viability, but also showcases real CubeSat mission capability.

3. Hardware fabrication and testing

Preliminary hardware fabrication and feasibility testing is begun on the blade assemblies, to prove that a sail blade of sufficient area can stow in the proposed volume and can deploy and pitch reliably. Three blade assemblies are fabricated, each accommodating a different blade chord. The assemblies attach to oversized rotary actuators, which can pitch the blade assemblies at 1.5 Hz, the frequency corresponding to the spin rate of the vertical test stand used in the Plum Brook vacuum chamber test. Twenty-meter-long sail blades, fabricated by L’Garde and designed for the Plum Brook test, roll onto the blade spools. Each blade consists of two 10-meter sections of 5 μ Kapton, glued together with an overlapping butt joint. The glue sandwiched by the Kapton acts as an excellent rip-stop feature. Three other locations along the blades also have the rip-stop, formed by using spare sail material adhered chordwise to the blade.
Fig. 7. Blade assembly during vertical deployment testing. The blade is smooth and relatively wrinkle-free.

Fig. 8. Close-up of blade assembly during deployment testing. The blade roller constrains the blade at the root once deployment ends and pitch actuation begins.

The hardware is designed for early feasibility testing as well as the Plum Brook vacuum chamber test. In the Plum Brook test, a spinning vertical test stand, consisting of a shaft mounted on a pair of pillow blocks, a stepper motor, a slip ring, and an attachment collar, will rotate the blade assemblies at 180 rpm for initial blade deployment and slow to 90 rpm at the end of deployment. The actuator will then pitch the blade assemblies through a series of flight-like profiles. The test stand is fabricated and has been used to test spinning hardware.

Fig. 9. Vertical test stand with blade assembly attached.

4. Conclusion

Preliminary hardware testing indicates the viability of a heliogyro design for a 6U CubeSat. In vertical blade tests, deployment and blade pitch occur smoothly and without binding. Development will continue with further design iterations, improved control algorithms, and a flight-relevant test in the Plum Brook vacuum chamber. It is hoped that a flight demonstration can occur soon after, thereby enabling CubeSats to travel to destinations that are currently unattainable.

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References


