Design and Verification of a Mechanical System for Magnetospheric Mapping Missions

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Abstract—This paper describes the design and qualification of the Space Technology 5 spacecraft mechanical system. Key points include:

- Testing results for the “Frisbee” type Deployer system, which imparts a precise spin rate to the spacecraft;
- Layout of the structural bus, with emphasis on design for both compactness and accessibility during assembly;
- Design of the electronics housing, which serves an important dual purpose as the spacecraft structural backbone. Also included is a description of its special accommodations for electrical harness and the integration process;
- Electro-mechanical aspects of the separation connectors and shape-memory-actuated pin pullers;
- Unique challenges due to limited volume and resources were overcome through extensive testing and “skunkworks” type development procedures.

Overall, this paper encompasses the unique mechanical system design innovations to enable the 25 kg, fully functional Space Technology 5 spacecraft to blaze a trail towards scale-reduction and system functional integration for upcoming nano-satellite constellations.

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1. INTRODUCTION

The Space Technology 5 mission (ST5) primarily fulfills a technology demonstration function, while also providing science-grade research data. As such, the spacecraft serves as a trailblazer for future magnetospheric mapping missions such as Magnetic Constellation (Mag Con). The NASA New Technology lexicon describes micro-satellites as those weighing between 10 and 100 kg. A Nanosat weighs between 1 and 10 Kg.

Mag Con is part of NASA’s Living with a Star Program, which investigates phenomena involving the interaction of the Earth’s magnetic field with the Solar Wind. Magnetic field, plasma and energetic particle measurements must be performed in-situ, thus necessitating constellations of science craft in a distributed arrangement throughout the region of interest (Figure 1).
Because of high launch costs, the program plan for Mag Con is to pack the entire constellation on one Delta II rocket and use a “mother ship” to dispense the science craft to their final orbits. The more sensors in the field, the better the resulting map; however, the smaller each craft must be. Constellation missions such as Mag Con are forceful drivers for breaking new ground in the areas of science craft scale-reduction and subsystem integration into multi-functional units.

ST5 Overview—The ST5 spacecraft shown in Figure 2 weighs 25 kg, is 50 cm in diameter and 30 cm high. The structure supports an instrument boom 75 cm long, as well as 10 cm high communication antennas on the top and bottom decks. Miniaturized technologies shown in Figures 2 and 5 include:

- The science-grade magnetometer
- X-Band Transponder
- Cold Gas Micro Thruster
- Sun Sensor
- Lithium Ion Battery
- Variable Emittance Thermal Control

Because of the nature of the science investigations, this spin-stabilized, ecliptic-pole-pointing demonstration flight is in a high radiation orbit of ~100kRad/yr Total Ionizing Dose. Numerous steps, such as parts screening and radiation modeling, were taken to assure robust operation in such a severe environment.

Mechanical System Overview—The ST5 spacecraft (S/C) sits in its Deployer Structure cradle for launch as shown in Figure 3. Most notably, the interface between them is through three discrete hardpoints rather than a conventional circular clamp band. The hardpoint mounts are reinforced structurally through the S/C bus by the integral electronics enclosure, providing an extremely stiff load path. Upon deployment, the spacecraft is spun up like a Frisbee and released at a pre-determined rate from the launch vehicle. Limit switches and a flyaway umbilical connector between the S/C and Deployer allow for separation sensing and power and signal transfer from the launch vehicle.
Verification—The verification process demonstrates system performance margins when exposed to environmental conditions dictated primarily by the launch vehicle and its resulting orbit. Though usually accomplished by both analysis and test, verification may be done by analysis alone when sufficient margin is demonstrated. Card Cage analysis margins were sufficient to waive the tests, yet it went through testing because it is a core component.

Due to uncertainty of its launch vehicle provider, the ST5 project had to select worst case environments (dynamic loads, thermal extremes, payload envelope restrictions, etc.) from a survey of possible launch services. This made verification more difficult than usual, since sometimes different worst cases from different launchers had to be applied simultaneously. Ultimately the process was successful, and structural verification covered all worst-case requirements.

2. DEPLOYER STRUCTURE

Description
A well-defined spin rate is important for the ST5 and future magnetospheric science objectives. Because ST5 has no spin-up thruster, the mission spin rate is determined upon release. The space environment will not significantly degrade the spin. The mission spin rate is 20 RPM ±100%/-20%, but the mechanical team set a stricter tolerance goal of ±/–10%. The nominal spin rate prior to deploying the magnetometer Boom is 30 RPM.

The ST5 Deployer Structure provides launch-lock, spin-up and release of the S/C in one mechanism. Figure 3 illustrates its operational steps. All elements of the mechanism are re-settable and reusable, enabling the test of actual flight hardware rather than continually replacing one-shot devices such as pyro actuators or break wires. The pusher force is adjustable, and, using calculations that account for changes in S/C mass properties, allows a “dialed in” spin rate up until the moment of integration to the launch vehicle.

During verification, areas of concern were friction, the tip off due to uneven release and gravity negation.
Verification

Verification of the Deployer Structure had three parts: motion and stress analysis, structural test, and deployment performance testing. Testing was accomplished with a flight-like Engineering Test Unit (ETU) of both the S/C and Deployer Structure.

Motion Analysis—This analysis focuses on predicting the spin rate three separate ways.

The energy conversion method equates potential and kinetic energies of the initially compressed pusher spring and the final spinning state of the S/C. This method is fast and accurate, allowing easy investigation of mass property and spring parameter effects on spin rate. It gives only end-state information however, no intermediate or time-function results.

The differential equation method gives time-function results, and is easily calculated, but is computation-intensive and requires piece-wise analysis.

The 3D Simulation method uses motion analysis software such as MSC ADAMS to calculate rates as a result of applied forces. These tools allow easy modeling of complex behavior, and permit the importation of 3D Computer Aided Design information for visualizing the resulting motions. This technique is more specialized, requiring experience with the software to create the model, and is slower to yield results. When calculated using identical parameters, each of the three techniques yielded results within 0.5% of each other.

Structural Analysis—Structural (including normal modes) analysis showed substantial positive margins on both material strength and minimum natural frequency. The primary system-level natural frequency is 50 Hz, and is governed by the mechanism and stanchion stiffness between the S/C and the Deployer Structure base. This high frequency is due to the compact size and stiff design of the ST5 structural bus. In most spacecraft, the S/C bus usually dominates the system modes through cantilever bending. ST5's octagonal prism is reinforced under the hardpoints by the monocoque electronics enclosure, making it effectively a lump mass supported in the Deployer Structure cradle.

Structural Test—Engineering Test Units (ETUs) of the Deployer Structure and S/C structural bus underwent three-axis random vibration, quasi-static loads and shock testing in order to validate the analysis and verify the design. Natural frequencies were within 5% of predictions. This test confirmed that the natural frequencies are also sensitive...
to the mechanism stiffnesses. In initial tests, wear was a problem at the mechanism interfaces. This degradation was also visible as a slight decline in frequency. Bushings and interface surfaces at the mechanisms were redesigned and refurbished. The structure underwent vibration a second time to verify their integrity. A partial deploy test between each axis of vibration verified function.

**Deployment Testing**— Early on, the proof-of-concept Deployer Structure demonstrated that friction in the mechanisms at ambient conditions was a negligible factor in the spin rate determination. The friction over the entire deploy path was measured at temperature extremes before and after vibration testing. The T/V tests confirmed that friction remained low even in extreme environments.

Gravity negation, on the contrary, was a big concern. Originally a deploy test on NASA’s Zero-gravity Research laboratory was planned. However this test was cut due to resource limitations. In the proof-of-concept phase, the deployment direction was downward with gravity. The equivalent zero-gravity spin rate was determined analytically by subtracting the effect of gravity. There was still uncertainty about whether the gravity aided the mechanisms, perhaps by overcoming friction, resulting in an artificially improved deployment. For qualification deployment in T/V, the S/C was deployed horizontally, in both clockwise and counter clockwise directions. This way, if gravity helped in one way, it would hurt in the other, and vice versa. Again, gravity was analytically subtracted from the data to yield a zero-gravity spin rate.

The spring characteristics, space craft mass properties and hardpoint geometry parameters form the input to the governing equations that dictate the spin rate. A test of 6 springs showed that stiffness variability was <2.5% from spring-to-spring and 4% for a given spring over temperature extremes (-70 to +70C). To reduce error, the spring characteristics are factored in during assembly and deployment temperature requirements are imposed. The S/C mass moment of inertia was measured to an accuracy of 1% in order to meet the final spin rate tolerance. Fortunately the spin rate is proportional only to the square root of the inertia inverse. The S/C mass properties test is further described in Section 3. Geometry values were easily determined from drawings and by physical measurement. Distance to the S/C Center of Mass had an error of ~1%.

Rate sensor selection was an important decision. Various inertial rate devices and accelerometers were investigated, but it became clear that they entailed specialized design for incorporation into a free-flying S/C, and were not guaranteed to handle the rigors of thermal vacuum testing (T/V). Finally a visual method was selected, using high-speed video images of the deploying ETU with photo targets placed strategically on the decks to yield spin- and tip-off-rates. Frame by frame comparison of target positions on the digitally-acquired image yielded rates of translation and rotation. The ETU was viewed through a window in the T/V chamber. The view direction was normal to the ETU spin plane, and a mirror in the camera field of view allowed an orthogonal view of possible out-of-axis tip-off.

Figure 4 shows the ETU on its test stand in the T/V chamber. The horizontal bar is the test frame, and the bars with wires attached are shock-absorbing tethers to catch the deployed S/C. The block in the lower left is a mirror for the orthogonal view. The vertical tubes in the background are part of the temperature-controlling chamber shroud. The camera view port is visible in the shroud between the ETU and the mirror.

Four tests under environments were performed: hot and cold with a clockwise spin, and hot and cold with a counter clockwise spin.

Results from the deploy tests are summarized in Table 1. After compensating for a ~7% error due to the test stand support structure recoil, actual spin rates are within 10% of predictions. The remaining error is attributable to tether and sensor harness loading, and gravity-induced friction at the mechanisms due to mistiming. In a zero gravity field, these mis-timings will have negligible effect. These results meet the mechanical team’s design goals of 30 RPM ±10%, and are well within the tightest mission level tolerance of -20%.

**Table 1** – Thermal Vacuum Deployment Test Results

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Spin Rate (RPM): Measured</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW RT</td>
<td>28.1</td>
<td>30.0</td>
</tr>
<tr>
<td>CW Hot</td>
<td>27.1</td>
<td>30.0</td>
</tr>
<tr>
<td>CW Cold</td>
<td>29.3</td>
<td>30.0</td>
</tr>
<tr>
<td>CCW RT</td>
<td>29.4</td>
<td>30.0</td>
</tr>
<tr>
<td>CCW Hot</td>
<td>27.7</td>
<td>30.0</td>
</tr>
<tr>
<td>CCW Cold</td>
<td>28.3</td>
<td>30.0</td>
</tr>
</tbody>
</table>

* Compensated for test stand recoil

Recoil of the test stand underscored a critical condition to account for during on-orbit deployment: the recoil of the Launch Vehicle Upper Stage. Recoil losses and potential interferences must be carefully assessed to assure mission success.
3. STRUCTURAL BUS

Description

Figure 5 illustrates the bus construction and component layout.

The "Card Cage" electronics housing serves a vital dual function, protecting the electronics cards from radiation and other effects, as well as serving as the spacecraft physical backbone. The decks, with the hardpoints attached, are tied together by the card cage. As evidenced in the figure, the Card Cage forms a monocoque load path from the decks to the Deployer Structure around the electronics. Analysis shows that the cards see minimal loading when the Card Cage walls are stressed.

Sheet metal "clamshell" sidewalls wrap around the deck edges and close out the S/C interior. The solar panels are thin honeycomb sandwich construction with graphite composite facesheets. The graphite serves to bleed off accumulated charge from energetic particles in the space environment, and provides radiative temperature control of the S/C. A Kapton layer insulates the 28% efficient Triple Junction solar cells from the conductive panel. The panels are mounted to the sidewalls on composite flexures that accommodate differential temperature expansion between it and the adjacent aluminum structure.

Assembly and test starts with the Card Cage and S/C components integrated to the decks in parallel. The Integration and Test (I&T) fixture shown in Figure 6 allows easy access to the open S/C, while keeping them in close proximity for electrical communication from one deck to the other. Most harnesses to the opened top deck cross at the virtual hinge at one end of the Card Cage. All harnessing to the exterior passes through connectors in the spacecraft skin.

Once the decks are attached to the Card Cage, the S/C interior is still accessible from the sides. The sidewalls attach next and are fastened to the card cage ends. They also support critical hardware such as the skin connectors, Solar Panels, Boom snubbers and Nutation damper. Final steps in the S/C build up are Solar Panel installation, boom stowage, and thermal blanket installation. The Integration and Test Stand shown in Figure 6 allows the entire S/C to rotate for all-round access.

The S/C spin axis must point true in inertial space to within 0.5°. This allows for uniform science data capture. The components are arranged in the spacecraft to optimize its inertia properties and minimize the trim weights required for spin balance.
Verification

The ETU bus underwent mass properties and spin balance testing to provide important input to the spin rate predictions. The Deployer Structure and bus were analyzed sequentially and qualification tested simultaneously for structural loads. Significant results of the analysis have been described in the preceding section.

Spin Balance—The S/C is balanced without the boom, even though the on-orbit operational mode has the boom fully deployed. Air friction on the boom due to the 150 RPM test spin rate would have invalidated measurements. To address this, the boom is designed to be mounted in the spin plane through the S/C center of gravity, thus minimizing its effect on the overall balance. The ETU has been balanced to within 0.3°.

Vibration—Vibration control was accomplished with an extremal strategy for both acceleration and force. Piezoelectric force gages inserted between the Deployer Structure base and shaker table limited excessive loads into the ETU by mimicking the structural impedance of the launch vehicle interface.

The small components attached to the decks showed very high stiffnesses, with most resonances above 200 Hz. Accelerometers at strategic locations aided in the determination of component-specific vibration levels for future component-level tests.

4. CARD CAGE

Description

The ST5 electronics housing, or Card Cage, typifies the implementation of multi-functional structures (MFS) technologies needed for future scale-reduction in space systems. It is made of A356 aluminum, an alloy optimized for the investment-casting process. More innovations of this type are critical for enabling ground-breaking designs in future Nanosats.
The assembly shown in Figure 7 is the S/C nerve-center, accommodating command signals and power for the entire spacecraft. The Card Cage is the primary structural load path, since it spans the spacecraft width and ties the decks and all three hardpoint interfaces together and to the Deployer Structure. Three additional electronics boxes and the boom are mounted to the Card Cage exterior, making it the veritable core of the spacecraft.

This casting has built-in features to support electrical function, such as cable channels, card supports and connector cutouts. It allows up to eleven connectors to be attached to electronics inside. Harnessing for the ST5 S/C carries both power and signals to minimize magnetic contamination of the science data. To facilitate this, each card also provides traces for the other functions, eliminating by-pass harness within the enclosure. Signals transferred within the Card Cage between the Power Supply Electronics and the Command and Data Handling Subsystem use a back plane "mother board" that connects the base of each card.

Recent advances in investment casting technology have made this component possible. The walls are as thin as .065" (1.5mm) over relatively long spans. Despite this, machining tolerances are held to less than .005" (.1mm). Casting tolerances are less than 0.02" (.5mm) over the maximum 18" (45cm) dimension. Deep pockets, undercuts, and complex contours are easily accommodated at low cost. There exists now significant heritage to electronics box casting, and finished product strengths of 27 ksi (190 MPa) meet the primary load path requirements.

Analysis margins alone were sufficient to consider this component qualified by NASA standards. Since it forms such an integral part of the design, an ETU Card Cage went through qualification testing along with the rest of the structure. Accelerometers on a card mockup inside allowed further insight into its dynamic behavior.

An accelerometer attached to the C&DH mockup during vibration showed a resonance of 268 Hz. Analysis predicted card frequencies of 231Hz for the Command & Data Handling (C&DH) card, and 271 Hz for the Power Supply Electronics (PSE).

5. ELECTRO-MECHANICAL PARTS

The wave of the future for small S/C systems is found in compact, well-designed mechanical elements that perform under the necessarily stringent resource requirements. The Structural-Mechanical subsystem employs non-pyrotechnic pin pullers from TiNi Aerospace, Inc. These low-shock devices used in the Deployer Structure mechanism and the boom release mechanism operate with Shape Memory Alloy (SMA) triggers.

Description

The pin puller shown in Figure 8 restrains the S/C in the Deployer Structure. During launch, it carries dynamic inertia loads of over 1500N in addition to the 400N static shear load from the pusher mechanism. Upon deployment, the actuator must release against the static shear load. The Pinpuller is rated by the vendor at 500N release shear load.

Extensive testing was performed to verify adequate capacity margins on this critical device. The device was chosen for its low mass (230grams) and because it induces very low shock. Mechanical shock is an issue such tight quarters.

Verification

Pinpuller vibration, T/V and performance verification was performed at the vendor site per ST5 specifications. However an exact knowledge of its capacity under worst case under environmental and electrical conditions was
needed to satisfy qualification requirements. Therefore firing tests were performed that probed the limits of temperature conditions, electrical pulse available from the launch vehicle, and applied load parameters. Three or more trials for each parameter set assured consistency of results.

Since the SMA device is heat-activated, time-to-fire performance as a function of temperature and power were predictable to the first approximation. The time to fire parameter is critical since the launch vehicle typically provides a duration-limited separation pulse. To pin this down, the test used nominal and worst case electrical parameters from the launch vehicle. Table 2 and Figure 9 show results from the firing test series. The parameters of temperature, applied voltage and current, pulse duration and load were well controlled, and the data shows that, regardless of temperature and power, the Pinpuller repeatedly fires with a capacity of 1kN, 2.5 times the expected load and 2.0 times its rated load. The time-to-fire was less than 40 milliseconds except for the low power cold and room temperature cases.

A similar though less extensive test series was performed on the 65N Boom release mechanism Pinpuller.

6. CONCLUSION

This paper has described the design of a very small science craft mechanical system and its verification for space flight. New applications of multifunctional structures, electromechanical components, and development under strict resource limitations have been addressed. The operational margins of miniaturized systems such as the SMA Pinpullers have been quantified for space flight. Innovative test methods have cut costs and delivered performance data efficiently and reliably.

**ST5 Status**—The S/C bus and Deployer Structure ETUs have completed qualification testing. Flight structural parts have been delivered to the project for Integration and Test of the subsystems. Development of secondary structure such as the Magnetometer Boom and a compliant mount for the separation connector is complete, and parts are being qualified and accepted for flight. The first ST5 flight S/C will go through environmental test as a system in mid-2004. Two identical follow-on units to complete the constellation will start integration and test as soon as the first unit completes testing. As of this writing, there is no contract in place for ST5 launch services.

![Figure 9 - ST5 Deployment Pin Puller Actuator Component Firing Tests @ 1kN](image-url)
Future Work—ST5 has made significant strides in scale-reduction and progress in multi-functional components. Much work remains to be done in the area of physical integration of subsystem functions. The approach to Electrical harness is one example. In systems as small as ST5, the terminations (connectors) become more significant, mass wise, than the wire and insulation. New approaches to electrical interconnections and integrating signal and power traces in the structure will enable future missions to further reduce in size.

As the disciplines merge, the development approach of each subsystem must co-align as well. The electrical and mechanical development philosophies are miles apart, partially of necessity because they address disparate functions and goals, but also for reasons of human factors such as corporate culture, the NIH syndrome, and simple personality differences. When the requirements get complex, it is natural to withdraw to the comfort of familiar procedures. A strong and effective systems engineering presence is vital for success during this process of integration.

The pace of technology development suitable for Nanosats is on the rise, and will lead to vastly improved cutting-edge systems for performing the new science measurements. Ultimately, these design innovations and creative methods for testing will be improved, expanded and infused into future missions of Nanosat science craft.

7. REFERENCES

BIOGRAPHY

Peter Rossoni is the Lead Mechanical Systems Engineer for the Space Technology 5 mission in NASA’s New Millennium Program. He started at NASA’s Goddard Space Flight Center in 1987, performing Structural Dynamics testing and mechanical system development for numerous scientific projects at all stages. During that time he has developed mechanisms for marine, medical and industrial uses. Mr. Rossoni earned a BSME from the University of Massachusetts at Amherst, and a BA in Humanities and Philosophy from Saint John’s College in Annapolis, MD

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