Strain Energy Deployment: Designing a Passive System

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The University of Colorado Boulder’s RocketSat-13 is working to design a strain energy actuated deployment of a panel stack, sequenced by pin/socket mechanisms, in partnership with ROCCOR (https://roccor.com).

RocketSat-13 will return the flight data (IMU, video, downlinked images, and environmental) to ROCCOR, who will determine the feasibility of manufacturing and selling the panel deployment system for solar array deployment.

This project is scheduled to launch in August of 2020.

The purpose of this document is to summarize the work done by Colorado Space Grant Consortium’s RocketSat-13 between Fall 2018 and Summer 2020 for the COSGC Research Symposium.

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I. Mission Overview

A. Mission Statement

RocketSat-13 shall design a rigid panel deployment sequencing mechanism and demonstrate the device’s feasibility in a microgravity environment via sounding rocket launch.

![Figure 1: Fully Deployed Panel Stack](image-url)
B. Mission Objectives

<table>
<thead>
<tr>
<th>Type</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Completely deploy a structure via its own strain energy</td>
</tr>
<tr>
<td>Primary</td>
<td>Utilize a sequencing mechanism to control the order in which the structure unfolds</td>
</tr>
<tr>
<td>Primary</td>
<td>Model the unfolding using the data collected by the IMU for verification of deployment</td>
</tr>
<tr>
<td>Primary</td>
<td>Collect environmental data and visually record deployment</td>
</tr>
</tbody>
</table>

Figure 2: Mission Objectives

C. Theory and Concepts

This design was inspired by ROCCOR’s Double Z-folded boom. The boom deploys chaotically, so we want to create a way to control it. It is a completely passive system relying on strain energy contained in tape spring hinges. The escapement devices (pin/sockets) reduce the deployment to one degree of freedom (one panel at a time). The deployment can be modeled using dynamics of rigid bodies. The design is applicable to solar array deployment for all sized spacecrafts.

D. Concepts of Operations

The Concept of Operations outlines the major events that take place during flight. Timer events are used to sequence the events. The subsystem code uses the Wallops provided timer events to align the deployment with apogee.

![Concept of Operations](image)

Figure 3: Concept of Operations

The table below (figure 4) outlines the Wallops timer events, when they occur, and the function of the RocketSat-13 payload at that time.
E. **Expected Mission Results**

The expected mission results are based on the requirements and goals agreed upon between the RocketSat-13 team and our industry partner (ROCCOR).

**Structure Deployment**

- Understand behavior of strain energy deployment
- Measure the rate of deployment
- Capture the behavior of the escapement mechanism

**Environmental Data**

- Dependent on flight conditions
- Characterize effect of temperature and humidity on deployment

**Prediction Model**

- Compare the deployment in micro-g to 1 g environment
- Contrast the predicted model to flight results

F. **Success Criteria**

The minimum and maximum success criteria was determined based on the goals of the team and the needs of the industry partner. The goal is to achieve the comprehensive success criteria, but the mission will still be considered successful if only the minimum success criteria is achieved.

**Minimum Success Criteria**

- Environmental data recorded from transit to deployment
  - temperature and humidity
- Successful deployment of minimum 3 panels
- Downlink low-resolution image of deployed system
Comprehensive Success Criteria

- Successful deployment of 5 panels
- High-resolution video of deployment
- Downlink low-resolution pre- and post-deployment images
- Environmental data from entire flight
- Accurate MATLAB prediction model for deployment
  - rate of deployment
  - forces on members

II. System Overview

A. Top Level Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Verification Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>The boom shall deploy to a height of no more than 12&quot; parallel to the rocket</td>
<td>Demonstration</td>
<td>Boom will be expanded to full length in the upright position to verify it doesn’t exceed 12&quot;</td>
</tr>
<tr>
<td>The mock solar array shall deploy in 5 minutes or less</td>
<td>Analysis</td>
<td>The system’s dynamical characteristics will be derived from environmental data, and deployment rate will be predicted via a MATLAB model</td>
</tr>
<tr>
<td>The full system shall fit on a single RocketSat-X deck</td>
<td>Inspection</td>
<td>Visual inspection will verify this requirement</td>
</tr>
<tr>
<td>The system shall not deploy prematurely when subjected to vibrations up to 2000 Hz along the thrust axis</td>
<td>Test</td>
<td>The system will be subjected to these vibration loads in June during testing week</td>
</tr>
</tbody>
</table>

Figure 5: Top Level Requirements

B. Description of Partnership

RocketSat-13 is partnering with ROCCOR to develop a sequencing mechanism for solar panel array deployment. ROCCOR has provided mentorship on the sequencing design and data modeling approach. They have had hands-on involvement both at ROCCOR and on the CU Boulder campus.

C. Wallops Special Requests

Wallops allows RocketSat-X to make special requests prior to testing and integration to support the completion of the corresponding experiment. RocketSat-13 has requested:

Deployables

Deployment rate greater than 1 inch/second
  - Escapement mechanism may help, but it is completely passive and it is harder to control deployment rate with strain-energy deployed system

Mass Ejection

Approximately 2 kg being ejected prior to re-entry at ~1 m/s
  - Tape springs, Panel Array, Escapement Mechanism, IMU / XBee system will be ejected

Deployment Orientation
West preferred on 3rd quadrant

* Want to avoid blinding the cameras because they are essential to success verification

All of these requests have been approved by Wallops Flight Facility.

D. Wallops User Compliance Guide

Wallops provides RocketSat-X with requirements that must be met to fly. The table below outlines how RocketSat-13 complies with the provided guidelines.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Status/Reason (if needed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of gravity in 1&quot; plane of plate?</td>
<td>Yes, on current 3D model</td>
</tr>
<tr>
<td>Weight 30.0+/- 1.0 (15.0 +/- 0.5) lbs?</td>
<td>Yes, on current 3D model, doesn’t include Ballast</td>
</tr>
<tr>
<td>Max Height &lt; 10.75&quot; (5.13&quot;)</td>
<td>Yes, on current 3D model</td>
</tr>
<tr>
<td>Bottom of deck has flush mount hardware?</td>
<td>Yes, on current 3D model</td>
</tr>
<tr>
<td>Within Keep-Out Zone</td>
<td>Yes, on current 3D model</td>
</tr>
<tr>
<td>Using &lt; 10 A/D Lines</td>
<td>Understand, do not plan to use</td>
</tr>
<tr>
<td>Using/Understand Parallel Line</td>
<td>Yes, using full parallel bus and strobe line</td>
</tr>
<tr>
<td>Using/Understand Asynchronous Line</td>
<td>Yes, using RS232 Async serial bus</td>
</tr>
<tr>
<td>Using X GSE Line(s)</td>
<td>1</td>
</tr>
<tr>
<td>Using X Non-Redundant PWR Lines (TE-1, TE-2, TE-3)</td>
<td>1</td>
</tr>
<tr>
<td>Using X Redundant Power Lines (TE-R)</td>
<td>1</td>
</tr>
<tr>
<td>Using &lt; 1 Ah</td>
<td>0.7 Ah</td>
</tr>
<tr>
<td>Using &lt;= 28 V</td>
<td>Yes</td>
</tr>
<tr>
<td>Using RF (if yes, list frequency and TX Power)</td>
<td>Yes, 2.4 GHz; 1 mW</td>
</tr>
<tr>
<td>Using deployable?</td>
<td>Yes</td>
</tr>
<tr>
<td>Whole team consists of US Persons</td>
<td>Yes</td>
</tr>
<tr>
<td>Using ITAR and/or Export Controlled hardware</td>
<td>No</td>
</tr>
</tbody>
</table>

Figure 6: Wallops User Guide Compliance

III. Structures

A. Finalized Designs

1. Full Mechanical System Overview

The mechanical elements of this design include an electronics box, camera housing, linear rails, a stepper motor, and the panel system.

![Figure 7: Mechanical Designs](image_url)
2. Panel Design

The array is composed of five panels manufactured out of aluminum. A slot is cut out of the inward facing end to allow the Hold Down Release Mechanism to be inserted through the panel stack. Small indentations have been cut into the panels to ensure that the tape springs lay flush against the surface. Lastly, each panel stack has mounting holes for the pin/socket mechanisms to be mounted in their respective location.

3. Tape Spring Design

Tape springs are thin metallic strips with a curved cross section. When back folded, the tape spring stores strain energy until it is allowed to retain its cross section. Because this system was designed to be completely passive, the strain energy is what activates the unfolding of the panel stack. Each panel has two tape springs attaching it to the panel below, placed on opposing sides. By nature, deployment by strain energy is chaotic. To solve this issue, the structures team has designed a pin/socket to sequence and control the deployment.

4. Pin and Socket Design

The pin and socket is designed to reduce the deployment to one degree of freedom. A design challenge imposed by a strain energy deployment is how chaotic and uncontrollable it is. This pin socket design ensures that only one panel can deploy at a time, restraining the next panel until the previous has made a 180 degree rotation.

5. Hold Down Release Mechanism (HDRM)

The Hold Down Release Mechanism restrains the panel stack until it is ready to be deployed and ejected. The HDRM is comprised of the sliding pin, HDRM casing, a long nose detent, a spring, and ejection pin. As the stepper motor drives out the panel stack, the ejection pin is pulled out from the HDRM casing, ejecting the sliding pin. The long nose detent is a restraining mechanism that locks the sliding pin in place as it is released. This avoids damage or interference of other payloads by keeping the sliding pin attached to the system. Images of the HDRM before and after ejection can be found in the appendix.

B. Linear Rail System

The linear rail system is composed of two horizontal rails, attached to the payload deck. The linear rails are mounted to the base of the panel stack. Each rail is located inside a series of wheels that rotate as the stepper motor drives out the panel stack. After deployment, the stepper motor will drive out the linear rails and panel stack system, and will not be recovered with the payload deck.

C. Electronics Housing

The electronics housing is designed to contain all internal subsystems. Attached to the front of the electronics house is the camera housing. This ensures that all electronics, cameras, and wiring connections are protected from extreme environments and splash down.
1. **Mechanical Deployment Sequence**

Figure 8: Electronics and Camera Housing

Figure 9: Initial State
Figure 10: Panels Driven out by Stepper Motor

Figure 11: Ejection of HDRM
Figure 12: Deployment of First Panel

Figure 13: Deployment of Second Panel

Figure 14: Deployment of Third Panel
D. Mass and Dimensions

The table below provides a breakdown of the payload’s mass. Wallops has places a 15 pound limit on each payload deck. The total mass is currently 14.86 pounds, leaving a margin of 0.14 pounds.

<table>
<thead>
<tr>
<th>RS-13 Mass Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subsystem</strong></td>
</tr>
<tr>
<td>Electronics and Camera Housing</td>
</tr>
<tr>
<td>AD&amp;E</td>
</tr>
<tr>
<td>Payload Deck</td>
</tr>
<tr>
<td>PCB and electronics</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
<tr>
<td><strong>Over/Under</strong></td>
</tr>
</tbody>
</table>

Figure 17: Mass Budget
E. Gravity Offload System

In order to simulate the zero gravity environment that the panel stack will experience during launch, the structures team designed a gravity offload system for testing in a 1-g environment. This gravity offload system is made up of 5 springs, 5 long wires, and a shower curtain rod. The shower curtain is mounted above the panel stack platform, with each wire connecting to the top of a panel. The tension in the wire reduces the effects of gravity on the system, better simulating the results we expect to see in flight.

IV. Avionics

A. Avionics Overview

The Avionics Team is responsible for designing the electrical systems, integrating hardware, and conducting subsystem tests.
1. Functional Block Diagram

This functional block diagram outlines all major connections between internal and external subsystems. Creation of this diagram is an essential step in understanding how the system works and communicates.

![Figure 19: Functional Block Diagram](image)

2. Schematics

![Figure 20: Schematic: Power](image)
Figure 21: Schematic: Peripheral

Figure 22: Schematic: Master
B. Subsystem Breakdown

The Avionics team is responsible for four of the major subsystems outlined in section .

Command and Data Handling (C&DH)

Environmental System (ENVS)

Photo and Video Capture (P&VC)

Array Deployment and Escapement (AD&E)

The success of this mission depends on data collection and evidence of the panel stack deployment. This includes monitoring the environmental conditions of deployment, collecting IMU data during deployment, capturing a high resolution photo before and after panel stack deployment, and video capture of deployment.

C. Command and Data Handling

The Command and Data Handling system is responsible for collection of IMU data. An IMU (Inertial Measurement Unit) collects accelerometer, gyroscope, and magnetometer data. This information will allow the science team to gather data on the panel stack position, rate of deployment, and behavior through the panel's rotations. The CDH system has both an internal and external system. The internal system collects baseline data during launch of the payload. The external system, located on the fifth panel in the stack is responsible for collecting data that allows the science team to create a dynamic model of the deployment. This system is made up of a PCB, Xbee, Razor IMU, and battery. This data is critical to success verification of this mission. In the event the team is unable to recover camera data, the science team will be dependent on clean and usable IMU data to confirm the panels successfully deployed. To create a baseline, the avionics team has tested the external IMU on systems simpler than the panel unfolding. These simple systems (circle, pendulum) are predictable and it is easier to create a mental picture of what data is to be expected. This also allows Avionics to confirm that the IMU's sampling rate is sufficient for collecting data at the anticipated rate of deployment. The external IMU system was tested on a prototyped panel stack and will be tested again during the Full Mission Simulation.

1. IMU Switch

The external IMU is activated by a switch made up of two wires and a capacitor. The wires are connected to the external IMU system when the panel stack is folded up before deployment. As the stepper motor drives out the panel stack, the wires are pulled out and disconnect from the system. This transfers the IMU system to battery power, instantly turning on the IMU for data collection. This ensures that the IMU is only collecting data during deployment and ejection. This data will be transmitted back to the internal CDH system and down-linked to Wallops.

D. Environmental Subsystem

The environmental subsystem is made up of a temperature and humidity sensor and Arduino Nano. The sensor will be located outside of the electronics box to record data on the flight conditions during launch. This system has been tested by introducing the sensor to extreme environments and confirming that the data collected demonstrates a proportional response.

E. Photo and Video Capture

The Photo and Video Capture Subsystem is composed of three cameras. The Arducam acts as the low resolution camera and will take a photo of the panel stack before and after is deployed. Two Go-Pros will act as the high resolution cameras and record the full panel deployment and ejection. Retrieving camera data is not only a redundant method of success verification, but also another way to verify the IMU data analysis through visual tracking.
F. Array Deployment and Escapement

The Avionics team is responsible for the electrical interfaces of the stepper motor. The stepper motor drives the folded panel stack out on the linear rails, causing the pin to be pulled and the Hold Down Release Mechanism to eject. In addition to wiring of the system, the avionics team has written code that provides the stepper motor with a timer event. This timer event will be communicated to the ADE system through a connection to the Wallops computer located within the sounding rocket deck. This will ensure that deployment of the panel stack occurs at apogee.

1. Software

The following diagram is a breakdown of the software designed by the Avionics Team. It outlines the sequence of communication between the subsystems and the Wallops computer.

![Software Flow Diagram](Image)

Figure 23: Software Flow Diagram

V. Science

The science team is responsible for all analysis of data collected during design, manufacturing, preliminary testing, and flight.

A. IMU Data Processing

Once the external IMU data from flight has been retuned, it will be uploaded to a MATLAB script written by the Science team that provides plots of gyroscope vs time, acceleration vs time, and a dynamic
model of the deployment. The following plots show the data collected during testing that will serve as a baseline for flight data. Additional test data can be found in the appendix.

Figure 24: Acceleration vs Time for Full Panel Deployment

Figure 25: Angular Displacement for Full Panel Deployment
Figure 26: Gyroscope Data for Full Panel Deployment

Figure 27: Panel Tracking During Deployment
B. Photo and Video Capture

The science team has designed a program in MATLAB that takes in footage from the Go-Pro and allows for visual tracking. This is done by manually selecting points on the panel stack in each frame to compile gyroscope and acceleration data. This information will be redundant to the IMU data analysis.

C. External Lighting

The external lighting system is designed to illuminate the panel stack while the cameras are capturing photo and video. This was tested by soldering surface mount LED’s, resistors, and a battery connector to a prototype board. A Go-Pro, one panel, and the lighting system were taken into a dark room to determine how many LED’s were needed based on the effectiveness of the panel and quality of the image. The science team determined that 3 LED’s were needed.

VI. Lessons Learned

A project of this intensity will inevitably pose challenges. Here are a few of the lessons the team has learned over the last two years.

- Strain energy deployments are chaotic and difficult to control.
- It is important to spend time revising prototypes and preliminary designs before manufacturing.
- Communication with team and industry partner is critical to mission success.
- Documentation is important for later reference and tracking progress.

VII. Conclusions

This project is an opportunity to better understand strain energy deployment and how it can be sequenced and controlled. To our current knowledge, an escapement mechanism of this complexity has never been flown in space before. Development of this technology is applicable to all spacecrafts, specifically small satellites with a need for solar panel technology. Not only does this provide students with the opportunity to support an industry level project, but also create a new and innovative solution to solar array deployment for all sized space crafts.
VIII. Acknowledgements

Thank you to Victor Andersen, Chris Koehler, Bernadette Garcia, and Sophie Orr, the faculty of the Colorado Space Grant Consortium at the University of Colorado Boulder for their continued support. Thank you to those who have been a member of this team at any point over the last two years. Their hard work has made this project possible. Additional thanks to Mark Lake, Kamron Medina, Andrew Tomcheck, TJ Rose, Kassi Butler, Phil Keller, and the additional ROCCOR faculty who have supported this project through their continued mentorship and support.

IX. Appendix

A. Pin Assignments

The tables below outline the connections between the Wallops flight computer and the RocketSat-13 payload deck.

<table>
<thead>
<tr>
<th>Pin</th>
<th>Function</th>
<th>Intended Use</th>
<th>Pin</th>
<th>Function</th>
<th>Intended Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Analog 1</td>
<td>Not used</td>
<td>20</td>
<td>Parallel Bit 7</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Analog 2</td>
<td>Not used</td>
<td>21</td>
<td>Parallel Bit 8</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Analog 3</td>
<td>Not used</td>
<td>22</td>
<td>Parallel Bit 9</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Analog 4</td>
<td>Not used</td>
<td>23</td>
<td>Parallel Bit 10</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Analog 5</td>
<td>Not used</td>
<td>24</td>
<td>Parallel Bit 11</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Analog 6</td>
<td>Not used</td>
<td>25</td>
<td>Parallel Bit 12</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Analog 7</td>
<td>Not used</td>
<td>26</td>
<td>Parallel Bit 13</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Analog 8</td>
<td>Not used</td>
<td>27</td>
<td>Parallel Bit 14</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Analog 9</td>
<td>Not used</td>
<td>28</td>
<td>Parallel Bit 15</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Analog 10</td>
<td>Not used</td>
<td>29</td>
<td>Parallel Bit 16 (LSB)</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Parallel Bit 1 (MSB)</td>
<td></td>
<td>30</td>
<td>Parallel Read Strobe</td>
<td>Parallel Stream for Photo/IMU</td>
</tr>
<tr>
<td>12</td>
<td>Parallel Bit 2</td>
<td></td>
<td>31</td>
<td>N/C</td>
<td>N/C</td>
</tr>
<tr>
<td>13</td>
<td>Parallel Bit 3</td>
<td></td>
<td>32</td>
<td>RS-232 Data (TP1)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Parallel Bit 4</td>
<td></td>
<td>33</td>
<td>RS-232 GND (TP2)</td>
<td>Downlink ENV5 Data</td>
</tr>
<tr>
<td>15</td>
<td>Parallel Bit 5</td>
<td></td>
<td>34</td>
<td>N/C</td>
<td>N/C</td>
</tr>
<tr>
<td>16</td>
<td>Parallel Bit 6</td>
<td></td>
<td>35</td>
<td>N/C</td>
<td>N/C</td>
</tr>
<tr>
<td>17</td>
<td>N/C</td>
<td>N/C</td>
<td>36</td>
<td>Ground</td>
<td>Not used</td>
</tr>
<tr>
<td>18</td>
<td>Ground</td>
<td>Not used</td>
<td>37</td>
<td>Ground</td>
<td>Not used</td>
</tr>
<tr>
<td>19</td>
<td>Ground</td>
<td>Not used</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 29: Pin Assignments: Telemetry
<table>
<thead>
<tr>
<th>Pin</th>
<th>Function</th>
<th>Intended Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GSE 1</td>
<td>Not Used</td>
</tr>
<tr>
<td>2</td>
<td>Timer Event Redundant (TE-RA)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Timer Event Redundant (TE-RB)</td>
<td>Power ON GoPro Camera and aux. lighting</td>
</tr>
<tr>
<td>4</td>
<td>Timer Event 1 (TE-1)</td>
<td>Not Used</td>
</tr>
<tr>
<td>5</td>
<td>GND</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>GND</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>GND</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>GND</td>
<td>Common Ground</td>
</tr>
<tr>
<td>9</td>
<td>GSE 2</td>
<td>Step down -&gt; Power on Arduino Due, Arduino Nano</td>
</tr>
<tr>
<td>10</td>
<td>Timer Event 2 (TE-2)</td>
<td>Not used</td>
</tr>
<tr>
<td>11</td>
<td>Timer Event 3 (TE-3)</td>
<td>Power stepper motor and send signal to Due to begin deployment</td>
</tr>
<tr>
<td>12</td>
<td>GND</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>GND</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>GND</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>GND</td>
<td>Common Ground</td>
</tr>
</tbody>
</table>

Figure 30: Pin Assignments: Power

B. Subsystem Images

1. AD&E

Figure 31: AD&E Prototype
Figure 32: AD&E Prototype
2. HDRM

Figure 33: HDRM Before Ejection
Figure 34: HDRM After Ejection
3. **P&VC**

![Arducam Low Resolution Camera](image1.png)

**Figure 35:** Arducam Low Resolution Camera

![Image Captured by Go-Pro](image2.png)

**Figure 36:** Image Captured by Go-Pro
Figure 37: External IMU System
5. **ENVS**

Figure 38: IMU Switch Prototype

Figure 39: Environmental System