Deployable Truss in a Near Space Environment

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The introduction of large scale structures in space is currently limited by the size of the transport vehicle as well as time and labor intensive assembly once in space\(^1\). Accordingly, investigation of methods to facilitate the further advancement of large scale structures in space is essential. One such method is the design and development of a large scale truss that can be stowed at a fraction of its size and launched into space. Once it reaches its intended destination, the truss can then be deployed and expanded to its full size.

The objective of this project was to design a three dimensional, folding truss using a shape memory polymer (SMP) composite material for the hinges. The truss will be launched to a near space environment, via a high altitude balloon (HIBAL). It will be launched in a folded state, approximately 2 feet in length, to near space, approximately 70,000 feet, where it will be deployed by providing power to heating elements attached to each of its hinges. Heating the hinges will cause them to revert to their original shape, thereby extending the truss to approximately 10 feet.

Introduction

The high altitude balloon (HIBAL) project was introduced to Wright State University in the fall of 2005. Since then, it has been the platform for many projects and experiments to be tested in a near space environment. Past projects have investigated tracking and recovery systems using global positioning systems (GPS), handheld amateur radio (HAM), and experiments conducted at altitude during the launches including a solar cell study and an SMP tube deployment. Information from these past projects has provided much of the necessary framework to guide the planning and launching of a deployable truss described herein. Figure 1 shows the typical setup of the HIBAL.

In aerospace technology, weight and storage space are some of the most limiting design factors. Therefore, the introduction of large scale structures in space is currently constrained by the size of the transport vehicle. Additionally, multiple, costly trips to space, with time and labor intensive assembly once there, need to be avoided. Investigation of methods such as the development of large scale deployable trusses is therefore needed to facilitate the further advancement of large scale structures in space.

The objective of this design project was to develop a three dimensional truss that can deploy in a near space environment. This design is compact, lightweight, and deployable within minimal time and labor. One potential use for this type of truss system is very large scale satellites. Depth perception in imaging is largely dependent upon the separation between the cameras or sensors. Therefore a large truss that can deploy in space with a camera attached to each end can survey with a 3-dimensional depth perception that a single camera system cannot achieve. This project is a proof of concept, deploying a truss in near space. The system that will carry the truss to the near space environment is the HIBAL. The HIBAL is a balloon apparatus that includes
payloads, or storage modules, that can carry limited amounts of material to near space altitude, approximately 100,000 feet.

The deployable truss members will consist of carbon fiber elements that are adhered to hinges, made of an SMP composite. The SMP material which will be used for the hinges of the deployable truss is a polymer matrix, as seen in Figure 2, with the capability to be heated and deformed. The exceptional characteristic of this material is its capability be heated, shaped and cooled, then to recover its original shape when reheated to its critical temperature. These characteristics combined with others such as high strain-to-fail ratios, high specific modulus, and low density can optimize a mechanical systems efficiency and functionality and make it ideal for applications requiring maximum strength at minimum weight.

The FAA (Federal Aviation Administration) has guidelines for launching an HIBAL which are specified in FAR 101. Within a payload can be multiple packages, each weighing no more than 6 lbs with the weight of the entire payload is limited to 12 lbs. It is, however, possible to shift the weight between packages if necessary to maximize launch capability. For example placing
the power source and computer for the truss package in the module with the guidance and recording equipment could allow for appropriate weight distribution. If there is any amount of weight above those specified the HIBAL will be prohibited from launching.

The power supply options are significantly limited by the weight constraints. The heating system must be as efficient as possible in order reduce the power required and therefore the weight of the system. Another limitation of this deployable truss system is timing. The objective is to deploy this truss in a near space environment, above 70,000 feet. For this project, the initial heating of the SMP hinges to start deployment of the truss will not begin until the system reaches 70,000 feet. The truss needs to be fully deployed by the time the balloon ruptures at approximately 100,000 feet. The balloon rises at a rate of approximately 13 feet per second which creates a truss deployment window of approximately 35 minutes.

The goal of this project is to deploy a three dimensional truss, from 2 feet in length to 10 feet in length, in a near space environment in order to model a truss deployment in space. The specification of 10 feet in length when deployed was chosen as a model with the aim of proving functionality while remaining within the confines of the weight limitations imposed by the FAA requirements for the HIBAL. The stowed dimension of 20% of the total deployed length was chosen as an initial experiment value which can be improved upon in future experiments.

The on-board computer plays a major role in the performance of this dynamic truss system. The electrical system will have to initiate certain heaters at specific times for the truss system to be successfully deployed. Robust code, which takes into account altitude and time, will have to be stored and executed using a Basic Stamp, a very small, lightweight microcontroller.

Timing, complete hinge deployment, straightness, and member rigidity once deployed are the major factors which will prove if this project is successful. A camera system composed of two (2) small digital video cameras will be used to capture the deployment process for a real time analysis of these factors. To determine possible problems which may occur during the final launch, a single section truss system prototype will be launched, deployed, and analyzed prior to the full truss. This launch will give vital information and data to use in troubleshooting and optimizing the final design.

The material chosen for the truss members was carbon fiber. This material was chosen for its high strength to weight ratio. The initial design of the truss members was of 3/8” hollow carbon fiber tubes. This decision was reevaluated due to the difficulty in connecting the round tubes to the flat SMP. Flat, carbon fiber strips, seen in Figure 3, were then chosen for the design. This allowed for simple adhering to the SMP, but left the difficult task of connecting the hinged members to the vertices. This problem is addresses in section 4.2.3.1.
The SMP material used for the hinges of the truss is a polymer matrix that has distinctive capabilities that could be very useful in aerospace applications. The capability of the SMP composite material to be deformed and recover its shape when reheated to a critical temperature, as shown in Figure 4, could open many doors in space based research. The SMP was donated by Cornerstone Research Group, Inc. (CRG). The mechanical and thermal properties of the SMP were provided by CRG.

For the initial hinge design, adhesive was to be used to attach the aluminum sheaths to the carbon fiber. Testing was done to find which adhesive worked best in the temperatures faced during launch which reach (-57)°C. Three test pieces were made using the three adhesives shown in Figure 5, Instant Krazy® Glue, Quik-Cure 5 Epoxy, and Rubber Toughened Super Glue Cyanoacrylate.
The 3/8 inch carbon fiber tubes were inserted and adhered ¾ of an inch inside the aluminum sheaths. Holes were drilled at both ends of the tubes and fishing wire holding a mass of 30 grams was tied to each end. To replicate the thermal environment expected during the HIBAL flight, the test pieces were placed inside a Styrofoam cooler (Figure 6) with blocks of dry ice placed on a grate above them. The entire system was placed outdoors with an ambient temperature of (-2)°C for 3 hours resulting in a temperature inside the cooler recorded as low as (-34)°C. None of the adhesives failed during the three hour testing period, but only the Quik-Cure 5 did not dry-up or fracture at any point around the tube’s perimeter. Although the design change later eliminated the need for adhesive, this testing provided information for future design iterations.

Figure 6: Adhesive testing in low temperature using dry ice

The same three (3) adhesives were tested in attaching the carbon fiber strips to the SMP. The strips were adhered to the SMP and the adhesives were set to cure for 24 hours. After observing that the force of the SMP composite’s movement caused all of the adhesives to fail, it was concluded that another form of stability was required. The knotted pin connections shown in Figure 7 were subsequently implemented.

Figure 7: Knotted pin connection: SMP to carbonfiber

An experiment was conducted to determine the deployment force of 6 different designs of the SMP hinges. Table 1 shows the hinge designs which were tested.
Table 1: Hinges tested for deployment force

<table>
<thead>
<tr>
<th>Hinge</th>
<th>Width (in)</th>
<th>Shape</th>
<th>Spacing (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>flat</td>
<td>0.092</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>flat</td>
<td>0.184</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>curved</td>
<td>0.092</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>curved</td>
<td>0.184</td>
</tr>
<tr>
<td>E</td>
<td>1.5</td>
<td>flat</td>
<td>0.092</td>
</tr>
<tr>
<td>F</td>
<td>1.5</td>
<td>flat</td>
<td>0.184</td>
</tr>
</tbody>
</table>

Figure 8: Hinge force test setup

The hinges were suspended above a digital scale, as shown in Figure 8, with 17.51V at .63A being supplied to the heaters for 90 seconds. The maximum reading on the scale was recorded for each trial and the results are shown in Table 2.

Table 2: Hinge force test results

<table>
<thead>
<tr>
<th>Hinge</th>
<th>Max Temp (C)</th>
<th>Trial 1 (g)</th>
<th>Trial 2 (g)</th>
<th>Trial 3 (g)</th>
<th>Calculated Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>83</td>
<td>35</td>
<td>34</td>
<td>35</td>
<td>0.338445</td>
</tr>
<tr>
<td>B</td>
<td>85</td>
<td>42</td>
<td>43</td>
<td>40</td>
<td>0.41202</td>
</tr>
<tr>
<td>C</td>
<td>81</td>
<td>58</td>
<td>51</td>
<td>48</td>
<td>0.51339</td>
</tr>
<tr>
<td>D</td>
<td>83</td>
<td>55</td>
<td>39</td>
<td>44</td>
<td>0.45126</td>
</tr>
<tr>
<td>E</td>
<td>78</td>
<td>58</td>
<td></td>
<td></td>
<td>0.56898</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ELIMINATED</td>
</tr>
</tbody>
</table>

The results in Table 2 show that hinge E performed the best, however when removed from the testing apparatus, hinge E would not straighten. This is determined to be due to the heaters being 1.5” wide while the heaters are only 1” wide and the thermal conductivity of the SMP did not allow the heat to spread to the edges of the hinges where the heater was not touching. As a result of this, hinges E and F were eliminated from the test. The results show that curving the hinge prior to stowing it increases the deployment force. The larger separation of the SMP sheets
increased the deployment force on the flat hinges, but decreased the force of the curved hinges. Of the remaining hinges, the hinge with the highest deployment force was hinge C, which was therefore chosen for use on the final truss design. The original design for the vertices consisted of a hinge attached to the cross-members and the triangular sections of the truss. Small, brass hinges were considered for the initial design, but eliminated due to shrinking and locking up in low temperatures, which would render the hinge immobile. This vertex, shown in Figure 9, design allowed free unidirectional mobility of the cross-members while eliminating the dilemma of shrinking.

![Figure 9: SolidWorks representation of vertex design](image)

The material chosen for the vertices was polycarbonate plastic due to its high strength to weight ratio and ease of manufacturing. The vertices were manufactured by Kerf Waterjet using a waterjetting technique. The final product is shown in Figure 10.

![Figure 10: Vertex of truss](image)

The preliminary design of the truss was a typical triangular truss with diagonal, supporting cross-members. This design was simplified to that shown in Figure 11 as the deployed truss with a stowed view shown in figure 12. The revised design is a frame rather than a truss, but this design verifies proof of concept of a deployable truss within the imposed time and budget constraints. The initial design required 6 SMP hinges per section therefore requiring 12 heaters per section. After redesign of the truss, eliminating the diagonal cross-members, the number of SMP hinges was cut in half. Coupled with placing a single heater between the SMP on the hinges, the new design reduced the number of necessary heaters to 3 per section. This reduced the required power, weight of the system, and dramatically reduced the overall cost.
In calculating the power requirements the only losses considered were the conduction losses to the carbon fiber. The radiation gains and losses were neglected because of the reflective property of the insulation. The convection losses were neglected due to the low density of the air at altitude combined with insulating the hinges. The formulas used to calculate the power requirements were provided by Minco, the manufacturer of the heaters selected for this truss design. Table 3 shows the calculated results for a single section in the lab and requirements for each controller for the actual launch. The equivalent resistance of 55.6Ω is the average resistance of ten (10) randomly selected heaters.

<table>
<thead>
<tr>
<th></th>
<th>Power Required (Watts)</th>
<th>Equivalent Heater Resistance (Ohms)</th>
<th>Supplied Voltage (Volts)</th>
<th>Required Current (Amps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Testing In Lab (per section)</td>
<td>3.39</td>
<td>18.53</td>
<td>18</td>
<td>0.43</td>
</tr>
<tr>
<td>Launch (per 2 sections)</td>
<td>17.49</td>
<td>9.27</td>
<td>18</td>
<td>1.37</td>
</tr>
</tbody>
</table>

Table 3: Power requirements for truss deployment

The final SMP hinge design required the heaters to fit in between the SMP sheets and flex along with the hinges. Selection therefore required a thin, flexible heater. The heaters also had to be capable of operating in the extreme environmental conditions of this experiment including very low temperature and pressure. The capability to provide the heat required to overcome...
temperatures nearing (-60)°C at 70,000 feet to 100,000 feet was a necessity. Heater size was also major a constraint as was discussed previously. Due to their capabilities and flexibility, Minco Polymide Thermofoil heaters were selected for use on this truss design. These heaters are rated for use in temperatures from (-200)°C to 200°C and are NASA approved for space applications. The 1 x 3 inch heaters, as shown in Figure 13, were chosen in order for the heaters to fit in between the SMP sheets on each hinge.

![Figure 13: Heater used to heat SMP for deployment](image)

As previously stated, insulation was necessary to fully negate radiation and convection losses in order to lower the power necessary to bring the SMP hinges to their critical temperature of 90°C. The ratio of solar absorptivity to emissivity ($\alpha_s/\varepsilon$) is what is used in determining materials used for solar collectors which maximize absorption of solar radiation and minimize radiation emission$^6$. Aluminum foil was chosen due to its relatively high ratio of ($\alpha_s/\varepsilon$) of 3.0, as well as its flexibility, low cost, availability and light weight.

The maximum temperature to which the SMP can be heated without causing damage to it is 130°C. With ambient temperatures reaching as low as (-57)°C, the required power to heat the hinges up to 87-92°C and keep them at that steady state temperature would be required to vary during flight. Accordingly, temperature controllers, shown in Figure 14, were incorporated into the heating system. The controllers keep the temperature constant by drawing the necessary current from the batteries when needed and sending that along to the heaters. There is a set point on the controller which has been set to 92°C. Five controllers were used, one controller per two (2) sections of the truss.

![Figure 14: Controller used to regulate temperature of heaters](image)

Considerations for battery selection included power requirements, weight, and the ability to operate in the harsh environment of near space. The power requirements require the batteries to supply 17.49 W to the controllers for the 15 minute duration of deployment. With, at most, two (2) controllers activated during deployment, it was decided to use two (2) smaller, lighter
batteries. The batteries chosen for the final truss deployment were Makita 18 volt 1.5 amp/hour lithium-ions, as shown in Figure 15.

![Batteries selected to power truss deployment](image)

**Figure 15: Batteries selected to power truss deployment**

The first deployment test was setup at room temperature, 23°C, and atmospheric pressure, roughly 101.325 kPa. The test was setup so that a single section of the truss deployed straight upward, simulating a worst case scenario having to overcome gravity. During this test, the truss deployed approximately 40% upward. The same test was conducted with the truss setup to deploy horizontally, and it deployed approximately 60% and drooped toward the ground. The test was performed again with the truss deploying straight down. This proved successful as the truss deployed roughly 98%. This experiment proved that the truss deployment could not overcome gravity, which is still present in near space.

A single section of the truss was used for deployment testing both in a vacuum to represent the low pressure environment at altitude and in a box with dry ice to simulate the temperatures expected at altitude. The vacuum testing was done with an ambient room temperature of 23°C. The vacuum chamber reduced the pressure to 5.3 kPa representing an altitude of approximately 75,000 feet. The truss deployed approximately 98% in 1 minute 45 seconds.

Deployment of the single section was also tested in a low temperature environment using dry ice in the same manner used to evaluate adhesives. The entire system, including the battery, was placed in a container and the truss was suspended from a grate in and dry ice was placed above it on the grate, as shown in Figure 16. The system was covered with a blanket and allowed to sit for 1.5 hours, the approximate time that the HIBAL takes to reach 70,000 feet. The truss was then hooked up to the battery and made to deploy. The initial temperature of the heaters was (-19.8)°C. The truss took 2 minutes 10 seconds to fully deploy under these conditions. The battery changed from an initial voltage of 19.61V to a final voltage of 18.55V after the truss was fully deployed. Figure 17 compares the final results of the vacuum and temperature testing graphically. As shown, the dry ice test took approximately three (3) times longer to reach maximum temperature at -19.8°C.
The payload box was designed to house, protect, and insulate the batteries, controllers, and cameras during the launch. The box is made of foam insulation with a MonoKote film adhered to it. The MonoKote film, when heated with a heat gun, acts as a shrink-wrap, providing puncture resistance to the foam. The stowed truss was attached to the payload box by placing a thin, light sheet of plywood on the inside bottom to secure the truss to using zip-ties as shown in Figure 18.
The basic stamp microcontroller, shown in Figure 19, is the electrical circuit component that initiates the deployment of the truss. Code was put into the basic stamp which tells it to supply power to the first controller to initiate deployment of the first two (2) sections of the truss when the HIBAL reaches 70,000 feet, \( t = 0 \) minutes. Furthermore, the code supplies power to the second controller to deploy the second two (2) sections at \( t = 2.5 \) minutes. The code switches the power from one controller to another using a relay switch every 5 minutes thereafter, completing deployment from controllers 1, 2, 3, 4, and 5 at \( t = 5, 7.5, 10, 12.5, \) and 15 minutes, respectively.

![Figure 19: Basic Stamp microcontroller](image)

A ground launch was performed to illustrate the truss’ functionality, as shown in Figure 20. In this circumstance the atmospheric pressure was about 101.3 kPa and 22°C. Although the hinges were insulated using aluminum foil, convection negatively affects the truss deployment. The ground launch involved a two section truss assembly deploying to 2 feet from a stowed state of about 4 inches. A wooden platform was built to help support the truss as it deployed. Once the trigger on the microcontroller is pressed, the top section deploys lasting about 1 minute and 30 seconds. The second section follows this same pattern taking the deployment process 3 minutes to complete. The truss successfully deployed during the hands off ground launch. This solidifies that the truss functions properly and it shows that the microcontroller functions. Due to the success of this deployment it can be concluded that we can control the truss deployment mechanically and electronically under our project’s constraints.

![Figure 20: Setup for hands off ground launch of 2 sections](image)

There are weather constraints which must be met for the HIBAL to be permitted to be launched. The weather restrictions, given in FAR 101 include ground wind speed to be less than 8 miles
per hour and cloud cover less than 50%. A preparatory checklist is used to ensure launch readiness prior to launching the HIBAL. Flight prediction software has been developed by past HIBAL teams that predicts the landing location after the balloon has ruptured and returned to earth. The prediction software takes into account wind speeds at different altitudes and predicts the location of landing using Google Earth, as seen in Figure 21. This coupled with payload tracking using a GPS signal emitted from the communications module, aides in locating the payload once it returns to earth. The FAA gets notified by fax of the launch time, location, and prediction.

Figure 21: Flight prediction using Google Earth

Bibliography


