Overview of Zero Pressure Balloons and Independent Manufacturing Design

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Zero pressure ballooning offers the ability to perform long duration flights with high mass payloads. The main challenge with utilizing zero pressure balloons is the cost of hiring a company to manufacture the balloon to mission specifications. The reason for the high price is that balloons must be assembled by sealing gores together with specialized sealing equipment to form the balloon envelope. By constructing an adjustable rail system and a custom heating element, assembly of balloon envelopes could be performed for a fraction of the cost of purchasing via a company. This process will allow university students to perform high altitude experiments with greater accessibility and less cost than before. This paper will cover basic zero pressure balloon operation and application, as well as how this balloon assembly method works and the design challenges that have been overcome.

I. Introduction

Research of Earth at and beyond the upper atmosphere is of increasing interest to scientists in recent decades, but the physical and environmental cost of research is growing at an exponential rate. Rocket Launch Vehicles (RLVs) are efficient for boosting large payloads into orbit for study, but the cost of manufacturing, testing, and clearing scientific payloads to space-hardware standards is often prohibitive to independent researchers and universities. Commercial and government research teams are making great strides towards more efficient, cleaner RLVs, but the increased use of RLVs for commercial spaceflight and research raises the question of long-term environmental damage. Zero pressure balloons, a form of high-altitude balloons, offer a viable solution to both environmental and monetary cost issues by allowing long-duration, low-pollution missions at an affordable cost to researchers.

Zero pressure balloons require far less manufacturing than their super pressure counterparts, due to the absence of high stress on the balloon envelope. Zero pressure balloons can transport relatively large payloads up to an altitude of 100 km for extended periods of time. The process of manufacturing the balloon envelope still poses a difficult, but surmountable challenge. Our research seeks to simplify the manufacturing process through a reusable, adjustable framework that would allow researchers and universities to construct mission-tailored zero-pressure balloons at their own laboratories. This paper presents our research in designing, planning, and constructing the balloon envelope.

II. History and Modern Use

A. History

The history of zero pressure balloons is well documented, but difficult to trace. Research shows the concept of technology was adapted from hot air ballooning in 1783 by Jacques Charles [1], after the Montgolfier brothers made the first recorded hot air balloon [2]. Charles' envelope used rubberized silk to contain hydrogen, as the gas escaped easily from loosely-woven materials. Because lighter-than-air gases such as hydrogen and helium are comprised of such relatively small atoms, companies such as Raven Aerostar began using polyethylene envelopes in the mid-1950s [3], as it offered lighter, more-efficient containment of the lifting gases. These polyethylene balloons were used in military experiments such as Project Farside to hoist an RLV to launch altitude, and by atmospheric researchers to study climates at high altitudes. Zero pressure technology has changed little since its conception and remains a reliable method of making scientific discoveries at altitudes too expensive to observe through other mediums.

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B. Present Day Use

Zero pressure balloons remain of specific interest to atmospheric researchers, climatologists, and more recently, large corporations needing long-term access to high altitudes. Super pressure balloons have become the standard of long-duration flights since they retain their helium at pressure, but these envelopes require precision manufacturing processes to evenly distribute pressure across gores at float altitude. NASA and other scientific organizations who seek to send high mass payloads into the upper atmosphere still rely on zero pressure balloons when mission float time-frames do not exceed several days. One of the most notable applications is for educational Balloon Satellite (or BalloonSat) programs through universities and educational institutions. These programs allow student researchers to repeatedly gather data at high altitudes with relatively little expense, but the cost of purchasing the zero pressure balloon causes many organizations to rely heavily on latex balloons, which limit payload weight and time at float altitude considerably. The ability to independently fabricate zero pressure balloons would make consecutive, high duration, high altitude balloon flights significantly more accessible.

III. Assembly Process

A. Fundamentals of Engineering

The envelope of zero pressure balloons are made up of multiple gores that are sealed together along their edges. The shape of these gores depends on the size of the balloon and the total number of gores that make up the balloon surface. On the balloon envelope, the actual load is distributed along the gore seals rather than the throughout the surface. The seals are reinforced with load tape so that the seal integrity is not broken. This results in there being minimal load acting on the gore itself, leading to a much smaller possibility of shearing the envelope surface. By increasing the number of gores, the load becomes more evenly distributed. Therefore, zero pressure and super pressure balloons often have upwards of 130 gores over the entire surface.

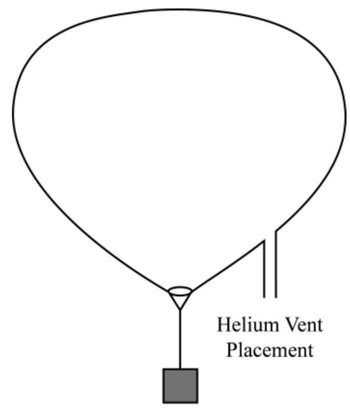

Figure 1

Since the concept of a zero pressure balloon is to reduce pressure on the balloon film, the construction of the balloon envelope needs to include special features to allow the internal pressure of the balloon to remain constant with the ambient pressure. One such feature is the inclusion of a vent (Figure 1) at or near the base of the balloon envelope that acts as a check valve for the helium [4]. This vent allows for excess helium to escape the balloon envelope once the pressure difference increases. The actual geometry of the vent can vary. More traditional vents are tubes that protrude from the envelope slightly above the base of the balloon and extend down, so that the opening of the vent coincides with the base. Other designs feature a vent that is attached lengthwise to the balloon envelope so that the vent opening does not float upwards due to rapid descent of the balloon. For certain payloads such as balloon elevated rockets, AKA rockoons, the base of the balloon envelope can remain open to act as a vent.

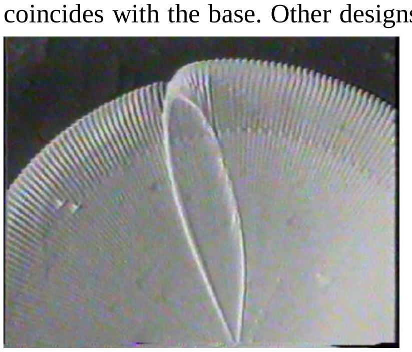

Figure 2

Also included on the balloon envelope are filling tubes near the crown. These tubes also act as check valves so that the helium can only flow in from the top, and not out. The reason that the tubes need to be located near the crown is that large balloons must be filled from the top to guarantee even load distribution between the gores. Uneven load can result in clefting of the balloon envelope [5] (Figure 2). This phenomenon results in distortion of the balloon envelope once it reaches equilibrium.

B. Concept of Design

As stated in the previous section, gore shape depends on the number of gores and the size of the balloon itself. The angle in radians that the gore makes with respect to the arc of the balloon, θgin Eq (1), is determined by dividing 2 pi radians by the total amount of gores, *N*.

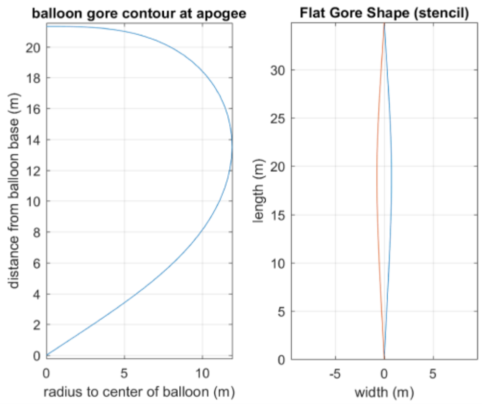

Figure 3

$$\theta g = 2\pi/N \qquad (1)$$

Then, the width of the gore, W in Equation (2), is determined by multiplying the gore angle by the radius, r, of the balloon at a certain height from the base.

$$W = r\theta g \qquad (2)$$

Using software such as MATLAB, the arc of the gore can be calculated and graphed using the method described above [6]. The shape of the gore can then be traced along the envelope material and cut to size. An example of gore shape outputs is shown in Figure 3. The seals along the gore edges are created using special heat sealers manufactured to fit the length of the gores. Traditionally, a copper strip is heated to a specific temperature using nichrome wire supplied with a current. This heat melts the plastic, which in turn forms the seal. Special load tape is the applied along the seal to strengthen the integrity of the plastic. This sealing process can be replicated by the assembly of sealing mechanism using common practices, such as general machining and 3D printing. A heat sealer similar to the model presented in Figure 4 can be easily reproduced and used as a heating element. This model includes casters that can move laterally along a curved track, so that the sealer can travel the entire curve length of the gore. This system can be translated into a rail assembly such as the one in Figure 5, where the track can be adjusted along pieces of aluminum shafts so that the specific curve of the gore can be replicated. The assembly is modular in design so that the sealing action can be scaled up or down to accommodate the size of the balloon.

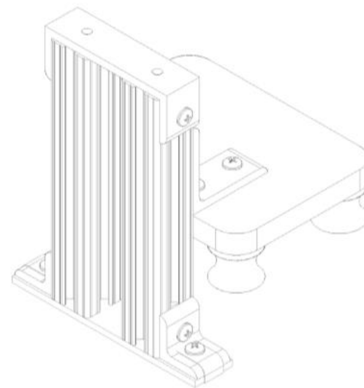

Figure 4

C. Procedure of Assembly

Assembly of the balloon envelope takes place in a level plane. The heat sealing apparatus' rail is preset to match the curved section of gore being sealed as defined by the MATLAB code, and is placed to the side for later use (Figure 5). Each gore begins as a flat, rectangular sheet of polyethylene, stretched over a surface on which the 2-dimensional curve from simulations is traced for reference. This first layer of polyethylene is left flat, and a second sheet is stretched over the first, also flat (Figure 6).

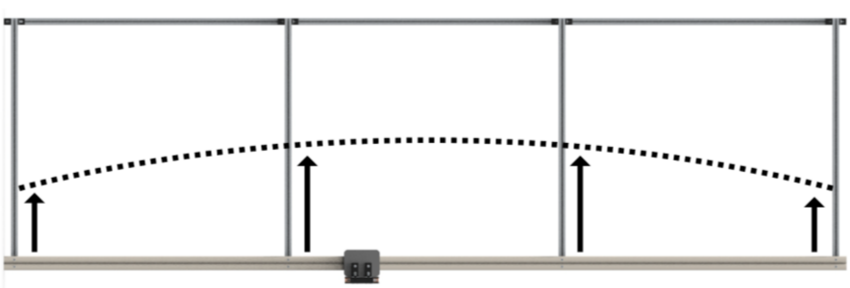

Figure 5

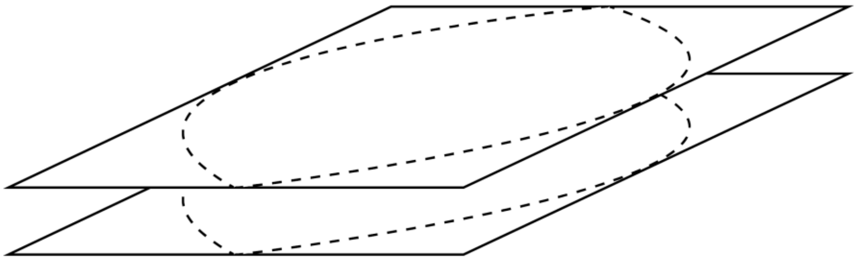

Figure 6

These two sheets are weighted to the surface to ensure no lateral movement occurs. The heat sealing apparatus and track is placed on top of the two sheets of polyethylene, and the heating element is pressed into the two layers of polyethylene to create the first seal. The heat sealer is then lifted, moved longitudinally down the curve to the next unsealed portion, and pressed again. This is repeated until the full gore seal is complete. Once the first full seal is complete, the track & apparatus are removed, and the remaining excess polyethylene outside of the curve is cut away. After ensuring a complete seal, an insulating layer of material is placed on the sealed half of the upper polyethylene sheet, and the unsealed half is folded over the insulated material (Figure 7).

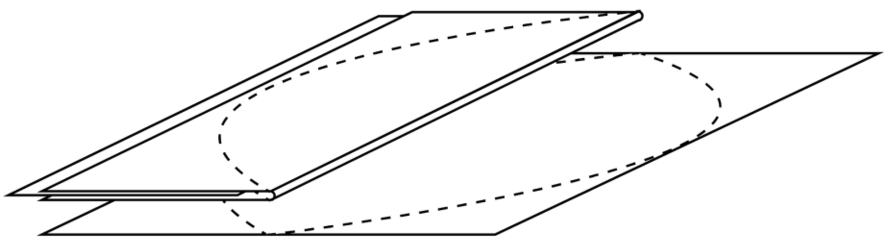

Figure 7

After the fold is complete, a new, rectangular layer of polyethylene is stretched flat over the entire assembly, and the heat sealing rail & apparatus is placed over this sheet. The two uppermost layers will be sealed together, and the upper layer is then folded in half as before (Figure 8).

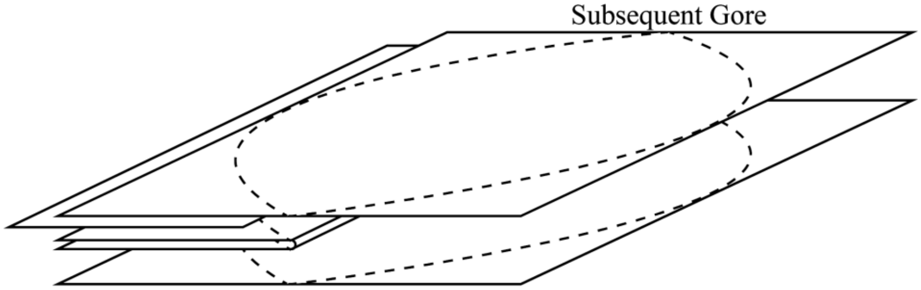

Figure 8

The previous steps are repeated until the total number of gores, minus one, are sealed together and folded. The final step is then to seal the final gore to the folded stack as before, leaving the opposite side flat. The insulating layer is then placed in between the lower and upper gore, opposite the stack of sealed gores (Figure 9). The heat sealer track will be reset to the opposite curve dimensions and placed on top of the uppermost and lowest sheets of polyethylene. The upper fore will then be sealed to the unsealed half of the lower gore, completing the balloon.

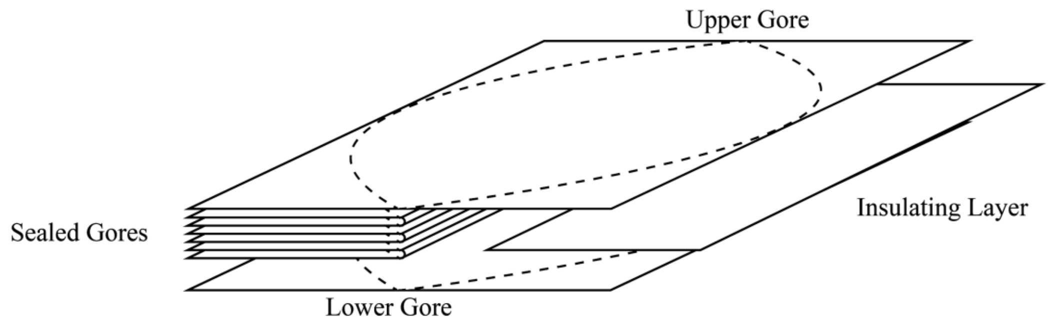

Figure 9

The final balloon envelope is thus inside-out, laid flat on the assembly surface. The envelope can then easily be manually inverted, orienting the fins of sealed material on the inside of the balloon envelope. This procedure is possible due to the minute thickness of polyethylene, and allows for increases in shape, size, and number of gores, while preventing excess torque on the material due to handling or shifting during assembly. A crown may also be added to the balloon envelope if necessary, sealed in sequence with each gore.

V. Scalability

Scale of the balloons for manufacturing research purposes does not exceed a gore length of 150 feet, but future flights may require larger balloon envelopes. As such, procedures for scaling the manufacturing process exist, but are limited by several factors. These limiting factors are, in order of magnitude from highest to lowest, manufacturing time, manufacturing location, number of balloons needed, and quality control. These factors have been assessed from the perspective of a university or research group in need of an undetermined number of balloons, that are unable to purchase these balloons, as large research firms or corporations are assumed to have the raw funds necessary to purchase balloons from an independent manufacturer.

A. Physical Limitations

Fabricating the balloon envelope from scratch is a time-intensive process, and tests have shown manufacturing time to increase exponentially with the size of the balloon. These increases can be mitigated in some areas, including automation of the heat-sealing process, quality control, and power management. Each component of the heat sealing track & apparatus can be effectively automated with the use of servos, pneumatics, and computer controllers. This would allow human supervision to focus on the procedure of assembly, quality control, and management of materials. Readings from temperature and force sensors along the heating element can be compared to optimum and previous values to ensure consistency between seals along the gore. These changes in values can then be recorded and affect adjustments in the power supplied to the heating element to compensate for errors away from the optimum sealing force & temperature. Automation would lead to shorter turnaround times in production and allow for subsequent flights in a shorter time-frame.

B. Cost Limitations

Several factors directly affect the cost of scalability, and it should be noted that there exists an asymptote in scaling the manufacturing process where the cost of the process exceeds the cost of outsourcing the balloon envelope to an independent manufacturer. These factors of cost include (but are not limited to) raw materials including lifting gases, materials for the enlarged track and heat sealing apparatus, manufacturing space, and labor. Different research groups will experience varying weights placed on these factors, and ongoing research is required to understand where the asymptote between independent and commercial manufacturing lies. Understanding this boundary will allow for greater efficiency in balloon manufacturing mission planning.

VI. Conclusion

Zero pressure ballooning is a tested and widely used method of performing high mass, long duration missions for scientific, military, and professional applications, but manufacturing presents a technical and economic challenge.

With advances in researching manufacturing methods, we have been able to significantly reduce the overall cost of designing and fabricating a zero pressure balloon, while creating an assembly method that is accessible for researchers limited by labor force, manufacturing space, and materials. Moving forward, we hope to effectively scale the operation in both balloon size and efficiency through better methods of automation and material management, that will allow us to accommodate higher payload masses, and better lifting gas retention. With these improvements, high-altitude research will be not only cleaner, but more accessible and cost-effective for future generations of researchers.

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