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The future of scientific ballooning

By Markus Pagitz*

Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK

This paper gives a brief overview of the historical development of scientific balloons and their capabilities. Furthermore, a recent programme by NASA is introduced that aims to develop balloons capable of carrying payloads of several tonnes to above 99% of the Earth's atmosphere for up to 100 days. It is shown that the currently investigated balloons suffer from instabilities that can be minimized using a different design paradigm for the cutting patterns. Finally, a novel balloon design, similar to the topology of radiolarians, is introduced that is potentially superior to existing designs.

Keywords: superpressure; pumpkin; radiolarian; balloon; ultra long duration balloon

1. Introduction

Although the scientific basis of ballooning was set out by Archimedes (287–212 BC), it took another two millennia until the dawn of the aerospace age in 1783 when the Montgolfier brothers made the first public launch of a large-scale hot-air balloon (US Centennial of Flight Commission 2003, www.centennialofflight.gov). This was the signal for a breathtaking development of aircraft that finally brought men into space in less than 200 years. Even though balloons were soon eclipsed by airplanes and rockets, they are still of importance since they can stay aloft without using energy. A brief historical overview of the development of scientific balloons and their application is as follows.

The first hydrogen-filled balloon, made by Jacques Charles, flew only 12 weeks after the impressive demonstration of the Montgolfier brothers. It turned out quickly that the hydrogen balloon was generally superior to the hot-air balloon. The reason for this was not its higher lifting capacity but the fact that hot-air balloons at that time were made out of paper and were usually ruined after one flight. Charles' first two hydrogen balloons were based on different designs. The first balloon was a superpressure design with a closed envelope. This led to increasing differential pressures during the ascent so that the envelope finally burst. To avoid another structural failure, he designed his second manned balloon with an opening at the bottom so that the resulting stresses in the envelope were relatively small and more or less independent of the altitude. Up to the present day, balloons of this kind are widely used and known as zero-superpressure designs.

*mp403@cam.ac.uk

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Most of the manned scientific balloon flights in the nineteenth century investigated the properties of the atmosphere. This changed when balloon sondes became available in the early 1890s. These zero-superpressure balloons were used to carry instruments to record the atmospheric pressure, temperature and humidity. However, they often drifted considerably away from the launch point so that meteorologists had difficulties in retrieving their instruments. The drifting problem was solved in 1892 by Richard Aßmann, who introduced superpressure balloons that burst when they reach a certain altitude, returning the instruments to the ground with the help of parachutes. These balloons were equipped with radiotransmitters in 1930 by Pavel Molchanov, making it possible for the first time to get real-time data of the atmosphere. Nowadays, thousands of sondes are launched every day around the world for gathering data that are needed to predict the weather accurately and to initialize numerical simulations.

After most of the atmospheric work was done with sondes from the mid-1890s, manned balloons were used as a platform for studying the Sun and cosmic rays without atmospheric interference. Victor Hess discovered in 1912 high-energy particles that could not be detected on the ground. Hence he concluded that radiation with a great penetrating power is entering our atmosphere from space. The discovery of cosmic rays, a name that was coined in 1936 by Robert Millikan, won Hess the 1936 Nobel Prize in physics. However, the increasing altitudes of balloon flights revealed a serious problem. The air pressure above 12 km is so low that gases begin to bubble out of the blood and balloon flights without a pressure garment or vessel often prove lethal. In 1927, Captain Hawthorne Gray of the US Army Air Corps made several flights to altitudes above 13 km for testing high-altitude clothing, oxygen systems and various instruments. On his third flight he ran out of oxygen during the descent and died. It was the last high-altitude flight in an open basket until 1955 when the American space programme required a thorough testing of spacesuits.

In order to undertake cosmic ray experiments at high altitudes (up to 23 km) Auguste Piccard developed in 1930 a pressurized, spherical gondola for two men with a diameter of approximately 2 m (figure 1*a*). The gondola was equipped with bottled oxygen and a system that prevented the build-up of carbon dioxide. Furthermore, he made small but important changes to the design philosophy of zero-superpressure balloons. Previous envelopes were completely filled on the ground and, due to considerable expansion, most of the gas was lost during the ascent. Piccard changed this by using an envelope that was five times larger than the gas volume needed to get off the ground. Therefore, he did not lose much gas during the ascent and had enough lift during the night to return safely to Earth. Figure 1*b* shows a draft of the balloon at flight altitude; note the upper attachment points for partial inflation on the ground. However, as with previous balloons he assumed a shape for the envelope that was far from optimal.

The last notable balloon flight before the outbreak of World War II was in 1935 by Captain Albert Stevens and Captain Orvil Anderson from the US Army Air Corps. A 100 000 m^3 balloon was used for this mission which is widely considered to be the first large helium-filled balloon. Helium replaced hydrogen nearly completely in the following decades on safety grounds. The only notable exceptions were the balloons that were used for spy missions over the Soviet Union.

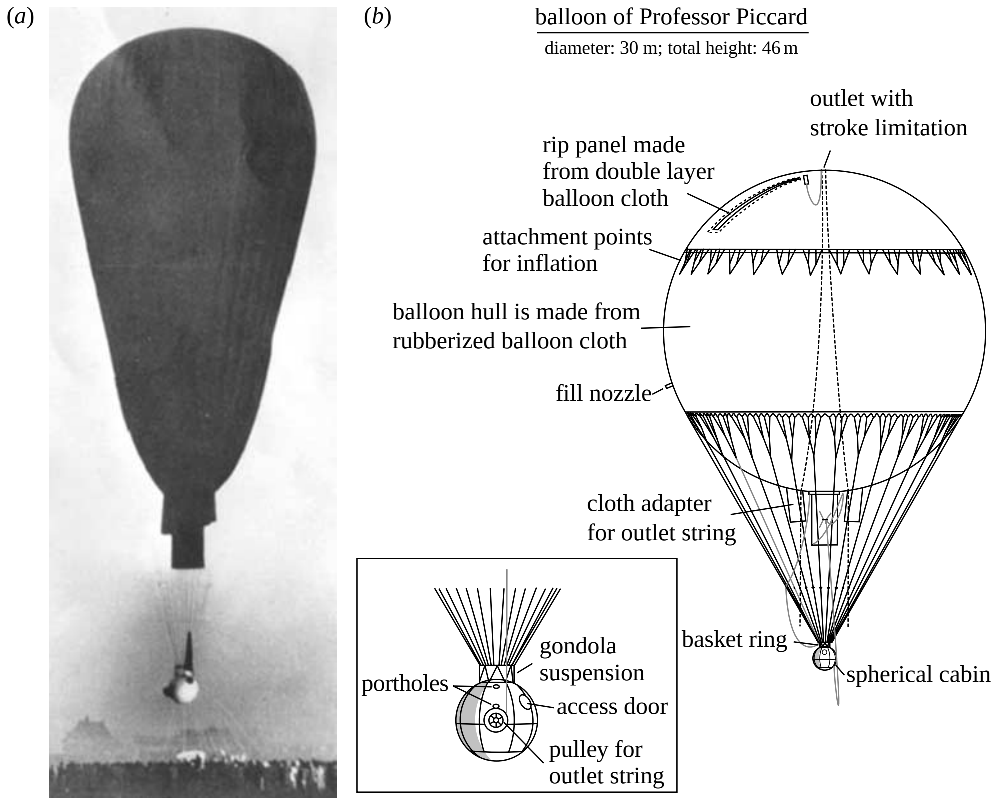

Figure 1. (*a*) Auguste Piccard's balloon shortly after launch, 1933, and (*b*) design drawing of the balloon (from www.centennialofflight.gov).

The huge and heavy balloon envelopes, generally made out of rubberized fabric, had clearly reached the limit of their potential at the beginning of World War II, and a new generation of balloons was developed after the war when polyethylene became widely available. The German expatriate Otto Winzen was the first to construct natural-shaped zero-superpressure balloons from n identical flat polyethylene gores by welding neighbouring lobes together and incorporating a stiff tendon along the common boundary (figure 2). This resulted in a highly efficient design since the curvature of the film between the load tapes is, as in the case of parachutes, considerably increased. Hence, the differential pressure is carried towards the load tapes with much smaller membrane stresses so that it became possible to design balloons with a larger payload to self-weight ratio. Furthermore, the longitudinal tendons provide an excellent attachment point for payloads so that no additional considerations are necessary. After the first flights of these balloons in 1947 it became obvious that they were clearly superior to previous designs. Up to the present day, hundreds of these balloons have been used as an experimental platform for a wide range of experiments. Some of them were used to study, for example, cosmic rays, the magnetic field and its interaction with cosmic winds, cosmic dust or micrometeorites. Other experiments used a cluster of several balloons that were launched simultaneously from different places to investigate global phenomena such as plasma flow. Many important results have been obtained on, for example,

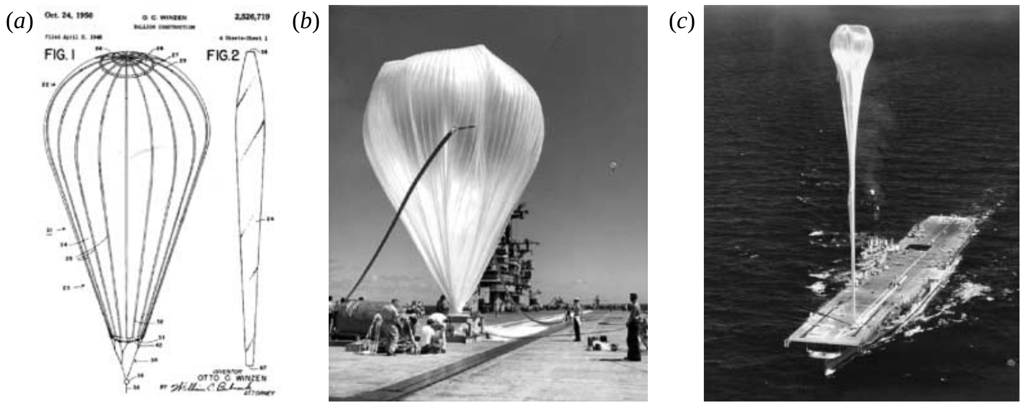

Figure 2. (*a*) Patent of Otto Winzen from 1950 for zero-superpressure balloons made out of polyethylene, (*b*) Winzen balloon is filled on the deck of USS Valley Forge (the carrier is used to compensate wind), 1960 (from www.centennialofflight.gov) and (*c*) the balloon is released from the carrier only 5% filled (from www.history.navy.mil).

the concentration of various gases in the atmosphere such as ozone, carbon dioxide, carbon-14 and nitrous oxide. Furthermore, the depletion of ozone by man-made propellants and the emission of nitrogen oxide from jet aircraft have been measured.

Materials technology, especially the ability to manufacture thinner polyethylene films, improved steadily in the second half of the twentieth century. Therefore, it became possible to construct balloons that were capable of carrying increasingly larger payloads to higher altitudes. By 1972, the largest balloons had a volume of 1 500 000 m^3 and lifted more than 6 t to low altitudes. One of these balloons was based on a further development of the Winzen design and reached a record altitude of 52 km in 1972. This record remained unbroken until 2002 when Japan launched a 60 000 m^3 balloon, made out of an ultra-thin linear low-density polyethylene (LLDPE) film with a thickness of 3.4 μm, to an altitude of 53 km.

It was previously pointed out that balloons are widely used by meteorologists for making vertical soundings in the atmosphere. However, before the 1960s it was impossible to get continuous data about air circulation patterns by drifting with the wind at constant density altitudes. This changed when the Air Force Cambridge Research Laboratories (AFCRL) started to work on small superpressure balloons capable of staying at constant altitude for several months. Superpressure balloons have, in contrast to zero-superpressure balloons, a closed envelope that is pressurized such that during the night there is still some residual pressure. This pressurization guarantees a nearly constant volume and therefore minimizes altitude changes during the day–night cycles. Furthermore, a flight altitude can be chosen by bringing the weight and volume of the balloon into equilibrium with the corresponding density of the air. The work of the AFCRL resulted in the global horizontal sounding technique (GHOST) balloons with a diameter of approximately 3 m (figure 3*a*). These balloons were able to reach altitudes of up to 24 km and were made from Mylar, a biaxially oriented polyester film with a high tensile strength and chemical stability. Between 1966 and 1976, 88 balloons were launched that broke many records and provided valuable data. A GHOST balloon circled the Earth in 10 days at nearly 13 km in 1966. Another GHOST balloon set a record by remaining in orbit for 744 days, circling Earth 63 times.

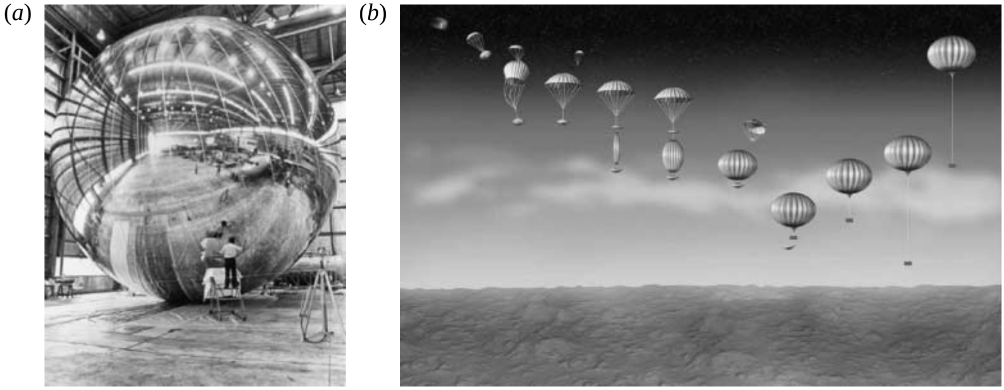

Figure 3. (*a*) Mylar superpressure balloon from GHOST programme, mid-1960s, and (*b*) typical deployment phases of a balloon during descent of a probe (courtesy NASA).

The first, and so far only, planetary balloon mission dates back to 1985 when the Russian VEGA probes released two balloons in the Venusian atmosphere. Helium-filled, spherical superpressure balloons with a diameter of approximately 3.5 m were developed for this purpose in collaboration with the French space agency. The balloons floated at an average altitude of 54 km in the most active layer of the Venusian cloud system at a speed of approximately $69\,\mathrm{m\,s^{-1}}$, exposing them to the corrosive effects of concentrated sulphuric acid. In addition to this hazard they had to survive a vacuum during their journey. Therefore, it was decided to construct the balloons from Ftorlon (a form of Teflon) cloth and film. The tether rope and straps between gondola compartments were made from Kapron (a form of Nylon-6). The mission was a success and the balloons measured temperature, pressure, wind speed and aerosol density until the batteries ran down after approximately 46 hours. Tracking of the balloons revealed vertical motions of gas masses that had not been detected by earlier probe missions. Figure 3*b* illustrates the typical deployment phases of a balloon during the descent of a probe.

2. NASA's ultra-long-duration balloon programme

The development of scientific balloons from World War II to the present day has resulted in robust and reliable zero-superpressure balloons that are capable of carrying payloads of several tonnes to constant altitudes for periods of approximately 1–2 days. Launching these balloons during the Antarctic summer increases flight duration to 10–20 days as not much ballasting is necessary owing to the lack of a day–night cycle. Another remarkable development was that of the relatively small spherical superpressure balloons from the GHOST programme that circumnavigated the Earth dozens of times at constant altitudes. However, up to the present day there is no balloon system available that can carry large payloads at constant altitudes for a longer period. Such a system would have a huge potential since it could provide a cheaper platform for experiments, telecommunication and observation than is currently available. In order to fill this gap, NASA started to develop ultra-long-duration balloons

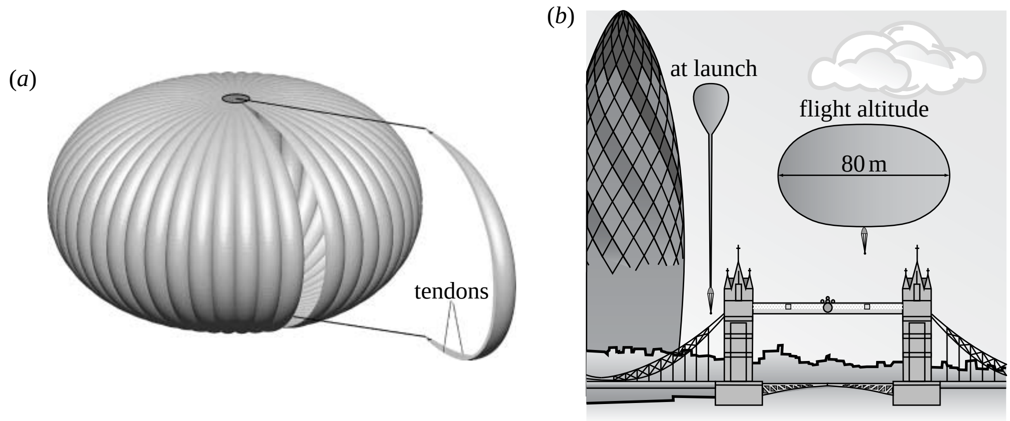

Figure 4. (*a*) Concept of pumpkin balloons and (*b*) size comparison of current experimental ULDBs with Tower Bridge and Swiss Re Tower (final ULDBs will be scaled up).

(ULDBs) in the mid-1990s. These balloons make use of improvements in material technology such as high-strength fibres and LLDPE. The goal of this programme is to develop a general purpose platform that is capable of carrying payloads of several tonnes for up to 100 days above 99% of the Earth's atmosphere. The initial ULDB concept was similar to the highly successful GHOST balloons, a classical sphere design. Nevertheless, it turned out that scaling this proven design to the dimensions needed for the ULDB programme is, mainly owing to the attachment of the payload, not trivial. Furthermore, the necessary membrane thickness increases linearly and the surface area quadratically with the radius of the balloon so that the self-weight is proportional to its volume. The current concept under consideration that avoids these problems is a pumpkin-shaped design. These balloons are, in principal, similar to zero-superpressure balloons that were introduced by Winzen except that they are closed at the bottom (figure 4). However, the resulting shape at flight altitudes differs considerably from zero-superpressure balloons since the differential pressure is nearly constant throughout the balloon. It is interesting to note that the pressurized shape of pumpkin balloons and parachutes is described by the same equations given by Taylor (1963).

Although the realization of this concept seemed to be straightforward, it turned out that the NASA design suffered from the same instabilities that were observed by Nott (2004) in the 1980s during his attempt to circumnavigate the globe in a pumpkin balloon (figure 5*a*). These instabilities turned out to be a rather serious problem and until today it is not clear if it is possible to overcome them without sacrificing too many of the advantages of this design.

3. The instability of pumpkin balloons

The buckling problems that affect pumpkin balloons are of two (connected) types. The first category comprises balloons that inflate properly into the intended axisymmetric shape but buckle into alternative equilibrium configurations if a critical differential pressure is reached. For example, Nott's pumpkin

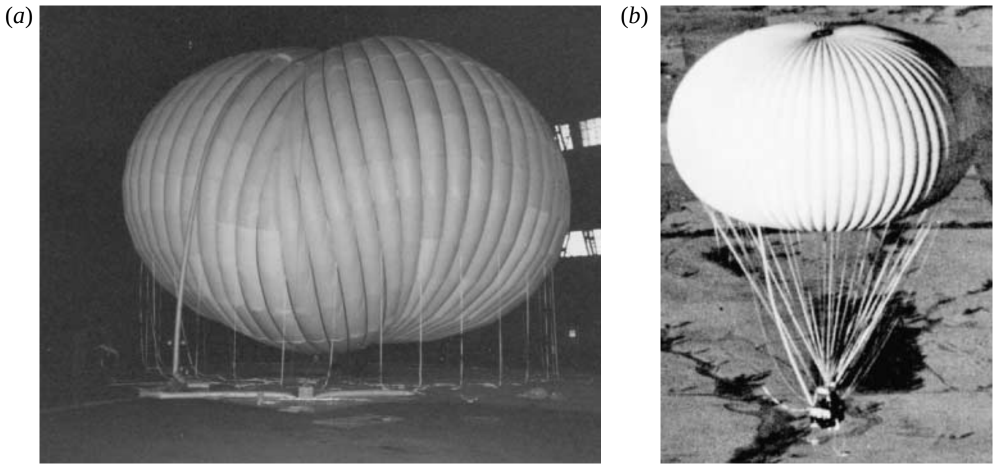

Figure 5. Julian Nott's Endeavour balloon. (*a*) Unstable pumpkin balloon and (*b*) balloon becomes stable after removal of four gores (courtesy Nott).

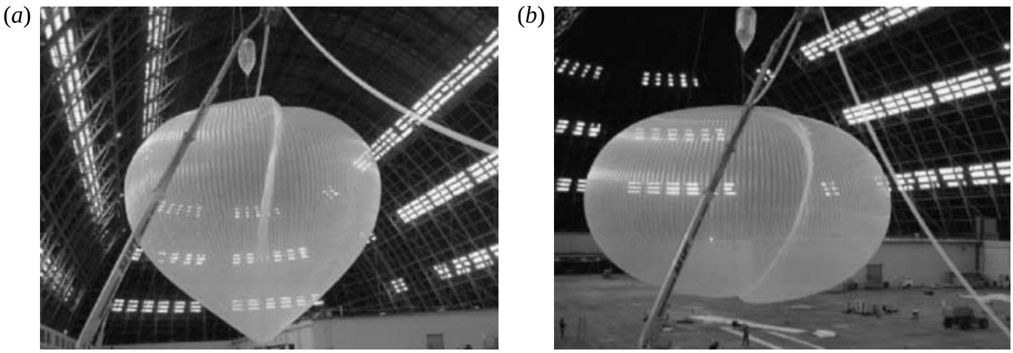

Figure 6. (*a*,*b*) Instability that occurred during the inflation of a 27 m diameter pumpkin balloon with helium–air mixture (courtesy NASA).

balloon inflated into the desired shape after he removed four gores. However, the balloon lost its rotational symmetry again after a critical pressure was reached. The second category includes balloons that do not inflate into the desired shape. Recent experiments by NASA suggest that some of these balloons inflate into a stable, rotational symmetric configuration if air is used but fail to reach this state for a helium or helium–air mixture (figure 6).

Previous work concentrated on the first category and it was shown by Calladine (1988) that pumpkin balloons buckle if a deformation mode exists for which the energy needed to deform the membrane and tendons is smaller than the energy released by the gas due to volume changes. However, in his analytical investigation he assumed a particular type of cutting pattern and buckling mode and neglected the elastic deformation of the membrane and tendons. The first numerical studies go back to Wakefield (2005) and Pagitz & Pellegrino (in press) in which the latter studied the buckling problem using the high degree of symmetry of pumpkin balloons. This became possible due to novel closed-form solutions for transformation matrices that block diagonalize the stiffness matrices of balloons so that systems with more than one million degrees of freedom can be reduced by about three orders of magnitude without loss of accuracy (Pagitz & James 2007).

It was found that the buckling pressures of pumpkin balloons depend heavily on the geometry of the cutting patterns. The first cutting patterns were so-called constant-angle (CA) and constant-radius (CR) designs which means that, assuming the cross-sections of lobes to be circular arcs, the subtended angle or radius of all cross-sections along the tendons is constant (figure 7*a*). Although the difference between both cutting patterns is rather small, for identical cross-sections at the equator, it turned out that CR designs are considerably more stable than CA designs since they provide less material towards the apices. The buckling pressures of small-scale experimental pumpkin balloons with a diameter of 10 m are shown in figure 7*b* for several buckling modes as a function of the number of lobes. Note that the subtended angle of both CA and CR cutting patterns at the equator is 118°. Typical buckling modes are shown in figure 8 and it can be seen that they split into two types. The first type (*n*-big–*n*-small) preserves the horizontal symmetry plane and results in regions that expand and contract whereas the second (*n*-up–*n*-down) leads to regions that move upwards and downwards, respectively. It is interesting to note that only the second type leads to an inextensional deformation of the tendons so that the buckling pressures for the first type are generally very high.

Current efforts try to simulate the instabilities that occur during inflation (second category). This is done by increasing the capability of the existing software to compute rotationally symmetric structures that do not possess a horizontal symmetry plane (as is the case during inflation). It is believed by the author that these instabilities can be described by a 1-big–1-small mode since moving some lobes together results in an increased pressure loading of the other tendons such that the structure deforms mainly inextensionally into a configuration with a higher volume. The observed dependence on the gas used is probably due to the different inflation shape when air is replaced by helium.

4. Optimization of pumpkin balloons

To find out that the sensitivity of pumpkin balloons to buckling changes dramatically for different cutting patterns was rather surprising since the differences between CA and CR designs are not large and the maximum membrane stresses are essentially identical. Therefore, the question arose of whether it is possible to design a cutting pattern that increases the stability of pumpkin balloons without increasing the membrane stresses that are known from CR designs. It turned out that optimizing the geometry of cutting patterns such that the critical buckling pressure is maximized is identical to minimizing their surface area under consideration of a stress constraint.

Figure 9*a* shows a comparison between CR and optimized cutting patterns for a different number of lobes where the width at the equator is scaled to the same magnitude. It can be seen that the differences are, especially for balloons with a small number of lobes, rather large and the width of the cutting patterns are even smaller than needed to approximate a rotational symmetric surface. Figure 9*b* shows the buckling pressures of pumpkin balloons for CA, CR and optimized

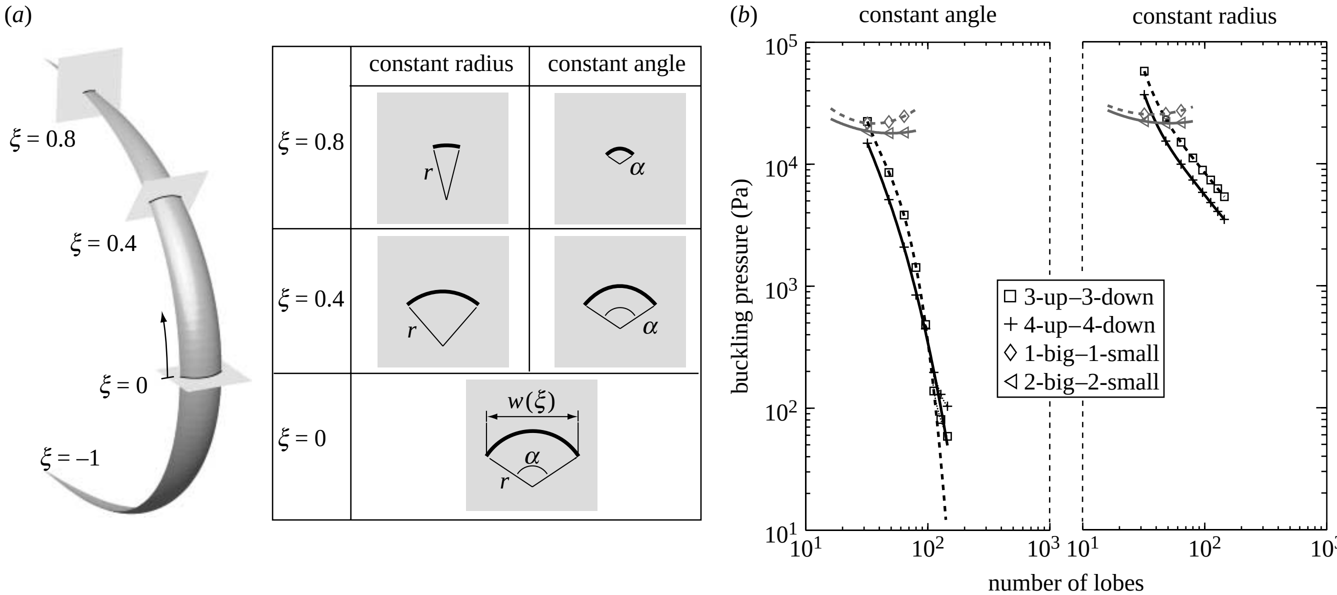

Figure 7. (*a*) Cross-sections of lobes for constant angle (CA) and constant radius (CR) cutting patterns and (*b*) buckling pressures for CA and CR designs.

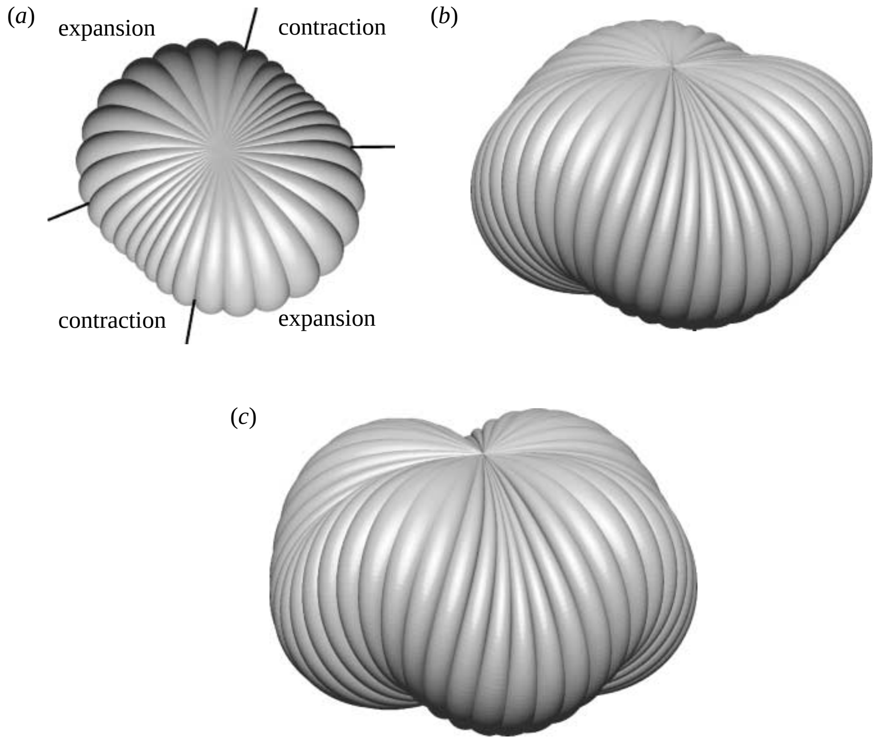

Figure 8. Critical eigenvectors of pumpkin balloons: (*a*) with horizontal symmetry, 2-big–2-small; without horizontal symmetry, (*b*) 3-up–3-down and (*c*) 4-up–4-down.

cutting patterns. Note that the optimization does not only improve the material usage but it also increases the buckling pressures considerably. The shapes of the inflated balloons before and after the optimization (figure 10) show that pumpkin balloons based on optimized cutting patterns possess a more spherical shape. Thus it could be argued that the increase in stability is due to an improvement in the surface to volume ratio.

5. Is there a future for pumpkin balloons?

Nowadays pumpkin balloons are still not functional despite a considerable development effort over the last decade. Recent experimental balloons were based on CR cutting patterns that were predicted to be stable if fully inflated. However, it was found that they did not reach the rotational symmetric configuration. This came a bit by surprise since previous small-scale balloons were inflated (unfortunately) by air and reached the desired shape. At the moment, it seems that changing from air to a helium–air mixture considerably increases the possibility that the balloon ends up in an undesired equilibrium. There are numerous ongoing efforts to simulate the observed buckling during the inflation process. However, a complete simulation of the inflation will not be available in the near future due to the numerical complexity that results from wrinkled membranes and self-contact. Nevertheless, it is believed that the instabilities that occurred during the inflation might be avoided by using the

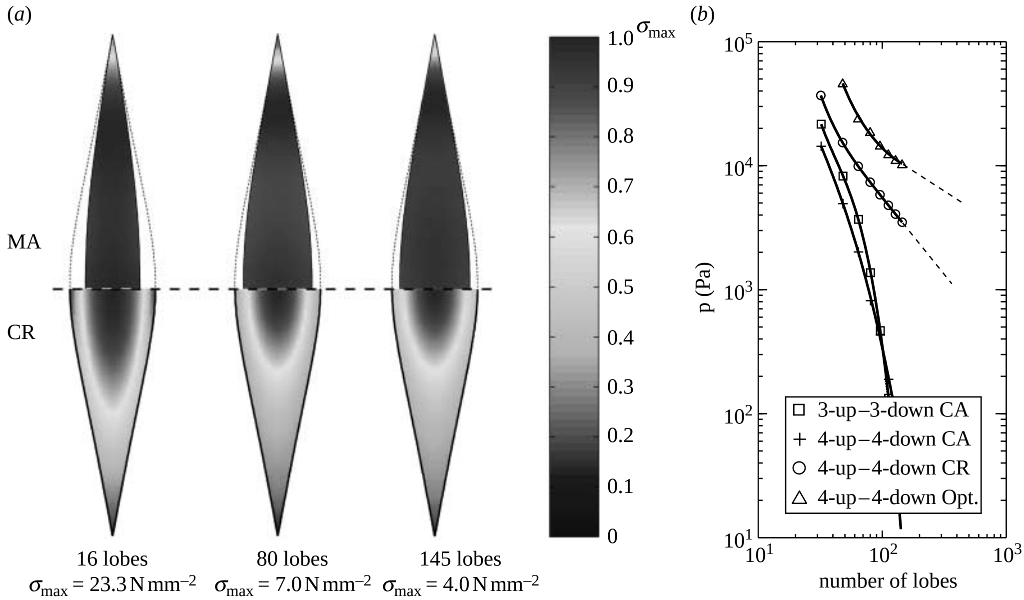

Figure 9. Comparison between optimized (MA) and CR cutting patterns. (*a*) Stresses at 500 Pa and geometry of cutting patterns and (*b*) buckling pressures.

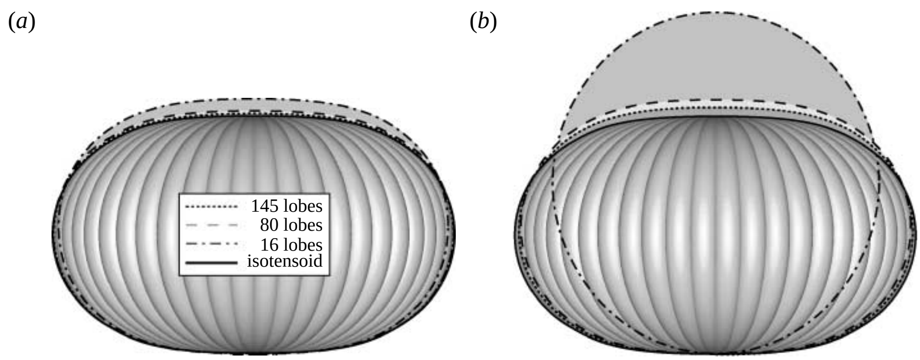

Figure 10. Shape of tendons for (*a*) CR and (*b*) optimized cutting patterns.

previously presented optimized cutting patterns. Therefore, NASA currently constructs pumpkin balloons that are based on this new design paradigm. Furthermore, nonlinear creep laws and new failure criteria are developed that are based on strains instead of stresses such that it is possible to reliably minimize the surface area (Rand 2007).

6. What is the optimal topology for superpressure balloons?

If the currently investigated experimental balloons turn out to inflate properly then there is a high probability that huge pumpkins with diameters of more than 100 m will soon be flying in our atmosphere. However, this is not a certainty and it might be necessary to look for different structural concepts. The major

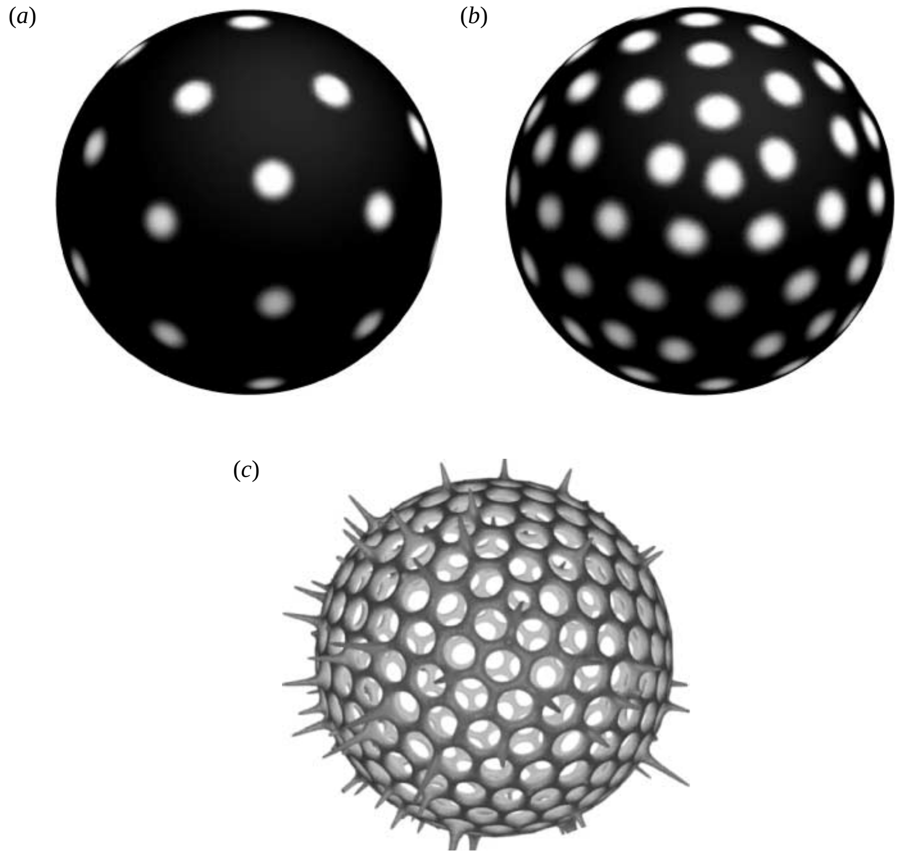

Figure 11. Optimized sphere with (*a*) 95% of material, (*b*) 85% of material and (*c*) radiolarian skeleton (Aulonia hexagona).

problem of pumpkin balloons is the uniaxial alignment of the tendons and the consequent high surface area to volume ratio. In contrast, an optimal design distinguishes itself by providing an easy way to attach the payload, a surface with a minimum curvature and finally an optimal surface to volume ratio.

Finding such a design can be achieved with the help of topology optimization (Bendsøe 1989). In the first step, we assume a hollow sphere that is subjected to a uniform differential pressure. The optimization algorithm can switch the thickness of all surface elements between the current and a minimal value so that the overall amount of material is reduced to a prescribed value by simultaneously maximizing the stiffness of the structure. Figure 11*a*,*b* shows the structure after removing 5% or 15% of the material where the resulting topology is similar to radiolarians (figure 11*c*). It is interesting to note that the growth of the skeleton of radiolarians is driven by the need to keep a certain altitude in the ocean. Therefore, a silica skeleton grows around areolar vesicles that provide the necessary buoyancy (Mann & Ozin 1996). A corresponding balloon, as shown in figure 12*a*, that is based on this design has the great advantage that the surface to volume ratio is much better than for pumpkin balloons and that the membrane carries the differential pressure biaxially. However, the attachment of the payload at a single

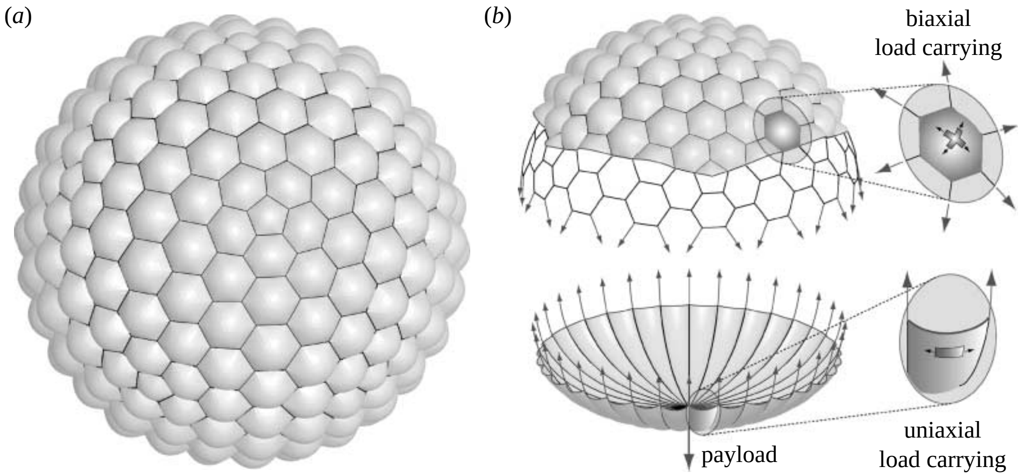

Figure 12. (*a*) Optimal superpressure balloon for constant differential pressure and (*b*) optimal superpressure balloon for linearly varying differential pressures is composed of a pumpkin and radiolarian design.

point, as it is preferred by NASA, is rather difficult since there are only three tendons at each knot so that the resulting stresses would be unacceptably high. Optimizing a sphere with a linear pressure distribution in which the payload is attached at a single point on the bottom of the sphere results in a structure that is sketched in figure 12*b*. The lower part is similar to existing pumpkin balloons and has the purpose of transferring the payload into many tendons, whereas the upper part is identical to the previously introduced design.

It should be noted that there are many structures in engineering that have a topology similar to radiolarians. Drew & Otto (1976) designed a pneumatic pavilion as a spherical cap that was stabilized by a hexagonal cable mesh. Tarnai (1989) reports that the buckling of a sphere under external pressure results in a dimpled surface that can be considered as an inversion of figure 12*a*.

7. Conclusions

It was shown how balloons and their capabilities evolved since the first public flight of the Montgolfier brothers in 1783. One of the last big gaps in this development is the construction of balloons that can carry large payloads to constant altitudes for several months and maybe even years. The limitations of the design concept that is currently being investigated by NASA were demonstrated, and optimized variations of this design have been presented. Furthermore, it was shown that it might be worth further investigating alternative designs that have a topology similar to radiolarians that are floating at constant altitudes in the oceans.

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References

Bendsøe, M. P. 1989 Optimal shape design as a material distribution problem. *Struct. Multidiscip. Opt.* **1**, 193–202. (doi:10.1007/BF01650949)

Calladine, C. R. 1988 Stability of the 'Endeavour' balloon. In *Buckling of structures: theory and experiment* (eds I. Elishakoff, J. Arbocz, Ch. D. Babcock & A. Libai). Studies in applied mechanics, pp. 133–149. Amsterdam, The Netherlands: North-Holland Publishing Company.

Drew, P. & Otto, F. P. 1976 *Form und konstruktion.* Stuttgart, Germany: Verlag Gerd Hatje.

Mann, S. & Ozin, G. A. 1996 Synthesis of inorganic materials with complex form. *Nature* **382**, 313–318. (doi:10.1038/382313a0)

Nott, J. 2004 Design considerations and practical results with long duration systems for manned world flights. *Adv. Space Res.* **33**, 1667–1673. (doi:10.1016/j.asr.2003.07.038)

Pagitz, M. & James, J. 2007 Symmetry transformation matrices for structures. *Proc. R. Soc. A* **463**, 1563–1583. (doi:10.1098/rspa.2007.1838)

Pagitz, M. & Pellegrino, S. In press. Buckling pressure of "pumpkin" balloons. *Int. J. Sol. Struct.*

Rand, J. L. 2007 A constitutive equation for balloon film. In *AIAA balloon systems conference, Williamsburg, VA, 21–24 May 2007.*

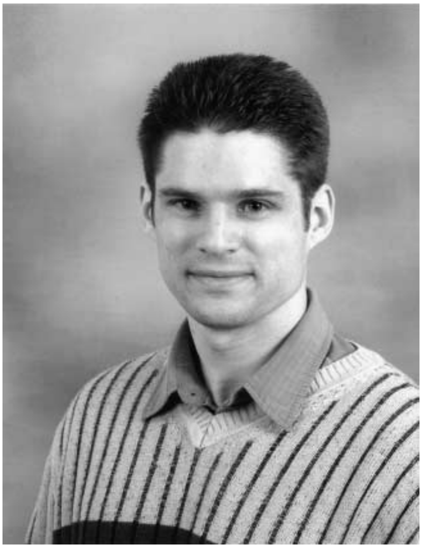
Tarnai, T. 1989 Buckling patterns of shells and spherical honeycomb structures. *Comput. Math. Appl.* **17**, 639–659.

Taylor, G. I. 1963 On the shapes of parachutes. In *The scientific papers of G.I. Taylor* (ed. G. K. Batchelor), pp. 26–37. Cambridge, UK: Cambridge University Press.

Wakefield, D. 2005 Numerical modeling of pumpkin balloon instability. In *AIAA 5th Aviation, Technology, Integration and Operations Conference, Arlington, VA, 26–28 September 2005.*

AUTHOR PROFILE

Markus Pagitz



Born in Nagold, Germany, Markus studied by means of a scholarship from the Hanns-Seidel-Stiftung at the University of Applied Sciences in Biberach, from where he graduated with a BSc in Civil Engineering in 2001. After he finished his MSc in Computational Mechanics at the Technical University of Munich in 2003, he went to Cambridge to study for a PhD in engineering with Sergio Pellegrino, working on balloon systems that are currently considered by NASA for missions to Venus, Mars and Titan. Markus was awarded a Research Fellowship from St John's College, Cambridge, in 2006.