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Norwich Inflatable Mars Solar Array (NIMSA): An Innovative and Autonomously-Deployed Inflatable Mars Surface Solar Array

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1. Summary

As we prepare to send humans to the harsh environment of Mars, the development of innovative, sustainable, and autonomous systems is of critical importance. The current architecture for manned Mars missions requires pre-positioning of critical life support systems in anticipation of the crew's arrival. These systems must be capable of autonomous deployment and operation, rugged enough to deter the harsh environment, and be comprised of redundant fail-safe systems. As electricity is pivotal to the success of any mission, power generation systems must also be autonomous, rugged, and redundant. Furthermore, maximum in-situ resource utilization should be emphasized in any design. The Norwich Inflatable Mars Solar Array (NIMSA) is a novel, innovative, and efficient approach to power generation that meets these needs and has the potential to be a vital component of future Mars missions.

Photovoltaic systems are a reliable and cost-effective technology for generating power, but delivery and implementation of a large array on the surface of Mars is challenging due to a number of factors. The Martian environment could potentially mitigate or eliminate the effectiveness of any solar power array. Another major consideration is that the angle and distance from the sun, based on the spacecraft landing site, fluctuates substantially during different seasons and time of day, which impacts solar panel performance and output.

A large system could easily capture sufficient energy to meet power requirements; however, transporting a large array would be challenging, expensive, and difficult to employ autonomously. Therefore, an array that can be compacted into a small volume for transport to Mars, and then be able to deploy to its operating state without assistance, is ideal. NIMSA is just that - a compact and autonomous structure that can be in place and functioning prior to human landings.

NIMSA's compacted launch volume and rugged design are enabled by virtue of its novel, innovative, inflatable truss design. This inflatable structure is designed to be strong, with air channels forming the trusses of the main structure. It utilizes the in-situ Mars atmosphere for installation with specialized pump technology. Flexible solar cells span the inflatable structure to achieve a large array area without compromising the efficiency or durability of the system. With consideration to the inflatable nature of the NIMSA, is it of high importance to have a reliable and rugged anchoring component to ensure the functionality of the array over its lifetime. This is achieved in the NIMSA by rigidly integrating the central assembly to the Martian Lander mainframe.

Martian dust accumulation is another important factor to mitigate in any solar array, as unabated accumulation over time can decrease efficiency or render it inoperable. Prevention of accumulation of dust on the array is critical for sustainable and reliable power generation over a long period of time. Therefore, another key consideration involves the need for a dust abatement solution. The NIMSA is designed with a built-in dust mitigation system, based on the interplay of an electrode to repel dust particles, paired with natural vibrations, and strategically-placed gaps for dust to filter through.

The report that follows details the state of the art technology and proven methods, which together allow NIMSA to meet design requirements without being mechanically over-complex. Capitalizing on in-situ resource utilization results in decrease launch mass, which is value added for other aspects of the mission. In space exploration, simplicity and reliability are important components of any design, and these are the cornerstones of NIMSA.

2. System Architecture

The following system requirements guided the design of the Norwich Inflatable Mars Solar Array (NIMSA) [1]:

- Area of photovoltaic (PV) cells at least 1000 m^2 per lander
- Total array mass less than 1500 kg
- Total launch volume less than 10 m^3
- Capable of surviving launch loads of 5 g axial, 2 g lateral, and 145 dB Overall Sound Pressure Level (OASPL)
- Must withstand Mars surface winds up to 50 m/s
- Greater than 1 g deployed strength
- Ability to deploy at -50°C and 15° slopes
- Operating height greater than 0.5 m
- Array must generate positive power output within 1 Martian Sol of landing
- Ability to survive daily thermal cycling from -100°C to 25°C
- Desired lifetime of 10 years under Mars conditions
- Dust mitigation and abatement methods

2.1 Central Housing

Located in the middle of the array is the Central Housing. The Central Housing is a rectangular frame that is 10 m long by 0.5 m wide. The frame has a square cross-section with 0.05 m sides. The frame is made of carbon fiber to maintain a small weight while still offering strength and durability. The Central Housing contains the compressors used in the inflation system as well as all other pertinent components (such as batteries and chargers). The Central Housing will be secured to the lander for transit and deployment.

2.2 Inflatable Structure

The inflatable structure consists of ten double-chambered air channels. Five of the channels will extend 26 m from each side of the Central Housing of the array (forming a total array length of 52 m). The width of the rectangular array formed by the inflatable is 20.38 m. Figure 1 shows the inflatable structure.

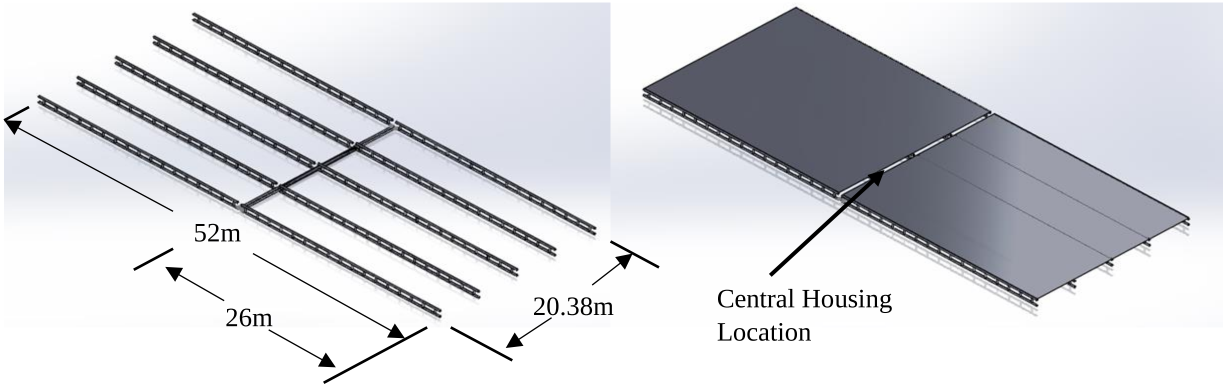
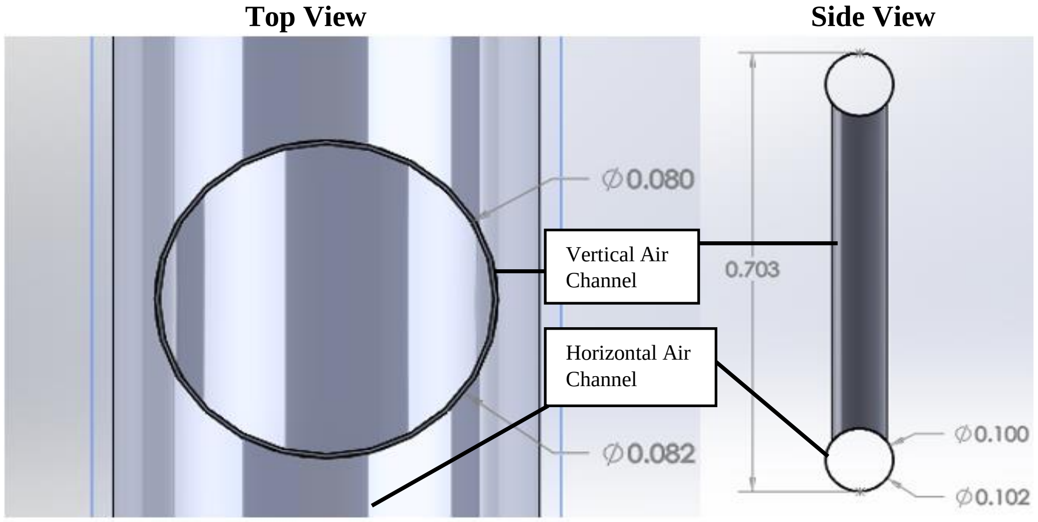


Figure 1. Inflatable structure with and without PV cells

All ten channels connect to the Central Housing at a unique location and are connected to an inflation system. Compressed air will be directed to one of the chambers by a common valve. Therefore, in each air channel, only one chamber will be inflated at a given time (leaving the adjacent chamber deflated). Double-chambered air channels make the NIMSA single-fault tolerant without compromising functionality or performance. If a puncture or other failure in a chamber were to occur, the common valve will switch to inflate the adjacent chamber. Each channel consists of two horizontal tubes connected by vertical tubes forming a ladder-like support structure – the inflatable truss design. The horizontal tubes will have a diameter of 10 cm, the vertical tubes a diameter of 8 cm, and all channels will have a thickness of 1 mm. The inner area of the air channels will be dusted with a powder to prevent the material from bonding together. The air channels are elevated to offer an operating height of 0.7 m. The pressure in each channel can reach a maximum theoretical pressure of 28 MPa before the channels will fail – well above the pressure attainable with the compressors. Figure 2 features a top view and side view of the vertical and horizontal air channels.



Top View

Side View

Figure 2. Dimensions of the Vertical and Horizontal Channels

Housed inside of the inflatable structure are pressure sensors in each of the chambers. The internal pressure of the inflatable will be measured to monitor and evaluate the uniformity of inflation. Given that the pressure of compressed air inside each closed chamber will be constant throughout, the location of the pressure transducer is not significant in evaluating the pressure throughout the entire chamber. To ensure that the system is single-fault tolerant and capable of functioning if failure were to occur with a single pressure transducer, there will be two pressure transducers located in each chamber. Therefore, with two pressure transducers in each chamber of a dual-chambered air channel, each air channel will feature four pressure transducers. Vectran is a synthetical material that will be used in the manufacturing of the inflatable structure. The pressure sensors placed inside the inflatable structure on the NIMSA will be the Vaisala BAROCAP® Sensors.

2.2.1 Vectran

Vectran is composed of a high-performance multifilament yarn spun from liquid crystal polymer (LCP) [2]. The fibers exhibit exceptional strength, almost twice the strength of other synthetic materials, such as Kevlar [3]. Pound to pound, Vectran is five times stronger than steel and ten times stronger than aluminum. The fiber can withstand a temperature range of –150°C to 100°C [4]. Vectran has been used as the inflatable material in previous Mars expeditions, such as the Mars Exploration Rover and the Mars Pathfinder in 1997.

2.2.2 Vaisala BAROCAP® Sensor

Vaisala BAROCAP Sensors are silicon-based micromechanical pressure sensors that have been proven to be reliable in a highly demanding environment, as evidenced by their usage on NASA's Mars Curiosity Rover [5]. Key properties include "good elasticity, low hysteresis, excellent repeatability, low temperature dependence, and superior long-term stability" [6].

2.3 Photovoltaics

Flexible PV solar cells will be attached to the top of the inflatable structure with 5 cm gaps in the middle of each section for dust to fall through. In total, the solar cells will have an area slightly over 1000 m^2 and will have a mass of 262.1 kg. They are designed to naturally arch downwards to aid in the mitigation of dust accumulation. With the flexible mesh backing, the PV cells can be rolled compactly for packaging and deployment. NeXt Triple Junction Prime Solar Cells will be used as the PV cells. Figure 3 shows a simplified view of the inflatable structure representing the arch in the PV cells.

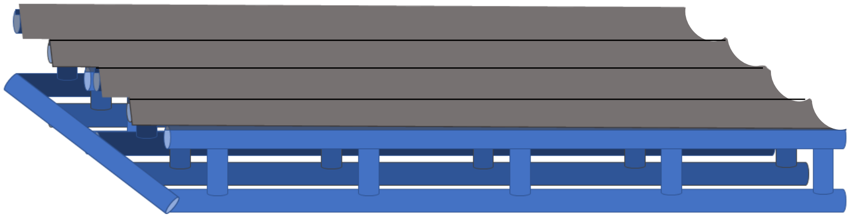


Figure 3. 3D sketch of side view of NIMSA

2.3.1 NeXt Triple Junction (XTJ) Prime Solar Cells

The NeXt Triple Junction (XTJ) Prime Solar Cells are comprised of GaAs and have a flexible mesh backing composed of a fiberglass that is weaved together. The XTJ cells are bonded to the mesh material by a polymer called Kapton and is 3.08 mm in thickness [7]. This polymer is often used in space applications due to its resistance to radiation and temperature [8]. The XTJ cells have a solar efficiency of 30.7%, a thickness of 80 µm, and mass of 50 mg/cm^2 [9].

2.4 Inflation System

There will be twenty compressors inside of the Central Housing – two connected to each double-chambered air channel. Two compressors are used for redundancy to make the design single-fault tolerant. The Vectran forming the inflatable structure for the air channels will be attached to the outlet of each compressor with an air-tight seal. For each pair of compressors, a single common valve will direct the compressed air into a single chamber within each air channel. Compressor pairs will be evenly distributed throughout the Central Housing to optimize the volume and mass.

Upon deployment, the compressors will have open access to the atmosphere as the top of the Central Housing will be opened for the compressors. The twenty compressors will be activated upon deployment of the NIMSA and powered by the battery packs provided for the initial set up of the array. Over a span of about 4.6 hours, the compressors will fill up each air channel to a desired pressure, enabling the array to take shape. Once the maximum allowable internal pressure has been reached, a pressure sensor will send a signal to turn off the compressors. If the pressure drops below a specified level (the minimum allowable internal pressure), the sensor will signal the compressors to reactivate. This serves as a means of maintaining optimal operating pressure inside of the inflatable structure. Similarly, if pressure drop is significant or the compressor running time is extensive (indicating a puncture or chamber failure), the common valve will be signaled to change and inflate the other chamber. The compressors used in the design of the NIMSA is the MOXIE CO2 Compressor by Air Squared, Inc. Figure 4 is an image of the MOXIE CO2 Compressor, provided by Air Squared, Inc.

Figure 4. MOXIE Air Squared Compressor (used with written permission from Air Squared [12])

If multiple failures occurred and an entire air channel (both chambers) deflates, the structure of the array will be largely unchanged and still capable of functioning. Under the circumstances of a single air channel completely deflating, the PV cells will still be exposed to sunlight and power generation will still occur. Figure 5 shows the location of the compressor pumps in relation to the Central Housing and *one side* of the array.

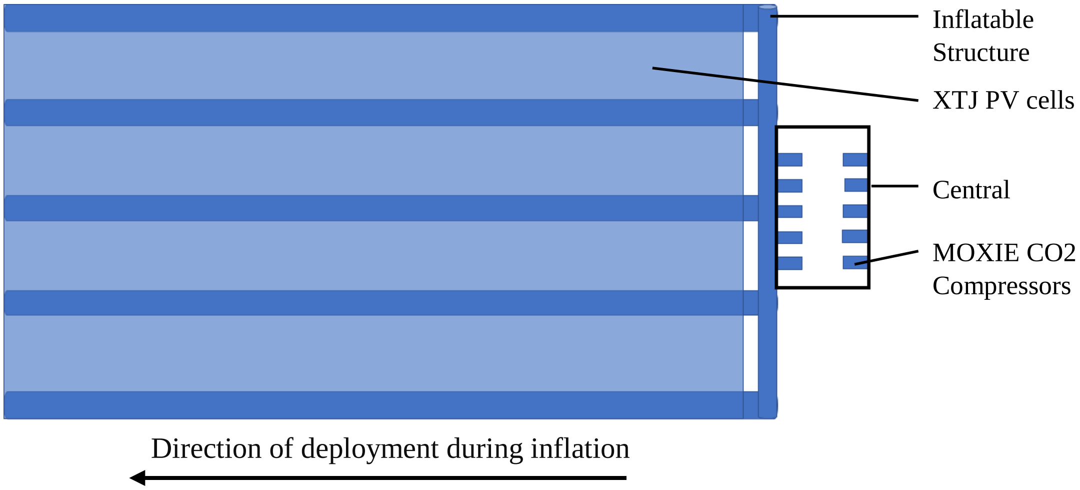


Figure 5. Top view of NIMSA

2.4.1 *Air Squared, Inc. MOXIE CO2 Compressor*

The Air Squared, Inc. MOXIE CO2 Compressor has been designed for a NASA Mars 2020 mission. The pump design developed for the Jet Propulsion Laboratory (JPL) can be used in its current design state or potentially modified (redesigned by Air Squared, Inc.) to meet design requirements [10]. The design features a semi-hermetic scroll compressor that takes the atmospheric pressure on Mars and matches it to the atmospheric pressure on Earth (ranging from 7 Torr to 760 Torr) [11]. The current design features a mass of just 2 kg, a mass flow rate 0.028 g/sec, conduction cooling using a cold plate, and the reliability required for an unmanned mission.

2.5 Dust Mitigation

To achieve highly efficient power generation using the PV cells, Martian dust accumulation must be mitigated and removed if necessary. This will be accomplished using an electrode to repel the dust particles as well as the natural vibration of the NIMSA. The electrode will be paired with a transparent material producing a dust shield. The shield will be placed directly over the solar cells (at specific locations), only adding a thickness of 2 mm [13]. With the natural winds being able to remove dust along the outer sections of the array, the shield will be used along the inner area of the array. Using this for only a couple of minutes per Martian Sol will assist in providing 90% efficiency on the cells [14]. The natural vibration will come from the Martian wind that will move the inflatable slightly and shake off the dust build-up. A 5 cm gap will run the length of the section of the array at the bottom of the PV arch. The fiberglass mesh will hold the two sections of the XTJ PV cells together in the arched shape while allowing for dust particles to fall through the 5 cm gap at the bottom.

An Electrodynamic Dust Shield (EDS) will be used as the repellent material. The EDS will be bonded to the solar cells at the highest points of the solar array (along the inflatable sections). They are placed along the highest points to repel the dust along the top sections and let it fall along the array towards the mesh gap in the middle, as shown in Figure 6. The EDS is not along the entire area of the array because, with the highest point repelling the dust, the rock slide effect will take place and carry the rest of the dust to the mesh gap. A timer will be used to activate EDS to repel the dust for two minutes every Martian Sol to maintain a higher efficiency by mitigating dust accumulation.

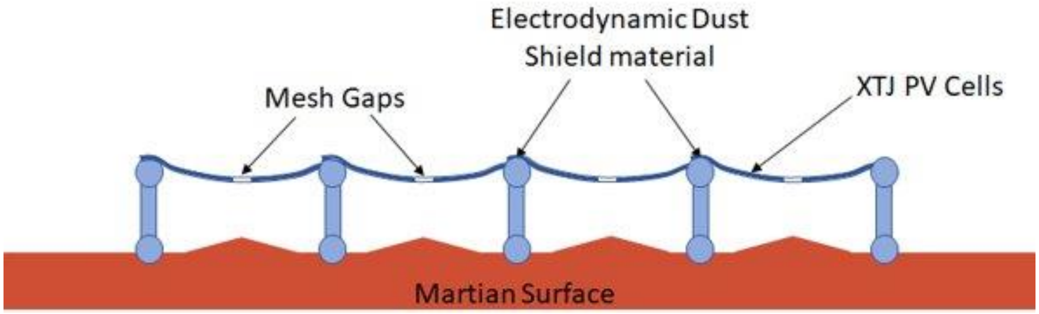


Figure 6. Side-view of NIMSA demonstrating structure and dust removal gaps in PV cells

2.5.1 Electrodynamic Dust Shield (EDS)

The transparent Electrodynamic Dust Shield is made of Polyethylene Terephthalate (PET) film that has a conductive Indium Tin Oxide (ITO) coating on one side and will be wired together into a circuit. The ITO coating acts as the electrode when voltage is sent through the material, therefore repelling the charged dust particles. EDS is highly flexible and temperature resistant up to 120 °C [13]. The ITO coating has a sheet resistance of 350 to 500 Ω/sq.

2.6 Anchoring

Specific anchoring components can be complex in design and still struggle to effectively anchor large components to the surface. In many cases, anchoring can be a great challenge due to the soft layer of Martian regolith on the surface. Anchoring the NIMSA will be primarily achieved by attaching the array to the lander. The Central Housing of the NIMSA will be secured to the lander, thus using the weight and stability of the lander for anchoring. Not only will this provide a very durable and strong anchoring component capable of withstanding intense and extensive dust storms, but it serves to double the functionality of the lander. This removes the necessity of using alternative or more complex methods of anchoring the array to the ground.

A unique benefit of the inflatable structure is that the array can adapt to different orientations caused by strong winds. It will be able to correct itself by reversing the direction of the compressor pumps and retracting, and then re-inflating again. This process will orientate the NIMSA, as the natural shape will regain form as compressed air fills the air channels. With this adaptability to ever-changing environmental conditions, the NIMSA is capable of self-anchoring and deploying at different locations.

2.6.1 Pathfinder Lander

The Pathfinder Lander is a protective shell that would house the solar array. Previously this lander has been used to house the Mars Rover. It will be altered to accommodate the dimensions and mass of the NIMSA. The lander consists of a base and three sides in the shape of a tetrahedron that would open to provide a flat surface for the deployment of the NIMSA [15]. It is composed of a composite material that allows the lander to be a strong and lightweight structure.

3. Conceptual Operations

3.1 Launch Configuration

At launch, the system will be stowed with the Central Housing at the center of the system and the inflatable structure rolled up. The Central Housing, considering the open ceiling and components inside, will have an approximate volume of 1 m^3. The total volume of the XTJ PV cells and Vectran inflatable structure will be about 3.44 m^3. Thus, the compacted volume of the components of entire array is expected to be less than 5 m^3. Provided there will be other minor components in the design and the uncertainty of launch configuration, an accurate estimation of the launch volume is difficult to calculate. It is anticipated that the total launch volume will be less than 10 m^3. The total mass of the primary components of the NIMSA is expected to be less than 700 kg. Table 1 lists the volume and mass of the primary components of the NIMSA.

Table 1. Mass and volume of primary NIMSA components

Component	Volume (m^3)	Mass (kg)
Vectran Inflatable Structure	0.196	288.2
Central Housing	0.052	104.0
MOXIE CO2 Compressors	0.108	36.0
XTJ PV Cells	3.244	262.1
Electrodynamic Dust Shield	0.01	4.2
Total	**3.61**	**694.5**

The inflatable structure will be deflated, tightly rolled, and secured over the Central Housing. On each side of the array, the XTJ PV cells are divided into four long sections spanning just over 25 m with a width of 5 m. In between each row of cells, there will be a five-inch gap between the solar cells that allows for the two outside sections to be folded on top of the two inside sections. On each side of the array, these rows will be tightly rolled until they come together at the Central Housing. The flexibility of the mesh on the XTJ PV cells allows for the rolling of the cells, and with a thickness of just 0.1 mm, the Vectran can be tightly rolled to maintain the condensed shape of the system while minimizing the volume and mass.

A simple clamping mechanism is to be used to maintain the shape in the launch volume. For redundancy, two clamping mechanisms are proposed to secure the NIMSA in its compacted state. Vectran is a material that provides an exterior cushion for the system in its launch state, making this design suitable for the stresses associated with launch and landing. Figure 7 shows a simplified look of the NIMSA in its condensed launch state.

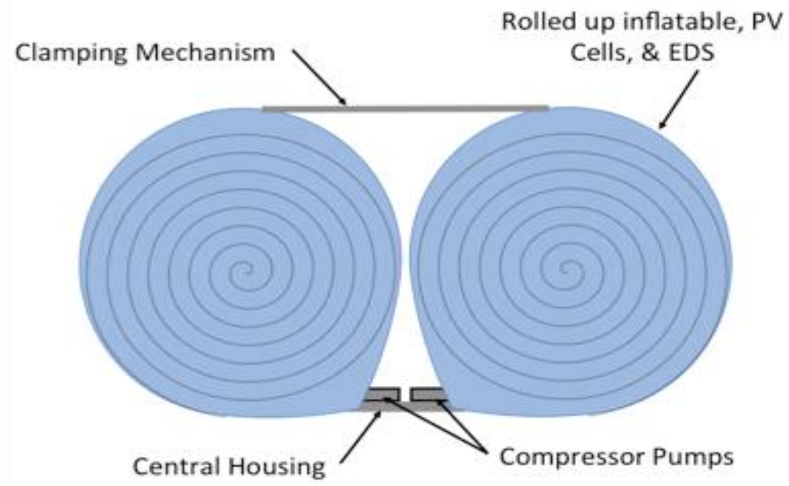


Figure 7. Orientation of NIMSA in launch state

3.2 Lander Integration

The NIMSA was designed under the assumption that it will use the Pathfinder Lander from the Mars Rover Expedition. The Central Housing of the NIMSA will be attached to a petal on the Pathfinder Lander to guarantee correct orientation upon landing. Regardless of the orientation of the Pathfinder Lander upon landing, as it unfolds, the NIMSA will be right-side up. Deployment will occur from this starting position.

In addition to housing the NIMSA during landing, the lander will double as a major anchoring component. By firmly supporting the Central Housing of the NIMSA, the lander will serve as a strong and steady base for the array that can withstand fierce dust storms and help to mitigate damage and unwanted locomotion of the inflatable.

3.3 Deployment

Upon landing, the magnetic locking mechanism will be released, and the inflatable structure will begin to roll out. Given the initial orientation, with the center of mass in the rolled-up structure being offset from the center of the Central Housing, gravity will begin to naturally unravel the inflatable structure. Once the compressor pumps in the Central Housing of the system have been exposed, they will be initiated. Figure 8 illustrates this initial step in the deployment process.

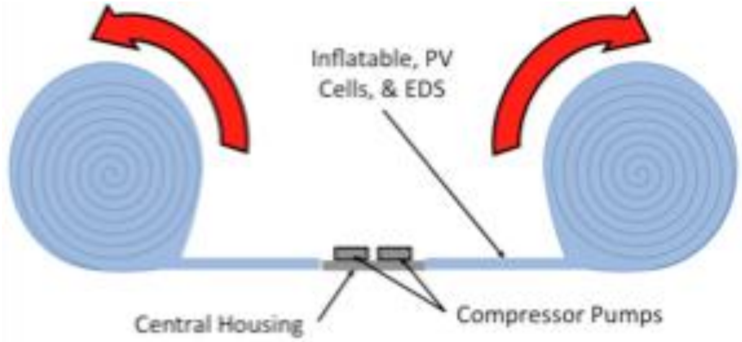


Figure 8. Initialization of deployment

The Mars atmosphere will be used by the compressors to generate high pressure air that will gradually inflate the entire system through individual air channels. Air flow through the air channels will extend the XTJ PV cells to their full length (Figure 9), and then unfold the outside channels to reveal all four sections (on each half of the NIMSA) (Figure 10). Extending in two directions from the Central Housing, the air channels and solar cells will unravel off the lander and extend beyond the edge of the lander to the Martian surface until fully inflated. Although more compressed air will be required to complete the inflation of the structure (including the vertical channels), the power generation can begin. The XTJ PV cells will begin to arch – settling into a final state of concavity – as the inflation is completed. A control system using pressure sensors will trigger the compressors to turn off.

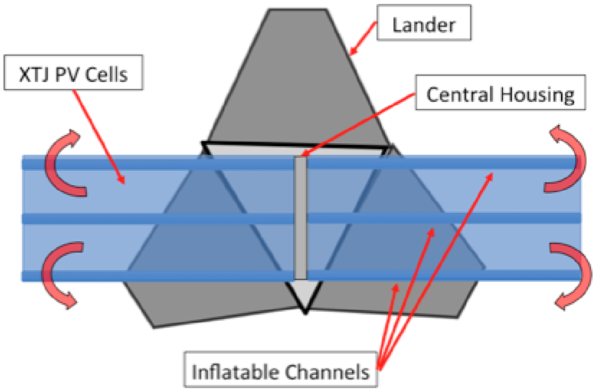


Figure 9. NIMSA extends off lander as inflation begins

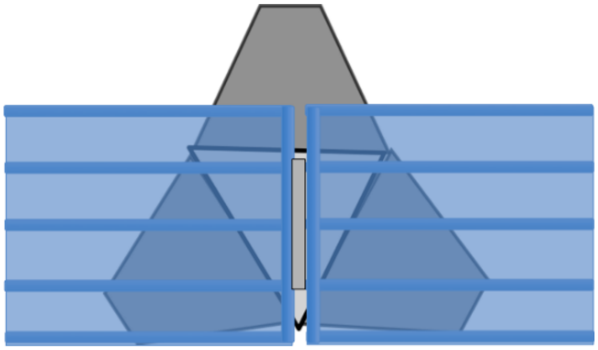


Figure 10. Fully unfolded NIMSA with all four sections on each side revealed

3.4 Operating State

In its deployed state, the NIMSA will form a rectangle spanning over 50 m in length and over 20 m in width. The elevated air channels that support the XTJ PV cells are supported by vertical air channels connecting to the ground level air channel. Dust abatement will be achieved using a few different methods that are integrated into the design of the NIMSA. Electro-static cells are strategically placed along the outside of each PV section to repel magnetically charged dust particles. Many particles on Mars feature a charge, thus, a small amount of power generated will induce a charge that can repel dust particles towards the gaps at the bottom of each array section (at the bottom point of the concavity). This will result in excess dust particles falling to the surface, as opposed to accumulating on the array. Capitalizing on the gaps between cells in the array, the NIMSA will utilize the natural vibration of the system to shake dust particles off.

The combination of gravity and the concavity of the XTJ PV cells will greatly reduce the accumulation of dust particles to ensure the sustainability of power generation. While the concavity of the solar panel blanket will result in decreased incoming solar flux due to the cosine effect, the depth of the concavity is relatively small such that a decrease in efficiency is minimized. Multiple compressor pumps with multiple air channels were used to account for the risk associated with a failed or damaged pump. In this design, if a single pump or air channel fails, the system can still function with minimal repercussions.

To maintain uniformity of internal pressure within the inflatable, Vaisala BAROCAP pressure sensors are implemented into the inflatable structure. They will continuously measure the internal pressure of the internal fluid. A control system with a feedback loop will be utilized to ensure that the uniformity of inflation is maintained. A predetermined operating range of internal pressures will allow for signals to be generated when the internal pressure exceeds the maximum operating pressure and when it falls below the minimum operating pressure. This system uses a bang-bang control system to prevent unwanted rapid switching that may result in additional wear on the components.

Using this simple control system, uniformity of the entire structure will be self-maintained. Sensors will also measure the time that the compressors are operating. If the compressors are found to be operating for more than the total time required for full initial inflation (per each air channel), this would indicate a puncture or complete failure of an air channel. This will signal the valve at the entrance to the air channel to switch to direct the air into the other chamber. This would be an application of the single-fault tolerant dual-chambered design to ensure that uniform inflation is maintained. Figure 11 is a block diagram of a control system that will be used to maintain uniform inflation. Figure 12 is a state machine that illustrates the system.

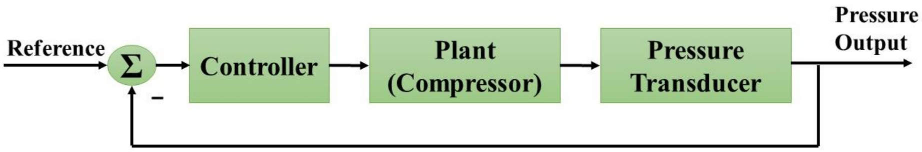
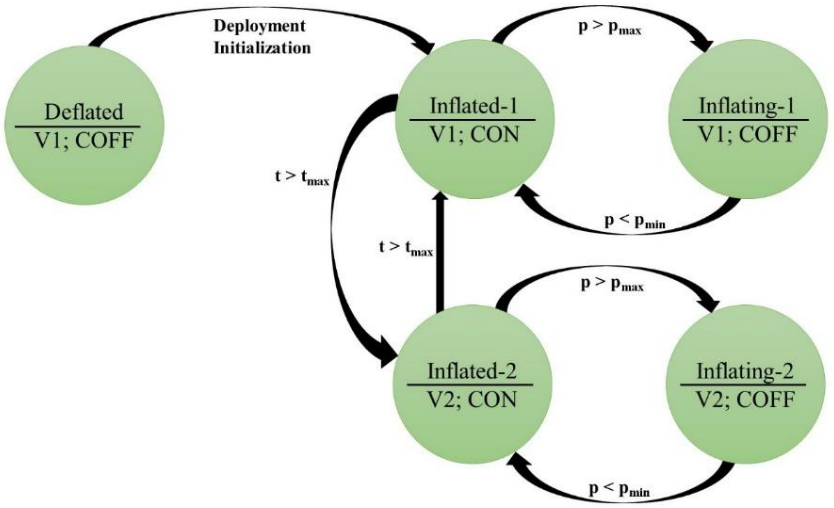


Figure 11. Control system for pressure sensors in NIMSA



LEGEND			
Deflated	NIMSA completely deflated	**CON**	Compressors turned on
Inflated	NIMSA at required air pressure or compressors on and air flowing	t_{max}	Maximum time for total inflation of NIMSA to occur
		t	Inflation time
V1	Valve directs flow into chamber 1 (within given air channel)	**p**	Internal pressure
V2	Valve directs flow into chamber 2 (within given air channel)	p_{max}	Maximum operating internal pressure
COFF	Compressors turned off	p_{min}	Minimum operating internal pressure

Figure 12. State machine for control system for uniformity of inflation

Upon deployment, the NIMSA will be in the *Deflated* state. Activation of the compressors will take the system into *Inflated-1*. This state will be altered once the maximum pressure has been reached (signaling the compressors to turn off) or if the predetermined total time for inflation has been exceeded (indicating a failure of an air chamber). While a specific air chamber is being used, the pressure will be the signal that turns the compressors on and off. The time of compressor operation would lend to a valve to adjust to redirect air into the second chamber of a specific air channel. Each of the ten air channels will feature this control system and self-regulate inflation. Therefore, it is possible for only one valve to redirect air to a second air chamber at a time.

3.5 Environmental Considerations

The NIMSA is required to provide sustainable power in a harsh environment that includes powerful dust storms and large daily thermal cycling. The MOXIE CO2 compressors are designed to operate in the temperature range seen on Mars (-100°C to 25°C) and within the atmosphere. The atmosphere, approximately 95% CO_2, 3% Nitrogen, and 2% Argon, is also very different than on Earth. These compressors are designed for full compatibility with the working fluid, enabling successful generation of high pressure air required for the inflation of the structure. The XTJ PV cells are flexible enough to withstand vibration and shaking from high winds, and being designed for space use, they are capable of functioning and generating power in low temperature conditions.

Cooling systems aren’t a major design condition because the low temperatures on Mars will serve as a natural cooling mechanism. Vectran, the material used for the inflatable structure, has been used for deployment on Mars before and has optimal properties over a very large temperature range and it can endure a radiation of 89.56 sV [2]. To verify that the exposed radiation over a 10-year span will be less than that which the Vectran can sustain, the radiation exposure on Mars was used. Equation 1 determines the maximum radiation exposure on Mars per year using a maximum solar radiation rating of 60 µSv/hr [16]. Equation 2 calculates the total radiation exposure over a 10-year span to demonstrate that the radiation exposure on Mars over ten Earth years (5.22 sV) is significantly less than the total radiation that Vectran is capable of withstanding (89.56 sV).

$$\left(60\,\frac{\mu sV}{hour}\right)\left(24.65\,\frac{hours}{sol}\right)\left(668.5991\,\frac{sols}{Martian\ year}\right) = 0.98886\,\frac{sV}{Martian\ year} \tag{1}$$

$$\frac{0.98886\ sV}{Martian\ year}\left(10\ Earth\ years\right)\left(\frac{365\ Earth\ days}{Earth\ year}\right)\left(\frac{Martian\ year}{686.98\ Earth\ days}\right) = 5.254\ sV \tag{2}$$

Another component of the environmental conditions is the powerful dust storms on Mars that may include high velocity debris colliding with the structure. Vectran has the strength and flexibility to absorb impact and avoid puncturing. The possibility of strong winds lifting and moving the NIMSA will be mitigated a few different ways. The design allows for free air flow underneath the array and gaps between the XTJ PV cells will also allow for air to flow through the array. This limits the lift forces that could build underneath the array that would cause the structure to be moved. The mass of the Vectran and XTJ PV cells throughout the array will provide an evenly distributed mass with a low center of gravity that will help to secure the array during storms. In the case that the NIMSA loses its orientation, it can easily be corrected. The system can be deflated, inflated again, and then return to regular operation. The inflation process will expand the air channels and allow for the array to be reoriented. By deflating and inflating, dust would be removed from the surface and this process could also serve to help mitigate dust accumulation.

3.6 Durability and Performance Criteria

The NIMSA was designed to operate for at least ten years. The technology used has been designed specifically for space missions and most of it has already been proven to be reliable by use in other missions. This design is very simple, rugged, and redundant – ideal for durability and reliability. Each subsystem features redundant parts and/or processes that account for the possibility of failure and can keep the NIMSA functioning effectively. Systems designed are not overly complex and the materials are highly durable. Additionally, part of the design is the expectation that human assistance will be possible at some point following the initial deployment. If damage or failure occurs at a compressor, PV cell, air channel or another location, astronauts will be able to provide on-site repairs upon arrival. Until then, the NIMSA can produce power despite failure to different components of the design. Ensuring the power generation can still occur without human maintenance was a key design consideration.

To verify that the NIMSA is functioning appropriately, different metrics can be used to evaluate the performance. First, the power generation over a sol at a specified location can be determined to ensure that the primary objective of the system is being met. A second metric would be to evaluate the power consumption during operation to ensure that the net power generated can contribute to the future Mars missions. Internal pressure within the inflatable structure can also be monitored to ensure that the compressors can provide the fluid flow capable of properly deploying the system. To evaluate the effectiveness of the dust mitigation techniques, the efficiency of the XTJ PV cells can be evaluated over time to identify if performance is maintained.

4. Performance

4.1 Estimated Power Output of System

The Estimated Power Output of the NIMSA System was calculated by first finding the average peak values for each location - North, South, and the Equator - with and without a potential dust storm. Data provided by NASA as part of the competition and was used to calculate the annual average solar radiation on Mars by taking every 25th peak magnitude from 0-700 in each given location [1]. Table 2 shows the average solar flux that was determined for the different locations: 30° South, Equator, and 50° North, each with and without a potential dust storm.

Table 2. Average solar radiation per sol for each location.

50° North	50° North (dust storm)	Equator	Equator (dust storm)	30° South	30° South (dust storm)
277.32W/m^2	273.93W/m^2	492.14W/m^2	463.93W/m^2	412.32W/m^2	370.90W/m^2

After the averages for each individual location were found, the energy produced each day was calculated. The curve of the of the parabola can be seen in Figure 13, where *F* is the average peak flux previously solved for. The curve was solved for using Equation 3 and the result can be seen in Equation 4.

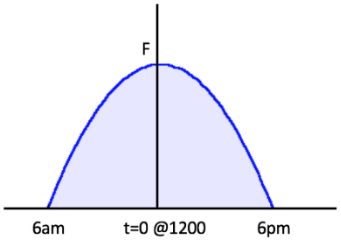


Figure 13. Parabolic curve of daily energy

$$f(t) = ax^2 + bx + c \tag{3}$$

$$f(t) = \frac{-F}{36}t^2 + F \tag{4}$$

Equation 4 was integrated to find the area under the curve and the result can be seen in Equation 5. Using Equation 5, the total annual output of the system was calculated (Equation 6).

$$E = \frac{8}{12} F \tag{5}$$

$$Total\ Power = \frac{8}{12}F * 688 * 0.3 * 1000 * 0.75 \tag{6}$$

In this equation, 688 is the number of days in a Martian Year, 1000 is the total area of the solar array (m^2), 0.3 is the efficiency of the XTJ photovoltaic solar cells, and .075 is the coefficient of losses [7]. The total annual energy output of the system can be seen in the Table 3.

Table 3. Annual Energy output for each location.

50° North	50° North (dust storm)	Equator	Equator (dust storm)	30° South	30° South (dust storm)
28.62MWh	28.27MWh	50.79MWh	47.88MWh	42.55MWh	38.28MWh

The total value of the annual output of the system for each location with and without a potential dust storm was divided by 688 to find the daily (per sol) power output of the system. Table 4 provides the estimated energy output per sol.

Table 4. Energy output per sol for each location.

50° North	50° North (dust storm)	Equator	Equator (dust storm)	30° South	30° South (dust storm)
41.60kWh	41.10kWh	73.82kWh	69.59kWh	61.84kWh	55.63kWh

To ensure the numbers calculated made sense the energy rating was solved for using Equation 7 and came out to be 84 MWh annually. All the annual energy values range from 0.5 to 0.65 of this value and are therefore reasonable.

$$Power\ Rating = V * I * A * C * H * D = 84\ MWh \tag{7}$$

$where,$
$V = 2.715\ V$
$I = 18.1 \frac{mA}{cm^2}$
$A = 27\ cm^2$
$C = 3703\ cells\ used\ in\ array$
$H = 24.65\ of\ hours\ per\ sol$
$D = 688\ of\ sols\ per\ Martian\ Year$

The daily energy output for each location can be seen in Table 3 above. The goal of 40 kWh per sol day was achieved as the lowest energy output would be 41 kWh and the highest 73 kWh.

4.2 Estimated Power Requirement of System

The volume of compressed air required to fill the inflatable and the MOXIE CO2 compressor specifications were used to determine the time required to inflate the NIMSA. Equation 8 was used to determine the volume of air required to inflate the NIMSA, and Equation 9 was used to determine the time required for inflation.

$$V_{air} = \frac{nL\pi D^2}{4}_{long\ channels} + \frac{nL\pi D^2}{4}_{vert.\ channels} + \frac{nL\pi D^2}{4}_{extra\ channels} \tag{8}$$

$$V_{air} = \left(20 * 26m * \frac{\pi}{4} * (0.1m)^2\right) + \left(170 * 0.5m * \frac{\pi}{4} * (0.08m)^2\right) + \left(4 * 4.97m * \frac{\pi}{4} * (0.1m)^2\right) = 4.667\mathrm{m}^3$$

$$t = \frac{V\rho}{\dot{m}} = (4.667\ m^3)\left(0.00195 \frac{g}{mL}\right)\left(\frac{(100cm)^3}{m^3}\right)\left(\frac{mL}{cm^3}\right)\left(\frac{h}{2000g}\right) = 4.551\ \text{hours} \tag{9}$$

The MOXIE CO2 compressor pumps operate between 0.105 and 0.160 kW per hour, so the maximum total power consumption during deployment will be 1.46 kWh [17]. The total area of the EDS is 31.2 m^2 and will operate for two minutes of every sol with a power requirement of 10 $\mathrm{W/m}^2$ [14]. Therefore, the total energy consumption will be just 0.0103 kWh at steady-state operation.

4.3 Inflatable Performance – Pressure Analysis

Pressure vessel calculations, assuming a thin-wall vessel, were done using a longitudinal tensile strength of 2800 MPa, gathered from Kevlar as a weaker comparable material to Vectran [18]. The maximum permissible internal pressure was found to be 28 MPa using Equation 10, far above the outlet pressure provided by the MOXIE CO2 compressor pumps of 770 Torr (approximately 0.102 MPa).

$$P = \frac{\sigma t}{r} = \frac{(2800 \times 10^6\ MPa)(0.001m)}{0.1m} = 28\ MPa \tag{10}$$

4.4 Launch Vehicle Dynamics

The solar array must be designed to withstand 5 g axial and 2 g lateral loads, as well as 145 dB overall sound pressure level during launch. An advantage of the NIMSA's rugged inflatable structure is that the design incorporates technology and materials designed for, and proven, to survive in space. For example, the MOXIE CO2 Compressor pumps are designed for a NASA 2020 Mars mission, Vectran has been used in a previous NASA mission to Mars, XTJ PV cells are designed for space application, and the Central Housing is designed for substantial loading.

It can be assumed that since each of the individual components are designed for functioning in the environment that is proposed, the NIMSA will be sufficiently strong for the launch, transit, and landing on Mars. Inflatable technology comes with many pros including the ability for the array to condense into its launch state. While packaged closely, the Vectran will provide extra support and insulation for the other components of the design and inadvertently increase the strength and integrity of the design.

Another advantage is that the NIMSA doesn't feature any small hinges, joints, or mechanical arms that are complex and prone to failure. Given the simplistic and innovative features of the NIMSA, the axial loads, lateral loads, and sound pressure level during launch are expected to be accounted for in the design.

To verify the performance aspect of the final design, a small-scale prototype will be produced and tested in a chamber with an atmosphere, variable temperature, and gravity to simulate the Mars environment. To test environmental conditions, a fully inflated Vectran structure with PV cells prepared can also be placed in a wind tunnel to verify the ability for the design to withstand the dust storms and prove to be a feasible source of sustainable power generation. Other simulations will be conducted to ensure successful operation and sufficient durability during launch or re-entry. Once the tests are run, the prototype will be deployed to ensure all components of the design maintain proper functionality.

5. Conclusions

With the objective of developing a solar array capable of autonomously deploying and functioning on the Mars surface, withstanding the harsh environment, and being easily transported on a lander, the concept of creating an inflatable array was developed in the NIMSA.

The key benefits of this design include the simplicity and innovation that an inflatable design provides. The flexibility of the PV cells and inflatable Vectran enable the array to be easily compacted into a small launch volume. Upon deployment, the installation of the system is simple and autonomous, and power generation will occur quickly. Dust abatement methods are simple but effective, enabling the sustainable power generation to last in the challenging environment presented on Mars.

This design can have major implications for NASA's pursuit of human exploration on Mars in future missions. With power generation being one of the greatest challenges faced, the NIMSA will provide a reliable source of electricity that is mission critical. The simplicity of the design will allow for the arrays to be easily manufactured and implemented into missions. As the requirement for power increases, multiple arrays can be sent to Mars and the size of a single array can be increased to meet the power demand. This concept can also be tailored and expanded for use in other NASA missions with power generation requirements. Inflatable technology has the versatility to be successfully applied to various environments and array designs to provide optimal efficiency and functionality for each unique application.

The next objective will be to further prototype and test the design for feasibility and functionality. Further modifications can improve the effectiveness of the design and result in the development of a truly innovative technology. With NASA's resources and expertise, the NIMSA can become a critical component to the monumental achievement of human exploration on Mars.

Appendix

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