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CONCEPTUAL DESIGN AND MOTION ANALYSIS OF ROBOTIC SPHERE AND SOFT AERIAL ROBOT FOR SPACE EXPLORATION

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This paper deals with the category of exploratory robotic systems, which is a necessity as the thirst for extraterrestrial survival becomes imminent. Therefore, a robotic system has been proposed along with its conceptual design and motion analysis for its working on the Martian surface. The robotic system consists of two major modules: a robotic sphere and a soft aerial robot (bio-inspired). The robotic sphere will perform the land-based exploration while the aerial robot will navigate through the Martian atmosphere. The soft aerial robot will be encapsulated inside the robotic sphere so that it can be protected from unexpected disastrous events like sand storms which are prone to occur. The system as a whole utilizes rigid components as well as soft actuators. The traversing of a robotic sphere is based on the principle of a shift in the Center Of Mass (COM), while the bio-inspired flapping in the aerial robot is achieved by using Shape Memory Alloy (SMA) springs. Motion analysis has been carried out for both the modules and results are presented. Motion captures at various instances and derived parametric plots are discussed. A result for SMA spring simulation is also included. The specific materials of the components has not been included and can be considered for future studies. The papers opens up a huge domain for soft robotic systems to be used for exploratory purposes. This paper consists of original piece of work, presenting a major piece in writing for the first time.

1. Introduction

Robotics is the prominent field that has brought a major advancement in human lives. This field has affected almost all the sectors from industrial to agricultural automation. Robots are widely used for exploration purposes as it becomes very important for gaining new insights from the things that were not known before. Exploration robots has given understanding to researchers for further developing modern complex systems. Now, as mankind is aiming to find a new home (extraterrestrial), it becomes inevitable to develop systems that can visit and explore those planets or bodies so that we can prepare ourselves about the environment and physical conditions of that particular body. The most likely planet in our solar system, and also as many scientists believe could sustain life, is Mars. Previously, rigid conventional robots like Perseverance rover has been sent to Mars for understanding the red planet. However, conventional robots have many drawbacks like they are rigid, bulky and expensive as compared to soft robotic systems, which is also a developing field. The soft robotic systems are compliant, resilient, highly embeddable and analogous to biological systems. The use of soft systems are found to be more adaptable to unknown environment, which is a requisite for exploratory robotics. Thus this literature presents conceptual design and analysis of one such system which can be perceived as hybrid robotics system as it uses some rigid components along with providing motion using soft actuators. After a brief review on smart materials and soft actuator [1] [5], the subsequent section deals with the two major modules of our system: robotic sphere and soft aerial robot (bio-inspired).

2. Robotic Sphere-An Overview

This is a spherical structure, traversing on surface and exploring the land as it moves in a particular direction. A spherical structure is least likely to get damaged as it has no other extruded parts. The below section discusses the principle and conceptual design for the same.

2.1. *Principle for Locomotion of Robotic Sphere*

Using from first principle, if we analyze the basic understanding of how spherical objects can move, without any external push or pull, we know that when a system is not in equilibrium, it will tend to cause the motion of the rigid body in a way to reach the equilibrium or mean position, which is the lowest energy state of the body. To visualize, imagine a hemispherical bowl having a ball inside it. Now when the ball is displaced from its equilibrium and released, it has a tendency to move towards its mean position. However let us say if we displace the ball and then using some method it is forced to stay at that position, in this case the entire hemispherical bowl will tend to rotate in order to bring Center Of Gravity (COG) to the lowest energy state. The change in COM of system will create a moment and tends the system to rotate. This principle of changing COM has been adopted for conceptual design of our spherical robot.

2.2. *Conceptual Design*

The conceptual design of spherical robot can be further divided into various components and their combine working is explained after explanation of these components. The various components are:

2.2.1. *Rotating Ring*

A rotating ring structure, which can move 360° inside a spherical structure has been presented as shown in figure 1(a) (section view) and 1(b) (isometric view). The rotating of this ring will guide the robotic sphere for traversing in any necessary direction. It has an extruded portion at the center for encompassing the electronics used for actuation. The ring can be rotated with the help of micro motor at the pivotal points which are connected to the robotic sphere. The ring will contain the slider and ball assembly.

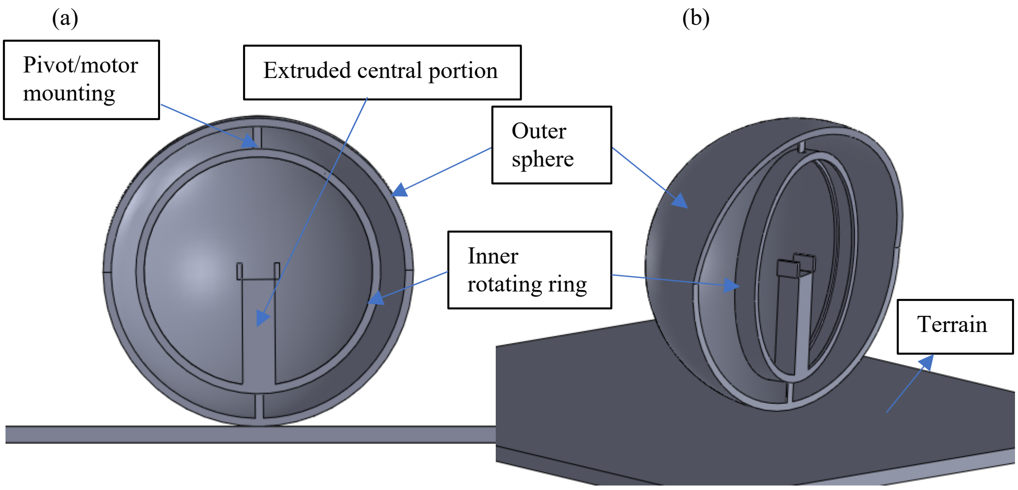

Figure 1. (a) Section view of rotating ring. (b)Isometric view of sectional rotating ring.

2.2.2. *Slider and Ball Assembly*

The rotating ring will further contain a slider and ball assembly which will pave the way for changing the COM of system. The slider is allowed to rotate on the ring. The slider is designed such that it contains the ball and make the ball traverse as the slider moves on the ring. The initial position of the ball, when the robotic sphere is at rest, is as shown in figure 2 (a). Figure 2 (b) shows the displaced position when the sphere is in locomotion.

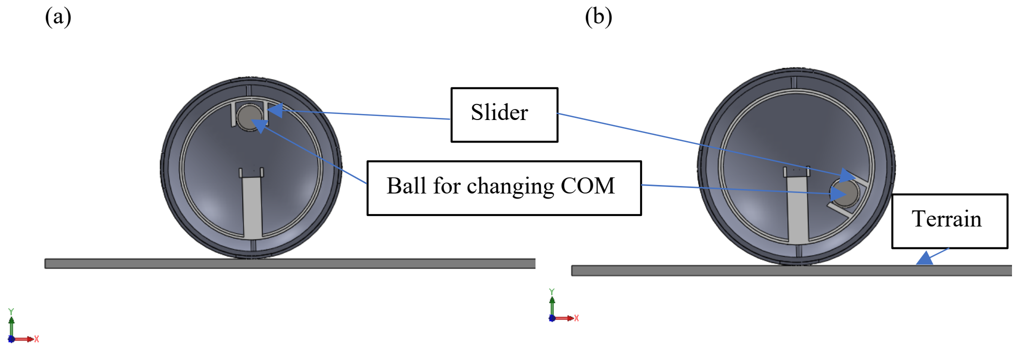

Figure 2. (a) Position of slider at mean position. (b)Position of slider while traversing towards right.

2.2.3. *Retracting Mechanism*

Since our robotic sphere will encapsulate the soft aerial robot, there has to be a retracting mechanism which will act as a door for aerial robot to move in and out of the robotic sphere. This can easily be achieved by retracting a portion of robotic sphere with the help of hinges which can be controlled using micro motor. This assembly will be mounted near the sphere and due to the clearance given between the spherical surface and ring, the motion on the robotic sphere will not be hindered after implementation of this mechanism. See Figure 3.

2.2.4. *External Lamination and Solar Panels*

Since the idea is to send this system for space exploration, sufficient energy requirements must be achieved. As a result of this, the outer surface of the sphere will have a grid shaped structure which will contain the solar panels for generating energy for traversing the robot. The solar panels will be embedded inside the grid and further the grid will be laminated (harder lamination) which will protect the panels from damaging while moving on the rocky surface.

The dimensions of sphere are: external radius of 190 mm, thickness of lamination is 3mm, external diameter of ring is 155mm and that of slider is 150mm. The diameter of ball is 30mm. The length of extruded portion is such that aerial robot is at the COM of system. The thickness of all surfaces is maintained at 5mm. Material selection for robotic sphere may include graphene (high conductivity) to spherical body, lightweight materials like ABS for slider and rotating ring, plain carbon steel to ball for changing COM.

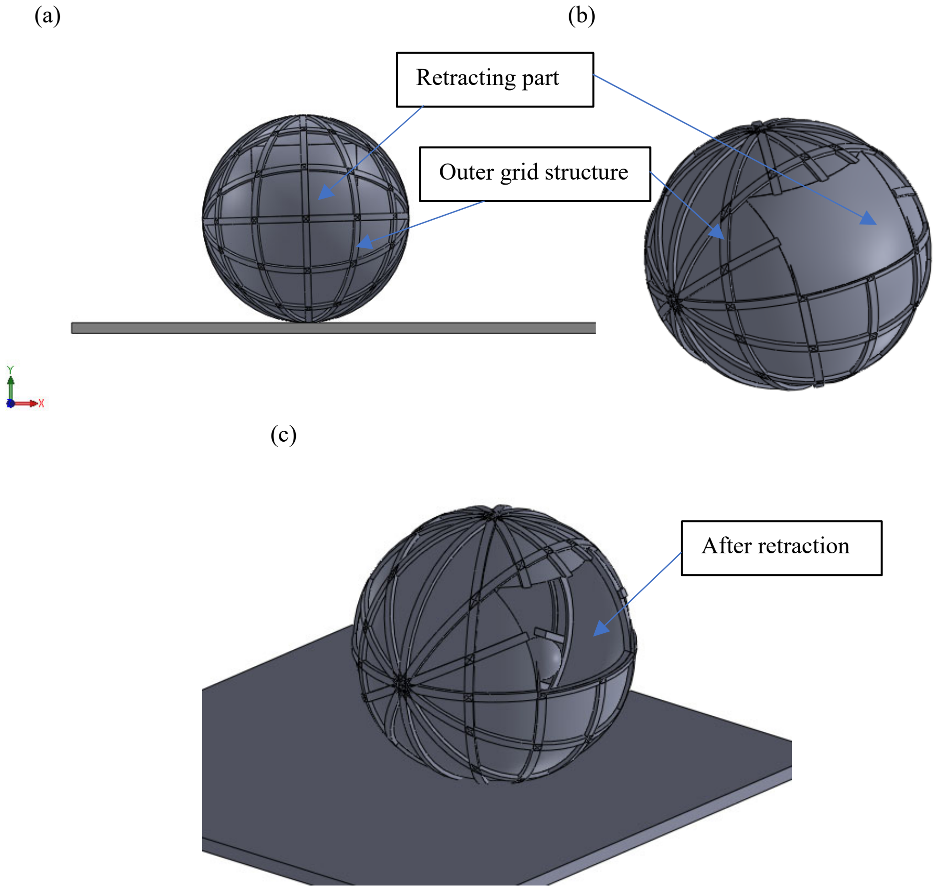

Figure 3. (a) Grid structure for embedding solar panels. (b) Figure depicting portion on sphere for the retracting mechanism. (c) Retracted portion on robotic sphere.

2.3. *Working*

The initial position of the robotic sphere will be when the COM coincides with the geometric center of the robot. One end of the slider will be attached to the central extruded portion with the help of SMA springs i.e. the SMA springs will provide the necessary actuation for movement of slider on the ring. The analysis of the SMA springs are presented in the later text. When the robot is to traverse on the Martian surface the SMA springs will actuate the slider, shifting the COM and thus creating a moment for locomotion. This moment will be forced on the rotating ring and as the ring is connected to the sphere, the sphere rotates and due to friction between the spherical surface and Martian surface, the sphere locomotion takes place. The direction for locomotion will be decided by the rotating ring. To move in a particular direction the lateral axis of the ring will be aligned in that direction with the help of micro motor placed at a pivotal point.

2.4. *Motion Analysis*

The motion analysis of the robotic sphere was carried out in the solidworks software and the results are presented hereafter. The analysis is carried out under Martian gravity ($3.73 m/s^2$) which is equal to 0.38 times the gravity of Earth.

The first analysis was done simply under Martian gravity after displacing the ball in order to analyze the working of COM method for locomotion. The motion capture at various time instances are shown in figure 4.

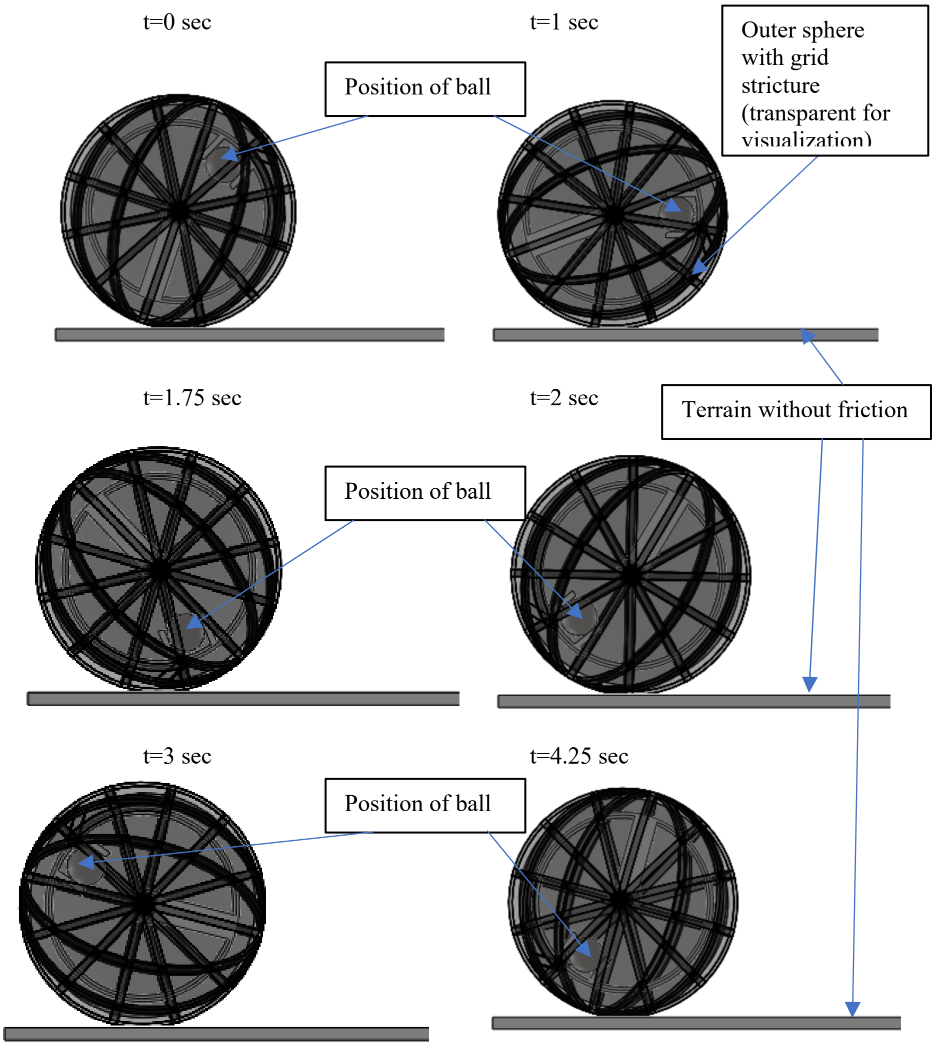

Figure 4. Motion captures of sphere under Martian Gravity (no friction between surfaces) depicting that change in COM can cause the rotation of the proposed design.

The successive analysis was done by applying friction in between spherical surface and terrain. A rotatory motor input was given to slider to animate the effect of SMA spring which can further be helpful for estimating specifications of spring. As gravity on Mars is low, the initial motion analysis with friction caused the sphere to slide in between instances. This was because when the sliding ball actuates the sphere and if it crosses the lower mean position, afterwards when it moves in forward direction (to the right, all analysis is done for traversing in the right direction of the reader), the inertia of sphere cause the rotation to nullify and hence sliding occurs. However if we provide enough actuation to our slider that it stays ahead of mean position most of the times in cycle then we can achieve pure rolling and non-sliding translational movement. The captures of ideal motion of the robotic sphere is depicted through figure 5.

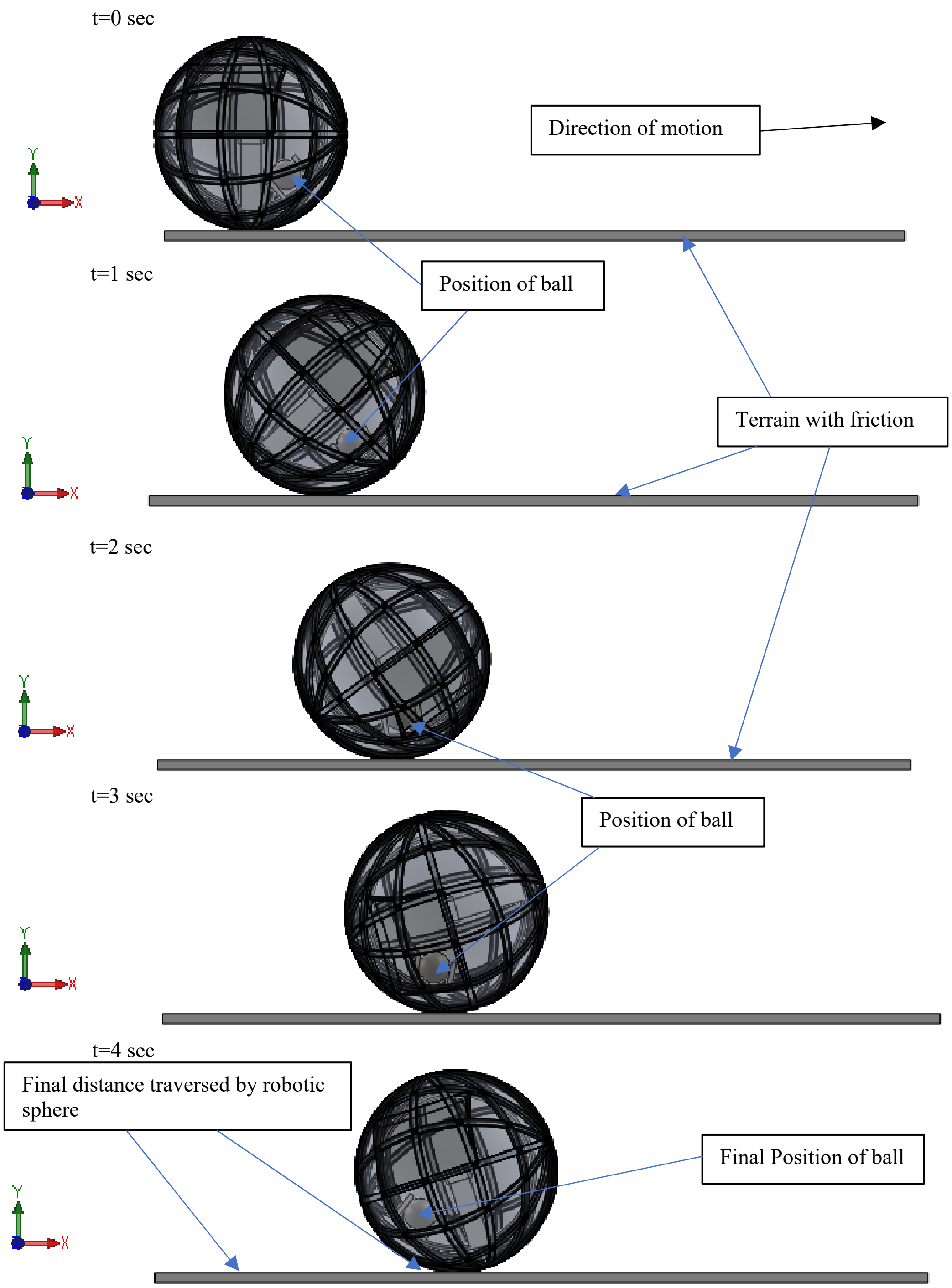

Figure 5. Time instances of robotic sphere while linear motion towards the right (clockwise rotation).

For analysis purpose the friction coefficient parameters (dynamic and static) were set to 0.7. The rotary motor was given the input for movement of 270° in 4.5 seconds. To overcome the inertial forces an initial linear motor of 7mm/s was given the system. The equation involved in the actuation can be visualized as:

$$Mg*dx = I*d\omega/dt \quad (1)$$

Various parametric plots derived from the latter presented motion analysis are displayed below (Figure 6).

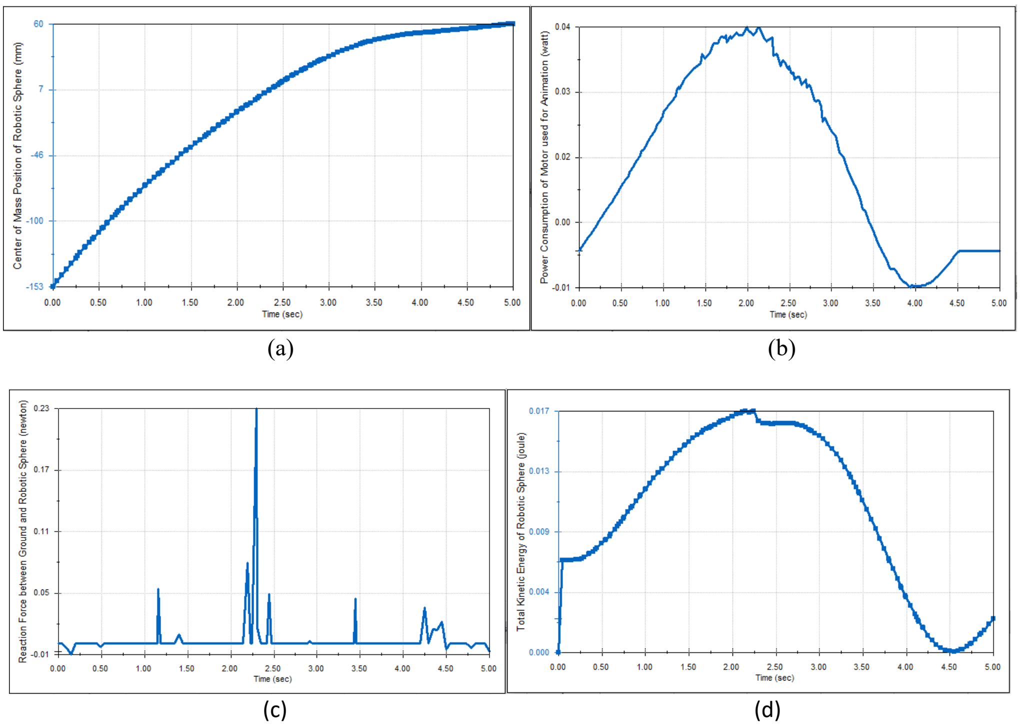

Figure 6. Parametric plots of robotic sphere. (a) Shows the displacement of COM of the system. (b) Power consumption of rotary motor given to slider. It increases initially for overcoming the inertial movement of sphere. (c) Plot of Contact force between terrain and robotic sphere. Peak signifies the instance when the ball is in the lower most position. (d) Total kinetic energy increase and then decreases with time. Delay time in increment is dedicated to overcome the inertial state of sphere.

3. Design of Soft Aerial Robot

Biological systems has always amazed us by proving its immense adaptability within unplanned environment. They motivate us for developing various systems which are compliant as well as robust at the same time. The design for soft aerial robot is thus bio-inspired and is analogous to a bird. The conceptual design is based on extracting the oscillations caused by SMA springs and converting them for flapping, using suitable mechanism.

3.1. *Conceptual Design*

Inspired from [2], the design comprises of body, flapping mechanism, wings and traversing actuation. The solidworks model of various components are presented in figure 7.

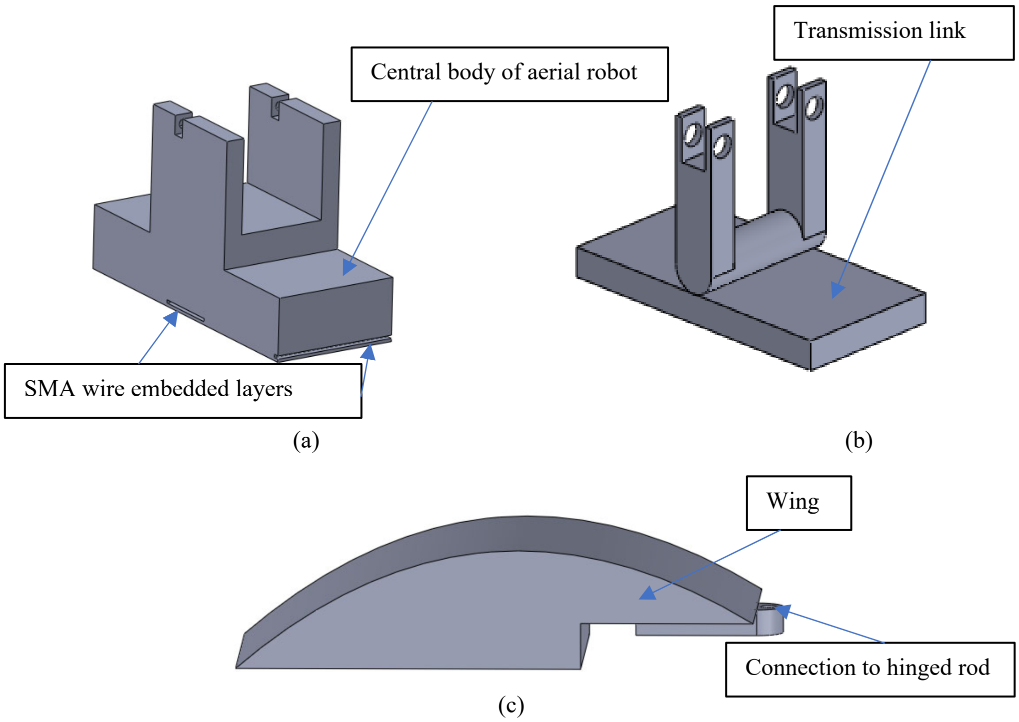

Figure 7. (a) Body of the aerial robot. (b) Transmission link for conversion of the oscillation of SMA spring to flapping. (c) Wing design.

The final design of robot is presented in figure 8.

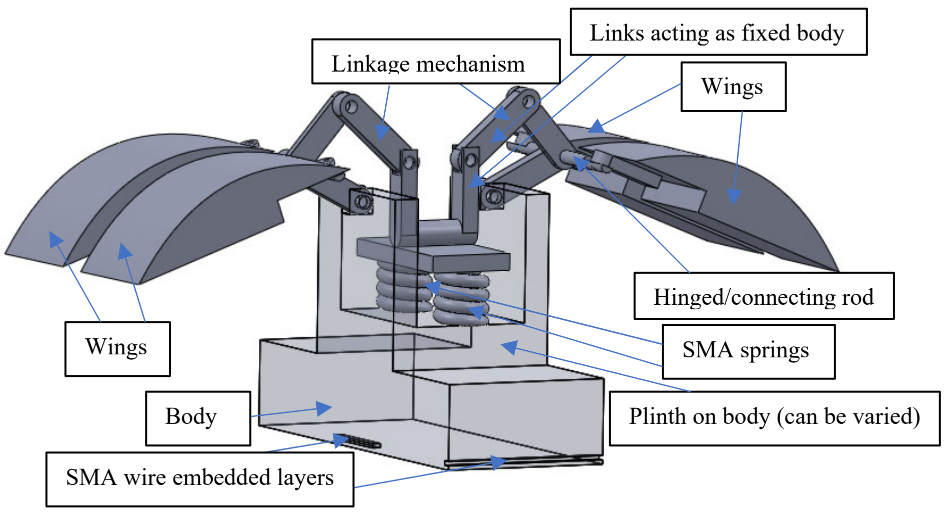

Figure 8. Isometric view of soft aerial robot.

The flapping mechanism can be visualized from figure 8. The SMA springs are attached to the body and the transmission link. The transmission link is basically a part of whole flapping mechanism and the mounting of wings is done on a rod passing through the output of the flapping mechanism. Four wings are adopted from view point of better control. The two cut portions on the body of the robot represents the layers of SMA embedded wire. Due to expected low power requirements of this robot, an efficient solar cells can be mounted on the rest of the body to fulfill its power requirements.

The length of the wing is kept 30mm. The extrusion of wing is 15mm. The dimensions for rectangular base of the body are 20×10×50mm. The rod on which wings are mounted are 25mm long. The section in which springs are mounted are 14mm wide and 20mm long and 5mm thick.

3.2. *Working*

As the SMA springs are actuated with the help of electronics which are embedded inside the body of the robot, the oscillations cause the mechanism to move back and forth and thus creating a flapping mechanism. After escaping from the robotic sphere, the robotic bird will be in a hovering state. To move it in lateral and longitudinal direction, the SMA embedded wires are actuated accordingly. To better visualize consider the wires are initially in equilibrium state and that they will not cause the robot to move in any direction. Now when they are actuated they act as a cantilever but are restricted in their motion due to tightly attached to the robot body. Hence this actuation will cause the entire body to react to this moment and thus tilting of body is achieved. While on other hand the flapping mechanism is already actuated as the bird is in hovering state. The overall motion due to both these actuation will enable the aerial robot to navigate in any necessary direction.

3.3. *Motion Analysis*

The motion analysis of the aerial robot was carried out in the solidworks software and the results are presented hereafter. The figure 9 shows the motion capture instances at mentioned time.

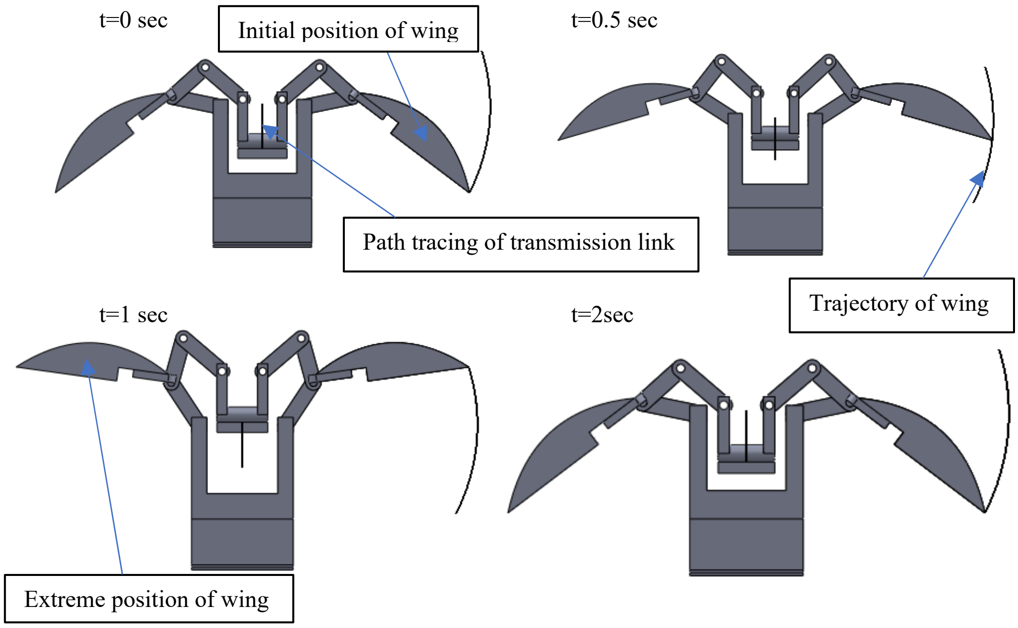

Figure 9. Cycle of flapping having time period of 2 sec. The black mark shows the path of the associated component.

The movement of the transmission link and therefore the required amplitude of oscillation by SMA spring is around 9mm i.e. this is the safe distance for oscillation, avoiding the contact to flapping mechanism with body (leaving around 3mm of distance between transmission link and body). For analysis purpose, a linear actuator having oscillation with 0.5 Hz frequency was provided. However testing can be done varying various parameters and thus optimizing the functionality of system. Also varying angles between the fixed link, shown in figure 10, can be helpful for other motion analysis.

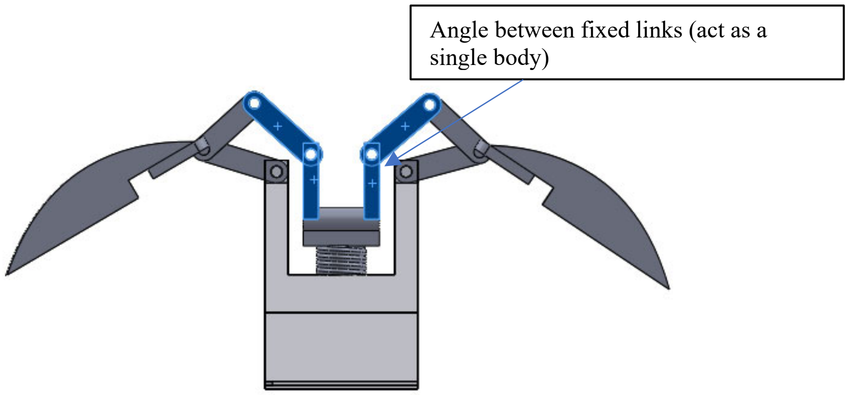

Figure 10. The extent of flapping can be varied by changing the angle between the marked link.

Various parametric plots obtained from the motion analysis are presented in figure 11.

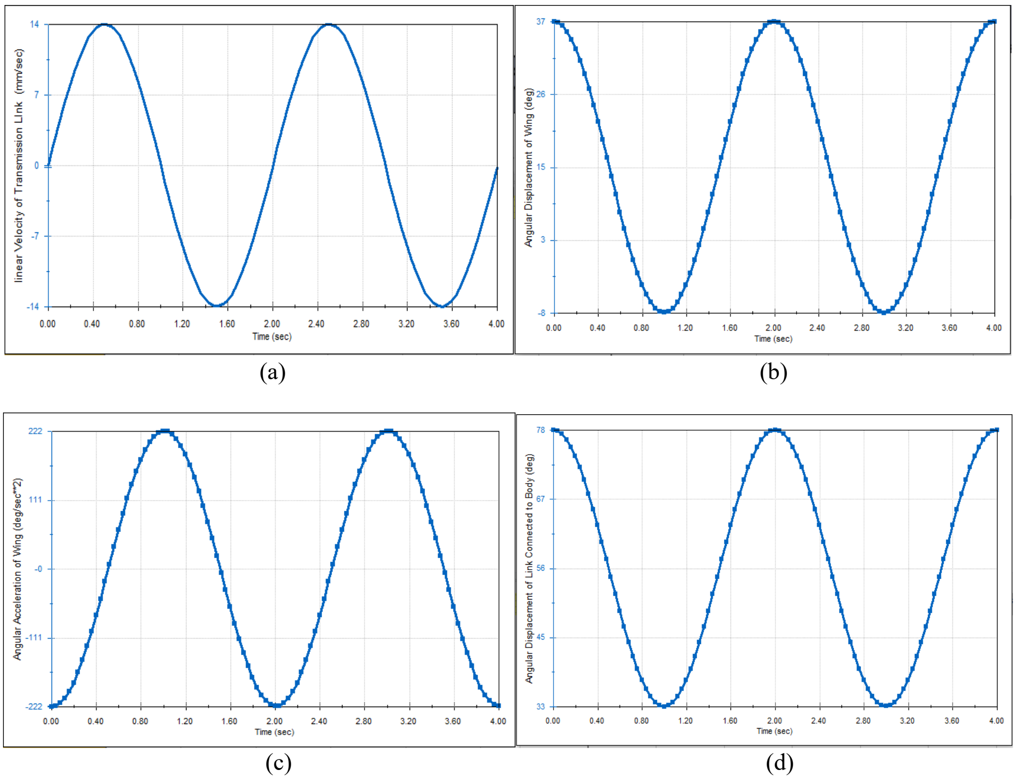

Figure 11. Parametric plots of soft aerial robot. (a) Linear velocity of transmission link. (b) Flapping angle is set to angular displacement of 45 degrees. (c) Angular acceleration of wing for 45 degree rotation. (d) The link connected to the body and the hinge rod of wings shall also move 45° and is proven by this graph.

3.4. *SMA Spring, Bimorph Simulation*

Shape Memory Alloy springs has been used at number of places in our design. The characteristic study of SMA spring of dimensions and properties, as mentioned below are taken in general and are not related to the exact dimensions for our design, as studied in Ansys software are presented in this section. [3]

Spring Specifications: Wire diameter- 0.77 mm
Coil Diameter- 5.69 mm
No of Turns- 18
Length of spring- n*d = 18*0.77 = 13.86 mm
Modulus of Rigidity G = 26 GPa
Stiffness constant = W/δ = G*d^4 / 8 D^3*n = 0.344 N/mm

The following is the plot distribution of directional deformation (figure 12) and equivalent stress (figure 13) of the spring. Similarly several other plots can be obtained and analysed for better performance of the spring as per requirement.

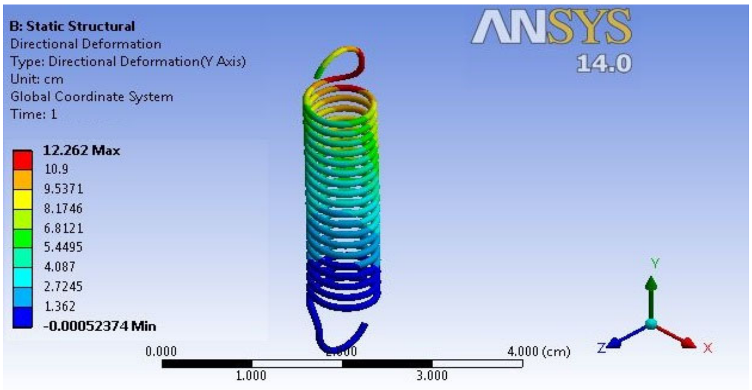

Figure 12. Directional deformation in Y-axis.

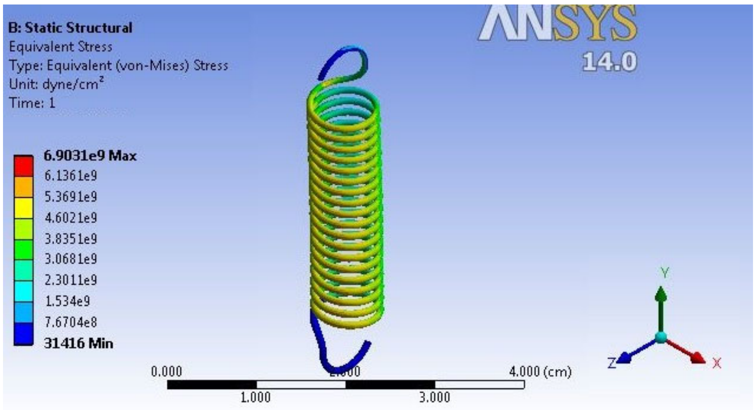

Figure 13. Equivalent Stress (Von Mises distribution).

The following reference figure (14) shows the simulation of SMA bimorph and similar data can be obtained for SMA embedded wire.[6][7][9]. Investigation on actuation characteristics of SMA bimorph towards flappers for aerial robots can be found in [4] and its design and development in [8].

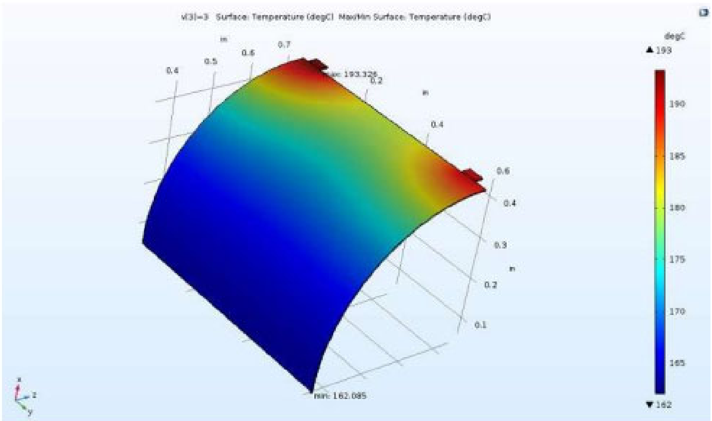

Figure 14. Temperature distribution of SMA bimorph performed in COSMOL and for 3V, a maximum temperature of 193° C was observed.

4. Proposed Final Assembly

The use of two bimorph actuators is adopted for holding the soft aerial robot inside the robotic sphere. The bimorph will hold the soft aerial robot at the central portion of the ring so that when sphere is traversing on Martian terrain it will not cause the aerial robot to fall or displace. The sphere protects the aerial robot from disastrous Martian environment. When the situations become favorable for aerial flight the robotic sphere in its stagnant position actuates the retracting mechanism. Simultaneously, the bimorph will be actuated in the outward direction, loosening the grip on aerial robot and thus the soft robotic bird takes off.

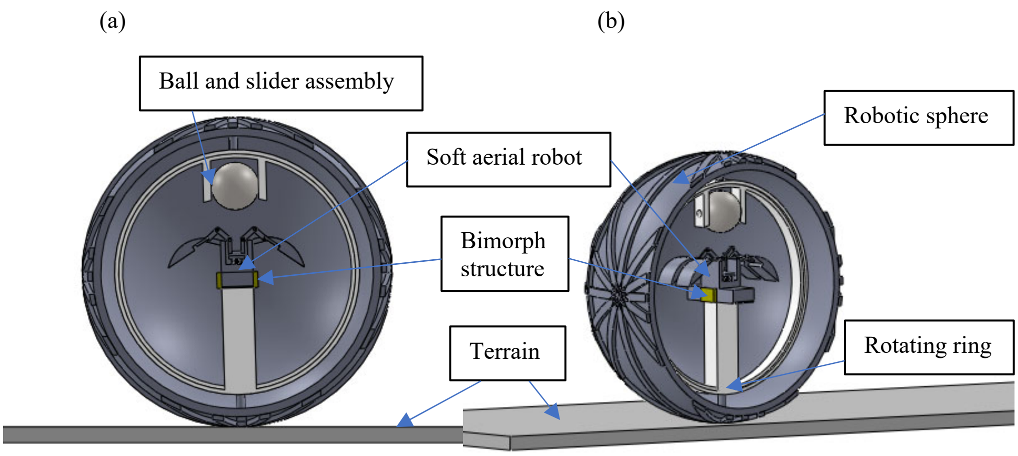

Figure 15. (a) Cross sectional front view of encapsulated aerial robot in robotic sphere. (b) Isometric view. (Note: the robotic sphere can be scaled up in case of collision of ball with wind.)

5. Conclusion and Future Scope

- The papers deals with conceptual design and motion analysis for the proposed design of exploratory robotic system.
- The paper covers design and analysis of robotic sphere and soft aerial robot for space exploration, taking mars as a case study.

- The analysis and parametric plots displays the feasibility of the design and that the presented design can be developed and tested.
- The motion analysis of robotic sphere under no friction condition with martian gravity depicted the feasibility of design. Further analysis of robotic sphere with friction coefficient of 0.7 showed the translation achieved by the sphere under ideal conditions.
- The motion analysis of soft aerial robot gave the amplitude of oscillation, for transmission link, around 9mm for linear actuator having oscillation of 0.5 Hz.
- The comparison between varying parameters and optimizing the functions of the system as well as fulfilling the power requirements of aerial robot provides a wide future scope for further working and developing of the proposed idea.
- Control and automation of soft robotic systems is a topic of interest of numerous robotic researchers. Selection of material for fabrication of such system is also a major concern. Thus developing such system will prove to be major breakthrough for the robotic industry.

References

1. Ron Pelrine, Roy Kornbluh, Qibing Pei, Scott Stanford, Seajin Oh, Joe Eckerle, Robert Full, Marcus Rosenthal, Kenneth Meijer. 2002. Dielectric Elastomer Artificial Muscle Actuators: Toward Biomimetic Motion. SPIE Smart Structures and Materials + Non-destructive Evaluation and Health Monitoring.
2. J P Whitney and R J Wood 2012 *Bioinspir. Biomim.* **7** 036001
3. I.A Palani, V. Singh, A. Laharia. Fabrication of SMA based hot water actuation heat engine. IIT Indore.
4. Akash, K.; Jain, A.K.; Karmarkar, G.; Jadhav, A.; Narayane , D.C.; Patra, N. & Palani, I.A. Investigations on actuation characteristics and life cycle behaviour of CuAlNiMn shape memory alloy bimorph towards flappers for aerial robots. Materials and Design, 2018, 144, 64–71. https://doi.org/10.1016/j.matdes.2018.02.013
5. Stephen Coyle, Carmel Majidi, Philip LeDuc, K. Jimmy Hsia (2018) Bio-inspired soft robotics: Material selection, actuation, and design. Extreme Mechanics Letters. 22. 51– 59.
6. Muralidharan M, Aishwarya K, Mithun R, Palani I A, Thermo-mechanical behaviour of SMA wire embedded PDMS actuator towards soft robotics applications, International Journal of Robotics and Automation, 2020. (IF-0.854)
7. Muralidharan M, Brolin A, Mithun R, Rajagopalan P, Sachin Bhirodkar and Palani I A, Actuation Study on Shape Memory Alloy Wire Embedded Polydimethylsiloxane for Soft Robotic Applications, Institute of Smart Structures and Systems (ISSS), National Conference on SMART MEMS, Smart Materials, Structures & Systems (ISSS, IISc Bangalore), TCE Madurai, 2018.
8. M. Muralidharan, A. Brolin, B. Mayank, P. G. Naveen, S. Jayachandran, B. Sachin, I. A. Palani, Design and Development of Polydimethylsiloxane (PDMS)/ Shape memory alloy (SMA) Integrated Bimorph for Soft Robotic Applications, Recent Innovation In Advanced Materials (RIAM) , Advanced Materials and Processes Research Institute(AMPRI), Council of Scientific & Industrial Research(CSIR) Bhopal, India, 2018.
9. M. Muralidharan, Palani I.A, Investigations on Multifarious Shape Memory Alloy (SMA) Structures towards the Development of Bio-Inspired Soft Robots,2020.