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Kinematic Modelling and Structural Analysis of a Spherical Robot: BALL-E

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Abstract: This paper presents a spherical mobile robot which is capable of executing rolling and walking motions. The proposed robot can also transform into a quadruped based on the terrain conditions. The advantage of combining these motions in the robot is that it improves the collision recovery and manoeuvrability over multiple terrains. Various conceptual designs are developed, and concept scoring is carried out to find the best design. The kinematic analysis is presented for the chosen design using the Denavit-Hartenberg (D-H) method. The inverse kinematics is solved using MATLAB and the corresponding robot configurations are plotted. The structural analysis of the robot is also completed using ANSYS Workbench.
Keywords: Spherical Robot, Kinematic Modelling, Dimensional Synthesis, Quadruped, structural analysis.

1. Introduction

Spherical mobile robots are becoming popular these days due to their functionality and unique features. The rolling motion makes it to be usable over a wide range of terrains, for unmanned operations in unpredictable environments and has better collision avoidance and recovery. There are many types of Spherical Robots available in the market. These spherical robots differ by the type of internal driving mechanisms to actuate the robot in the required direction. Many research works are going on in developing these internal driving mechanisms and their control strategies.

A spherical robot having a pillar-like structure with driving wheel and supporting wheels at the ends are discussed in [1]. In this spherical, robot the pillar will move inside the spherical shell and in turn, moves the sphere in the required direction. Some spherical robots are having cart like structure inside the shell which drives the outer shell [2][3]. Spherical robot having a ball inside the spherical shell that can be rotated by a motor with the help of rollers in a designated configuration is presented in [4]. This design makes the robot to be omnidirectional as the ball rotation drives the robot. A design that uses pendulum mass as its driving force is developed in [5] and [6]. The imbalance created by the pendulum moves the robot in the intended direction. Furthermore, a compound pendulum design is implemented in [7], which improves the stability and control of the spherical robot. A concept using conservation of momentum is proposed in [8], where the authors used high-speed rotors attached to two identical hemispheres that actuate the robot. Shifting the centre of mass of the robot is used as an actuation method in [9]. The controlled motion of the internal masses causes the locomotion of the robot. As an alternative, Shape Memory Alloy (SMA) wires are used to configure the outer shell by developing a suitable control strategy [10]. Similarly, an outer shell comprising of modular Lego-like blocks are designed in [11]. This modular design helps it to shapeshift and move in the desired direction. For all the spherical robots discussed above, controlling the path followed is difficult and motions are mostly unsteady due to the actuation mechanism. Power consumption is also a limitation in these designs and the use of renewable energy like solar/wind can also be explored. Placement of the components such as sensors, electronic controllers and the battery is also a challenge.

In this paper, a novel spherical robot mechanism is designed which can transform itself from sphere to a quadruped and vice versa as per need. In the spherical form, the robot can move by rolling over the surfaces and in the quadruped form, it follows legged locomotion. The conceptual design is made by type, number and dimensional synthesis. Furthermore, the kinematic modelling is carried out using the Denavit-Hartenberg (D-H) convention and is verified using MATLAB simulations. Structural analysis of the robot components is also presented.

2. Conceptual Design

This section details the conceptual designs developed for the spherical robot. All the conceptual designs are focused on novelty and to overcome the limitations of the predecessors.

2.1. Concept A

In this design spoke arms protrude from the surface of the spherical robot as shown in Figure 1. All electronics are inside the casing at the centre and spoke arms are actuated using a suitable mechanism.

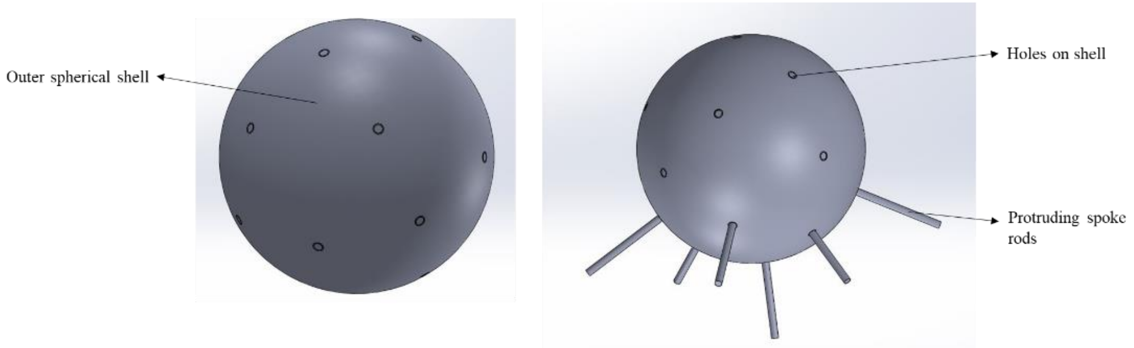

Figure 1. Spoke sphere

2.2. Concept B

It uses a combination of a pendulum and wheel-based spherical robot and also the design can be modified to have a head placed on top of it with sensors as seen in Figure 2.

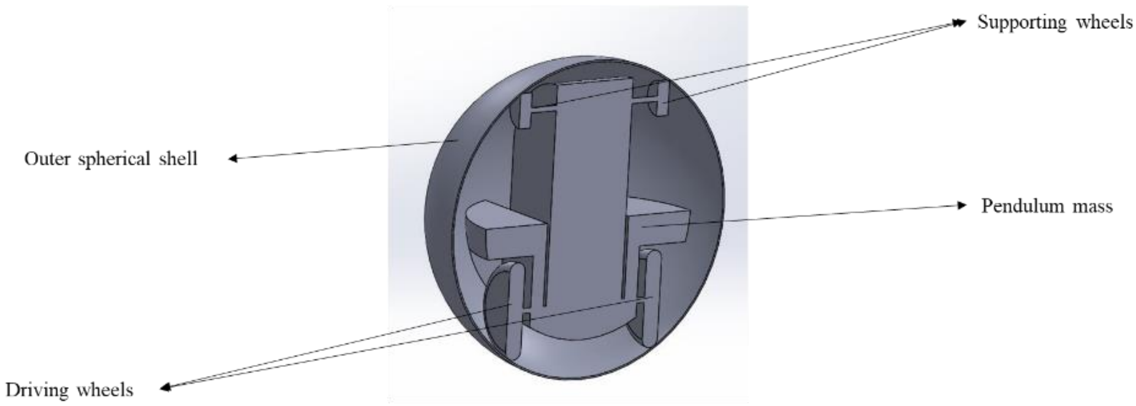

Figure 2. Wheelie robot

2.3. Concept C
The outer shell of the spherical robot is comprised of identical triangular curved panels which can be moved to facilitate the movement of the robot as in Figure 3.

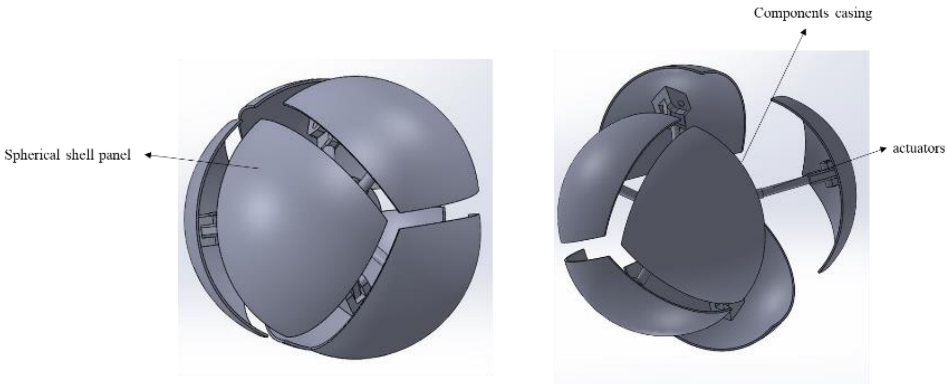

Figure 3. Trisphere robot

2.4. Concept D
In this design, the mass can be moved inside the spherical robot by sliding mechanisms, which in turn facilitate the movement of the robot as shown in Figure 4.

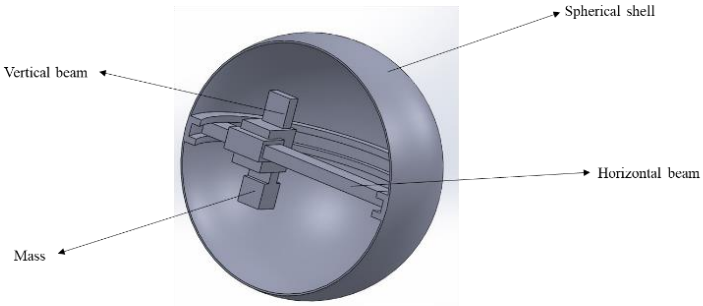

Figure 4. 3dsphere

2.5. Concept E
This concept is transformable spherical/legged robot by moving the robot legs which are attached to curved contours we can move the robot in a spherical form and when transformed it can act as a legged robot as represented in Figure 5.

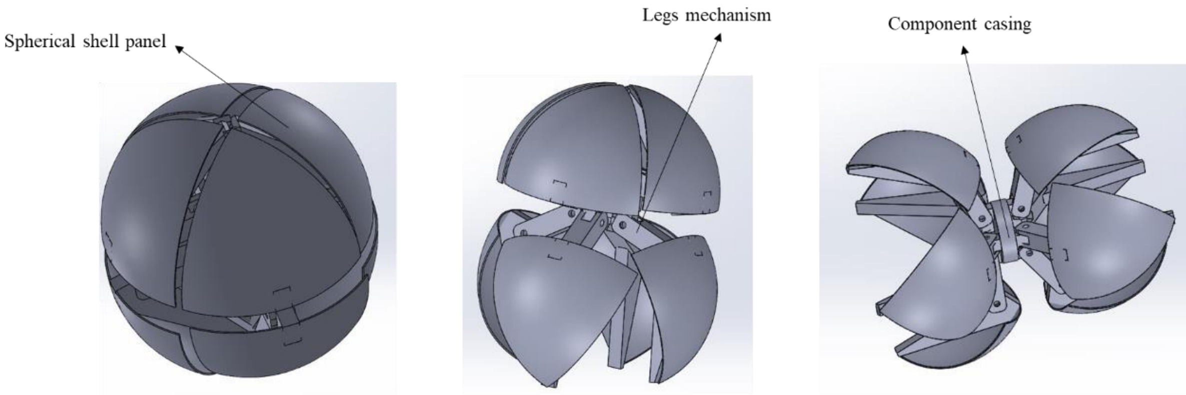

Figure 5. BALL-E

2.6. Concept F

In this concept, the outer shell is made of ferromagnetic material and the inner core is comprised of several electromagnetic coils arranged in a designated way and can be activated as per need and by activating the coils in the required direction the inner core moves in that direction causing imbalance for the robot to move accordingly as seen in Figure 6.

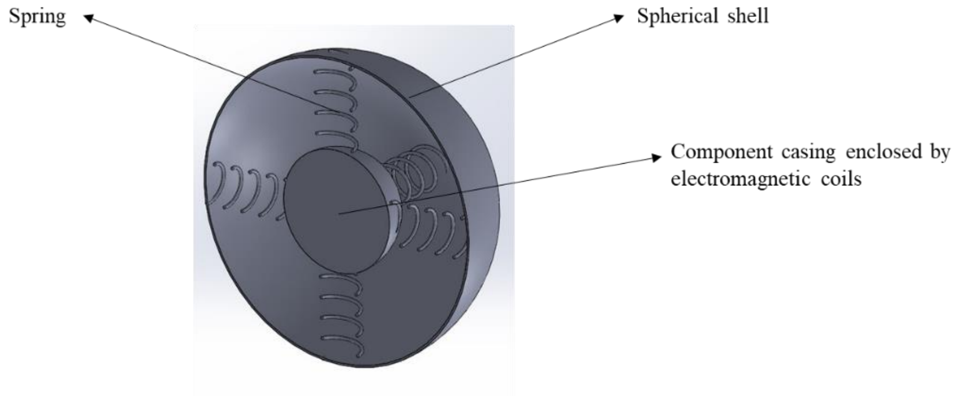

Figure 6. Springy

3. Concept Scoring and Selection

Concept scoring is a method for rating the concept designs and rank them based on a set of predetermined or user-defined criteria. It is helpful to weigh down the advantages and limitations of a design and to select the best design to satisfy the requirements. In this work, Manoeuvrability, Manufacturability, Cost, Stability, Speed, Power usage, Sensor compatibility and Ability to jump are selected as the criteria for scoring. The final scores obtained for each concept design and their rankings are listed in Table 1.

Table 1. Concept Scoring

		A		B		C		D		E		F	
Selection criteria	**Weight**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**	**Rating**	**Weighted score**
Manoeuvrability	25%	4	1	3	0.75	2	0.5	3	0.75	5	1.25	3	0.75
Stability	20%	3	0.6	4	0.8	3	0.6	3	0.6	4	0.8	2	0.4
Manufacturability	15%	3	0.45	4	0.6	3	0.45	4	0.6	4	0.6	2	0.3
Cost	15%	4	0.6	4	0.6	3	0.45	3	0.45	3	0.45	3	0.45
Power usage	10%	3	0.3	4	0.4	3	0.3	3	0.3	3	0.3	2	0.2
Speed	5%	4	0.2	4	0.2	3	0.15	3	0.15	3	0.15	3	0.15
Sensor compatibility	5%	3	0.15	4	0.2	2	0.1	4	0.2	4	0.2	2	0.1
Jumping	5%	4	0.2	2	0.1	4	0.2	3	0.15	4	0.2	3	0.15
Score		3.45		3.65		2.75		3.2		3.95		2.5	

Rank	**3**	**2**	**5**	**4**	**1**	**6**
Continue?	No	No	No	No	Yes	No

Though concept A has better control and stability, it is complex to design the internal mechanism. The cost and power usage are moderate, and the jumping motion can be accommodated with ease. However, sensor integration is difficult due to space limitation. Concept B has a good rating in all criteria except the jumping capability. Concept C is unsteady and hard to control compared to the other concepts. It has a reasonable cost and power consumption though it lacks sensor compatibility. Concept D does not excel in any criteria even though it satisfies the requirements. Concept E is innovative and fulfils the optimum requirements. Concept F is novel, complex to design, hard to control and there is a chance for the sensors to be interfered with by the magnetic field. By concept scoring, Concept E which is the transformable spherical robot is selected as the suitable design and developed further.

4. BALL-E, a Spherical Robot

BALL-E is a transformable spherical robot as shown in Figure 7 which can act as a quadruped robot as and when required. It comprises two hemispheres where the top hemisphere acts as a housing for sensors and electronics and the bottom hemisphere acts as quadruped robot when transformed. This Spherical robot contains 8 legs with 4 legs in each hemisphere and all the legs in a hemisphere are identical. All the joints in the leg mechanisms are revolute. Lower hemisphere legs have 4 links and 4 revolute joints. Upper hemisphere legs have 2 links and 2 revolute joints. Hence, there are 24 revolute joints in total and degree of freedom is equal to the total number of joints as all the legs are open chain.

Figure 7. Concept of BALL-E

4.1. Dimensional Synthesis

The spherical robot is symmetric about a vertical axis. It has two types of leg mechanisms for each hemisphere. Based on the size of real-life actuators and electronic components, the diameter of the robot is assumed to be 340 mm. Link lengths for the legs are derived from this assumption. The size of a single shell is 1/8th of the sphere and the diameter is 340 mm.

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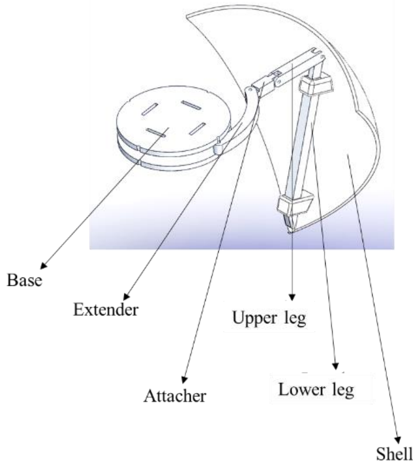

Figure 8. Lower hemisphere leg

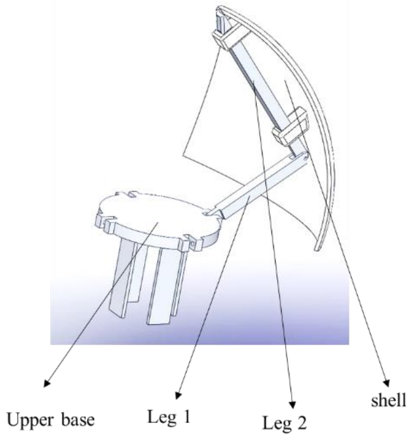

Figure 9. Upper hemisphere

The designs for leg mechanisms are presented in Figure 8 and 9. For the lower hemisphere legs, the length of the leg depends on the position of attachment to the shell. Consider the 2D view of a shell and lower leg the position as seen in Figure 10. The link length of the lower leg is found to be around 190 mm.

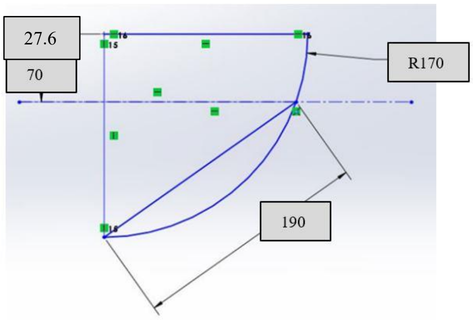

Figure 10. 2d view of leg and shell

The position of the base on the vertical axis is assumed and it affects the internal space available for components. The increase in the distance will provide more space to accommodate things but at a cost of interference between parts. Taking into account the maximum movement for lower leg and optimum space to accommodate parts, the position is assumed to be 70 mm. Upper leg link length is best if around 70 mm as it also helps in increasing the moving range of lower leg and shell. Link lengths of base, extender, attacher, the upper leg is interrelated. The exact link length is determined by obtaining link lengths for base and extender. Attacher link length is flexible as it only serves the purpose of connecting extender and upper leg. Hence, its dimension is fixed in the later stage of synthesis and the base diameter dimension is inversely proportional to extender link length. To avoid interference between legs, the base diameter is taken as 100mm. As the base diameter is fixed and the position of lower leg and shell is estimated, the sum of the link lengths of extender, attacher, the upper leg is equal to 110.8 mm. For maximum gait walk step of 300 mm, the attacher link length is assumed as 30 mm by the possible actuator placement. As discussed earlier upper leg link length is suitable around 70 mm and for ease of placement of extender, the upper link length is taken as 65.8 mm and extender link length becomes 82 mm. For upper hemisphere, the base diameter is taken as 190 mm, link length of leg 1 and leg 2 are equal to upper leg and lower leg lengths respectively for symmetry and functionality.

4.2. Kinematic Modelling

Kinematic modelling is used to relate the joint angles to the final pose of the robot. It helps in finding out the position of the end effector concerning base in terms of joint variables. D-H modelling is used to develop the kinematic equations of the spherical robot. The link length used for modelling is described in the previous section. Considering the lower hemisphere legs in Figure11, the reference frame is {0} and frames {1} to {4} are assigned to each joint up to the end effector. The D-H parameters obtained are given in Table 2.

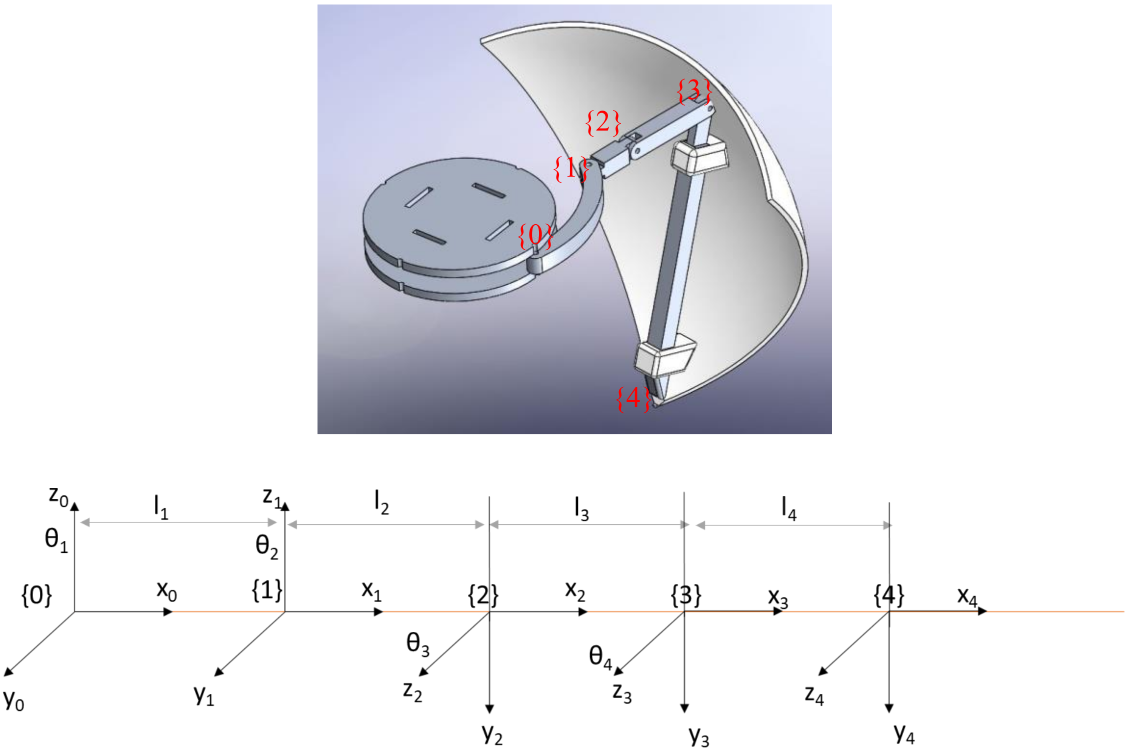

Figure 11. DH Modelling

Table 2. DH Parameters Table

Frames	Joint angle (θ_i)	Joint offset, d_i (mm)	Link length, a_i (mm)	Twist angle(α_i)
{0}-{1}	θ_1	0	L_1=82.01	0
{1}-{2}	θ_2	0	L_2=30	$\pi/2$
{2}-{3}	θ_3	0	L_3=65.8	0
{3}-{4}	θ_4	0	L_4=190	0

General transformation matrix from $i-1^{th}$ frame to i^{th} ith frame is

$$ {}^{i-1}_{i}T = \begin{bmatrix} c(\theta_i) & -s(\theta_i).c(\alpha_i) & s(\theta_i).s(\alpha_i) & a_i.c(\theta_i) \\ s(\theta_i) & c(\theta_i).c(\alpha_i) & -c(\theta_i).s(\alpha_i) & a_i.s(\theta_i) \\ 0 & s(\alpha_i) & c(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

where $c(\theta)$ is cos (θ), s(θ) is sin(θ).
Transformation matrix of the end effector with respect to the base,

$$ {}^{base}_{end\ effector}T = {}^{0}_{1}T.{}^{1}_{2}T.\ldots.{}^{n-1}_{n}T \tag{2} $$

Final transformation matrix for {4} wrt. {1} is,

$$ {}^{0}_{4}T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

where r_{ii} elements are components of the rotation matrix and p_i elements are components of the translation matrix.
The D-H parameters of a leg in quadruped and sphere form are visualized in Figure 12 using MATLAB. The joint variables can be verified from the figure whether it satisfies the desired configuration of the mechanism.

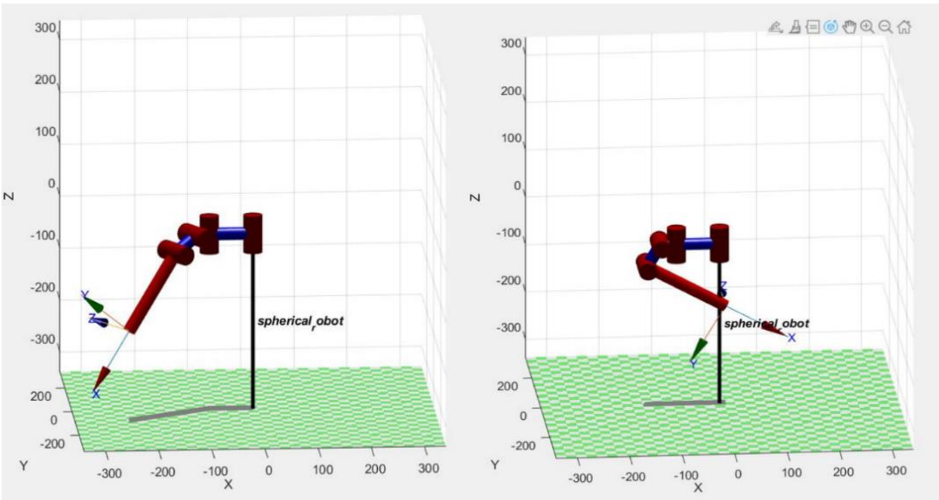

Figure 12. DH parameters

4.3. Inverse Kinematics
In this section, the inverse kinematics of the lower leg of the robot is detailed. The computational cost is higher for the geometric approach and hence the algebraic method is chosen for solving the inverse kinematics. The matrix equation to be solved is depicted in equation (4).

$$ {}^{0}_{4}T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} = {}^{0}_{1}T(q_1).\,{}^{1}_{2}T(q_2).\,{}^{2}_{3}T(q_3).\,{}^{3}_{4}T(q_4) \tag{4} $$

where the left-hand side is the final transformation matrix and q_i are joint variables.
The equations (5) to (7) are nonlinear simultaneous equations derived from the matrix equation above.

$$ [{}^{0}_{1}T(q_1)]^{-1}.\,{}^{0}_{4}T = {}^{1}_{2}T(q_2).\,{}^{2}_{3}T(q_3).\,{}^{3}_{4}T(q_4) \tag{5} $$

$$ [{}^{0}_{1}T(q_1).\,{}^{1}_{2}T(q_2)]^{-1}.\,{}^{0}_{4}T = {}^{2}_{3}T(q_3).\,{}^{3}_{4}T(q_4) \tag{6} $$

$$ [{}^{0}_{1}T(q_1).\,{}^{1}_{2}T(q_2).\,{}^{2}_{3}T(q_3)]^{-1}.\,{}^{0}_{4}T = {}^{3}_{4}T(q_4) \tag{7} $$

By solving the set of simultaneous equations, the joint variables q_1, q_2, q_3 and q_4 are obtained.

4.4. Structural Analysis

The prototype design has been developed in SOLIDWORKS and the total mass of the robot is estimated to be around 5 kg. The main components of the lower leg mechanism are shown in Fig. 8 which are base, extender, upper leg and lower leg. The structural analysis is carried out assuming that in a given instant, the robot's weight acts on the component in a specified direction during its motion. Material is taken as aluminium alloy due to the high strength to weight ratio and the affordable cost. The load acting on the components is estimated as 50 N considering the loads that may act on the robot while executing the motion. Loading scenarios are assumed based on motion and the structure of the leg mechanism.

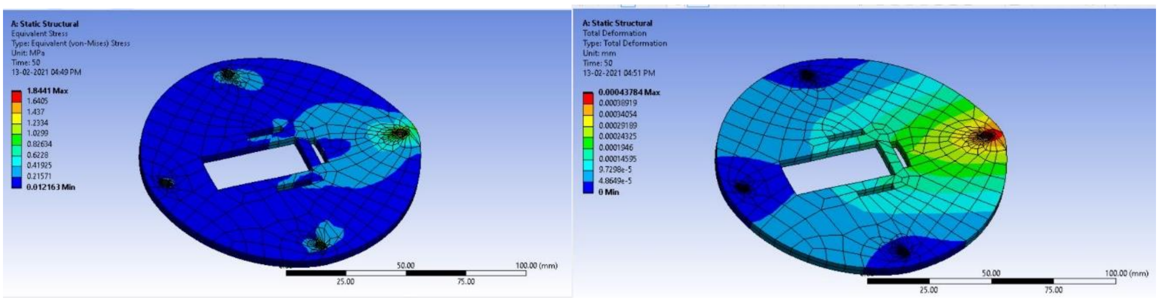

Figure 13. Base under load

As shown in Figure 13, the three holes of the spherical base plate are fixed and load is applied to the other hole radially. The maximum deflection of 4.378×10^{-4} mm is occurring at the hole on which the load has been applied and maximum equivalent stress of 1.844 MPa can be seen at the adjacent holes.

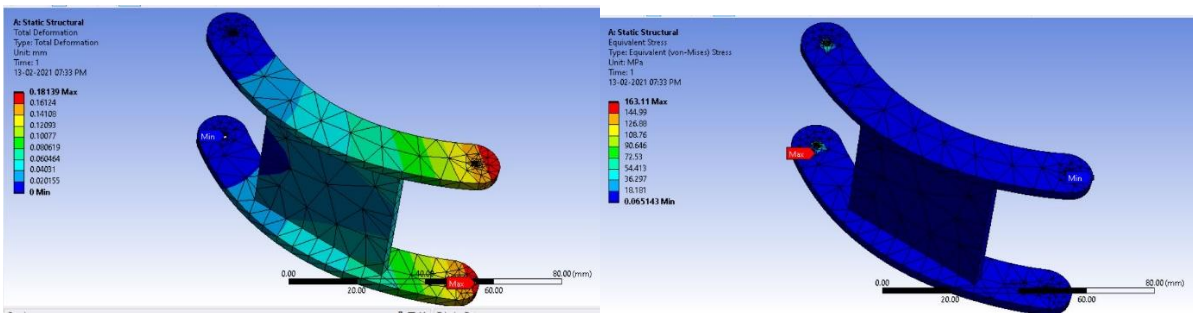

Figure 14. Extender under load

In the case of extender, it may undergo both bending and twisting forces. It was noted that stresses induced due to bending are more compared to others. The maximum deformation of 0.18 mm takes place at the load acting end and maximum stress of 163 MPa at the opposite end as of load as seen in Figure 14.

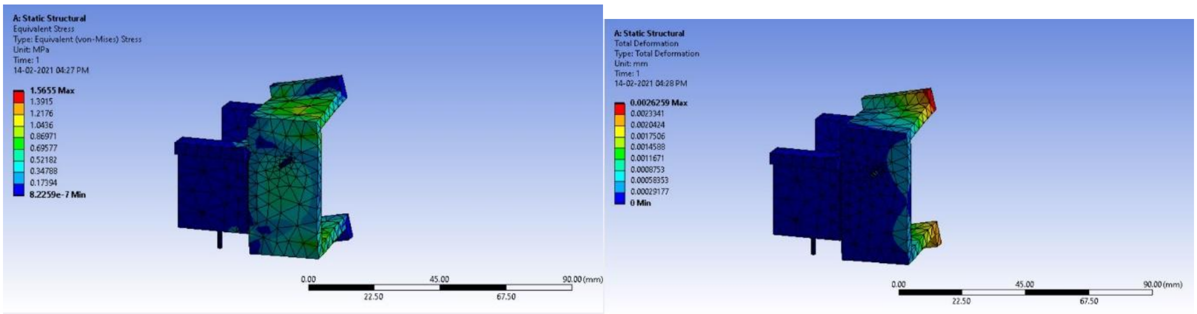

Figure 15. Attacher under load

Attacher acts as a bridge between the leg and base, extender assembly. Load acts on the walls of holders of actuators and causes a deformation of 2.629×10^{-3} mm and maximum stress of 1.565 MPa at the hinges of the top wall that can be observed in Figure 15.

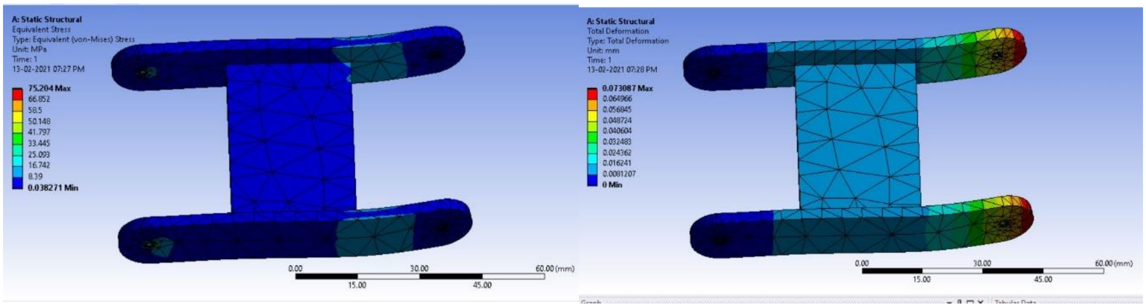

Figure 16. upper leg under load

The upper leg has a similar scenario as of extender in loading conditions. However, the stresses formed are less compared to the extender. The maximum deflection of 7.38×10^{-2} mm is observed at the load acting end and maximum stress of 75.204 MPa is seen at the opposite end of the load as depicted in Figure 16.

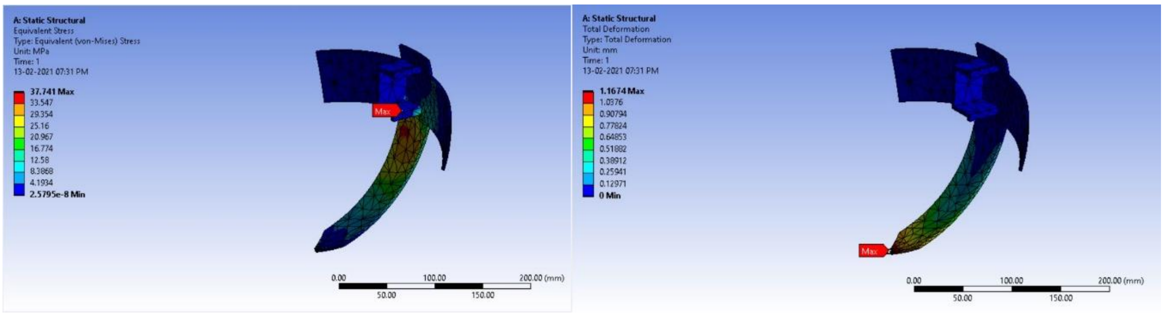

Figure 17. lower leg under load

The loading conditions of the lower leg varies based on the form of a robot that is sphere or quadruped. In sphere form, load acts on the circular section of the leg whereas in the other it acts on the end of the leg. It is found out that the stresses developed are more in quadruped state with a maximum deflection of 1.16mm at the tip of the leg and maximum stress of 37.741 MPa at the mid part of the circular section of the leg as portrayed in Figure 17.

5. Conclusion

In this paper, a novel spherical robot design is proposed. Conceptual designs based on the objectives are formulated and the best design is selected through concept scoring. Moreover, the type, number and dimensional synthesis are carried out for the chosen design. The kinematic model of the spherical robot is developed using the Denavit-Hartenberg (D-H) method and verified through MATLAB simulations. Inverse kinematic solutions are calculated using an algebraic method. Structural analysis under chosen loading conditions are performed using ANSYS Workbench and the results obtained are found to be satisfactory. The extender link in the mechanism bears more stress when compared to the other links and maximum deformation is observed in the lower leg. The dynamic analysis of the robot needs to be completed to obtain the equations of motion. The motion planning for both spherical and quadruped configurations are to be developed for generating the robot locomotion by inverse kinematics. The potential applications of the proposed spherical robot may include automated surveying, exploration in unknown environments, surveillance and security, light material transportation, etc.

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