DESIGN AND ANALYSIS OF A NOVEL TWO DOF HYDRAULLACALY ACTUATED SPHERICAL ACTUATOR FOR SNAKE ARM ROBOTS

By

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In the name of Allah, the most
Beneficent and the most Merciful

DECLARATION

I hereby declare that I have developed this thesis entirely on the basis of my personal efforts under the sincere guidance of my supervisor Lt Col. Dr. Kunwar Faraz Ahmad. All the sources used in this thesis have been cited and the contents of this thesis have not been plagiarized. No portion of the work presented in this thesis has been submitted in support of any application for any other degree of qualification to this or any other university or institute of learning.

Signature_____________

Muhammad Bilal

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Innumerable words of praise and thanks to Allah, the Almighty, and the Creator of the universe for carving the path for me and always helping me out in the best possible way. Without His Will and Mercy, I would not have been able to accomplish this milestone. I am grateful to my parents for their immense love, moral support, encouragement and prayers throughout my academic career.

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DEDICATION

To my parent and teachers.

ABSTRACT

Snake –arm robots are increasingly becoming popular because of their increasing importance in access related problems. The design of an actuator with high power density, large work space, large joint space, compact size, small weight is critical for the performance of a snake-arm robot and is subject of present research. Different type of actuators have been developed i.e. electric, hydraulic, pneumatic, piezoelectric etc. Electric motors are most common of them. Hydraulic actuators have the highest power density with at least ten times more power dense as compared to electric motors. But they are prone to leakage and are difficult to design in compact size and high accessibility. This paper focuses a novel design which skillfully utilizes the high power density of hydraulics, in a compact size without sacrificing the accessibility of the actuator. A two DOF hydraulically actuated spherical shape actuator has been designed. The said design was manufactured to verify the perceived motions. Important parameters were identified and different relations between them were established .Potential problems, there solutions and future recommendations regarding improvement of the design are discussed.

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INTRODUCTION

1.1 Introduction

Snake arm-robots are increasingly getting popular among researchers because of their ability to solve access related problems where conventional robots fail. Moreover they provide complex but innovative design and control opportunities.

Their ability to have access to confined spaces has led their applications in industry, security and defense, and robotic surgery.

In industry they are used for decommissioning and repair and maintenance of nuclear power plants. In aerospace industry they are used for manufacturing inside wings, ducts and jet engines. They are also used for wielding pneumatic sanders for all stages of surface finishing prior to final paint application and maintenance, over haul of the aircraft. In automotive industry snake-arm robots allow parts to be assembled in a different way.

Snake-arm robots are also used in bomb disposal and counter terrorism. Moreover they have proved to be of immense value in search and rescue operation especially in post-earth quake operations.

In the field of robotic surgery snake-arm robots are used in colonoscopy, endoscopy and neurosurgery.

The characteristic of snake-arm robot are directly related to the characteristics of its actuators. Actuators can be broadly classified into three types based on the power source that actuates it. They are electric, hydraulic and pneumatic.

Electric actuators are most widely used actuators because of ease of power transmission and control. They can be further classified into electromagnetic, piezoelectric, shape memory alloys (SMA) and electric muscles. Electric motor along with an attached worm-gear mechanism for self locking is the most widely used electromagnetic actuator. Piezoelectric motors are the latest replacement of electric motors for small application. Bimorph is a form of piezoelectric actuator with a close resemblance to bimetallic strips.

Hydraulic actuators are used where high torque and power transmission is required. Pneumatic actuators are another form of actuators which closely resembles hydraulic actuators.

This paper defines an ideal snake-arm robot as a robot with an infinite accessibility. The ideal snake-arm robot should consist of infinite actuators with each actuator having characteristics like infinite cantilever length, length to width ratio of one, infinite energy density and a torus joint space.

After a detailed literature review it is concluded that because of high power density hydraulic actuators are the most suited actuators for making snake arm robot with characteristics relatively to closer to an ideal snake-arm robot. Moreover they are difficult to design and implement. The most commonly available hydraulic actuators are the linear hydraulic actuators consisting of a straight cylinder and a piston. Rotary hydraulic actuators are also available. Both are 1-DOF actuators. Ideal snake-arm robot requires a rotary actuator which is 2 DOF such that axis of rotation of both DOF lie in a single plane. No such actuator was found in literature.

As a result the necessity to design a new and novel actuator was realized.

The main focus of the research is “To design a novel 2 DOF hydraulically actuated spherical shaped actuator” in order to improve the accessibility of snake-arm robots with high torque applications.

Hydraulic pressure is transmitted through flexible pipes. These pipes are good at transmitting a high pressure relative to the atmosphere. But they cannot transmit a low pressure relative to the atmosphere as they squeezes due to high pressure of the atmosphere resulting in the blockage of the pipe. Thus a high pressure transmission can only be achieved if a high pressure relative to atmosphere is utilized for the purpose of actuation. This further imposes a new constraint that the actuator we wish to design should utilize a high pressure relative to atmosphere for the purpose of actuation.

A 2 DOF rotary hydraulic actuator requires at least two 1-DOF rotary hydraulic actuator. Each 1-DOF hydraulic actuator will require a single pipe for power transmission and control provided both high pressure relative to atmosphere and low pressure relative to atmosphere is utilized. But if the constraint is to utilized only high pressure relative to atmosphere than the 1-DOF hydraulic actuator will require two pipes for power transmission and control provided such a modification is possible. Each additional pipe will not only increase the complexity of the actuator but will also increase the diameter of the snake-arm robot thus resulting in its reduced accessibility.

This problem is solved by applying the concept of the Omni wheel robot. An Omni wheel robot consists of three wheels all lying in the same plane. The wheels are arranged such that they lie on the vertex of an equilateral triangle and their axis of rotation intersects each other at the centroid of the triangle. If the wheels are bidirectional than the robot is 3 DOF system. Assume we are interested in a 2 DOF Omni wheel robot. I.e. we are not interested in the rotation of the robot about its centre. But we have the constraint that the wheels can provide torque in one direction but can rotate in both directions when an external torque is applied. Such an Omni wheel robot can be made if the direction of rotation of wheel in which they can apply torque is toward the centroid of the triangle. This Omni wheel robot is 2 DOF because it can move to any point in the plane but it cannot rotate.

Like the 2 DOF Omni wheel robot we should be able to achieve 2 DOF rotary hydraulic actuator by placing three unidirectional (free to move in both direction but can apply torque in one direction) rotary hydraulic actuators such that their axis of rotation is at 120^o from each other and their axis of rotation intersect each other at the centroid of the triangle on whose vertices they lie.

A rotary hydraulic actuator based on the concept just mentioned is designed and modeled in PROE. The model is manufactured to verify the perceived motion of the actuator. Important parameters of the actuator are identified and different relations between them are developed. A number of analysis based on these relations are performed. Potential problems are identified and their solution given. The thesis ends with important recommendations and conclusions.

1.2 Problem Statement

Snake arm robot is increasingly getting popular because of their use in access related tasks. They use different types of actuators including electric, hydraulic, piezoelectric; SMA actuators etc. of all these actuators, electric actuators are most widely used.

Piezoelectric and SMA actuators are technologically not matured enough .thus resulting in a limited practical use. Electric actuators are reliable and easy to control but have relatively low power density and lacks self locking capability when power is switched off. Self locking capacity can be added to electric actuator by use of worm gear mechanism but it increases complexity. Hydraulic actuators have a higher power density but are bulky and prone to leakage. Majority of the actuators are 1-dof and a higher DOF is achieved by cascading two are more actuators in a serial manner.

1.3 Research Purpose

The research carried out has the following goals.

1. Thoroughly study existing actuators.
2. Design a new actuator with better characteristic than the existing actuators. The important characteristics are
    a. High power density
    b. Light weight
    c. Self locking capability i.e. to retain its position when input power is switched off.
    d. Shape should closely resemble a sphere.
    e. 2-DOF motion without cascading 1-dof actuators in serial form.
    f. Large work space.
3. Making model and drawings of the design in PRO E such that the working of the design is completely understandable.
4. Analysis of important parameters of the design by mathematical modeling.

5. Partial fabrication of the design to practically demonstrate the perceived motions of the actuator.

LITERATURE REVIEW

Robots are becoming an important part of the modern society. They are continuously finding new applications. One such application is to have access to highly confined and inaccessible locations where other conventional robots fail. Robots specially designed for such kind of tasks are called snake or snake-arm robots. The actuator of the snake-arm robot plays a very important role in its performance.

Actuators can be broadly classified as conventional and non conventional. Conventional include electromagnetic or simply electric, hydraulic and pneumatic. Non conventional includes Shape Memory Alloys, Electro-Rheological Fluids, Magneto-Active Transducers, Piezoelectric Motors and Electro active Polymers.[1] Following is an overview of some conventional and non conventional actuators.

Professor Howe Choset is a leading researcher in field of snake robots. He has designed a number of actuators for snake robots using electric motors. Actuated universal joint is a 2- DOF actuator made up of two 1-DOF actuators cascaded one after another such that their axis of rotation makes 90^o with each other. See figure 1, 2. Angular swivel joint is a very compact actuator design. The 2 DOF motion is achieved by the combination of two consecutive 1 DOF angular actuators. See figure 3,4. Angular bevel joint design uses bevel gears in an innovative fashion. They are of three sub types i.e. angular bevel (Figure 5), double angular bevel (Figure 6) ,orientation preserving (Figure 7).

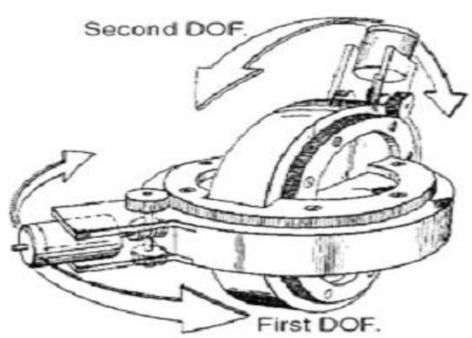


Figure 1, Actuated universal joint [2]

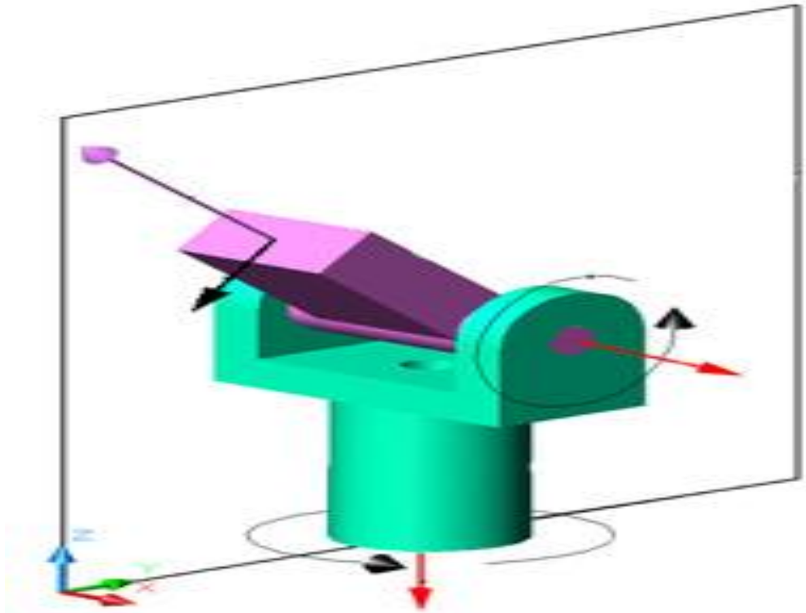


Figure 2, Actuated universal joint [2]

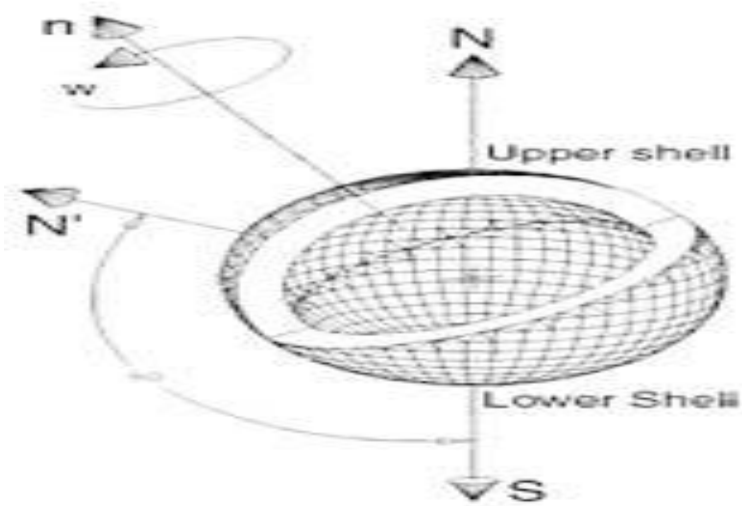


Figure 3, Angular swivel joint [2]

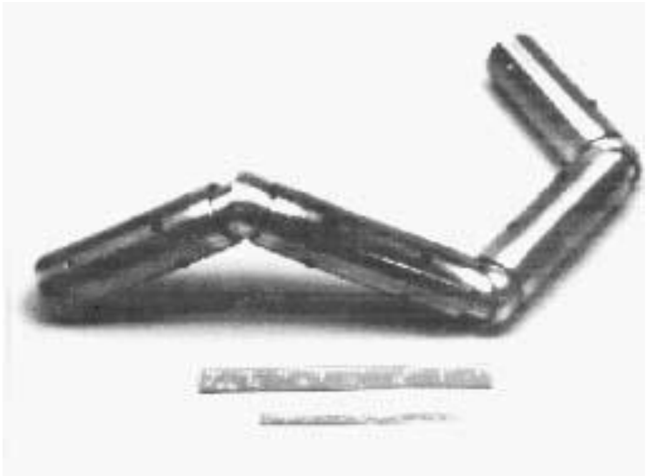


Figure 4, Angular swivel joint [2]

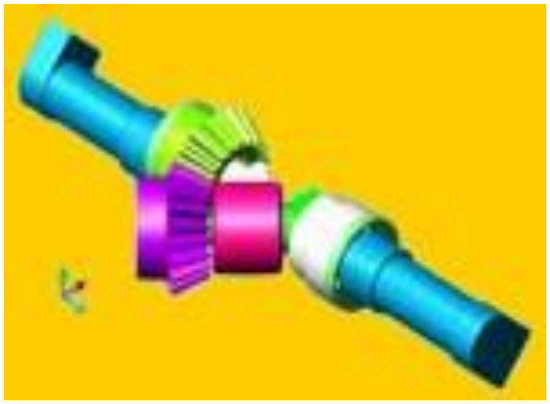


Figure 5, Angular bevel [2]

Figure 6, Double angular bevel [2]

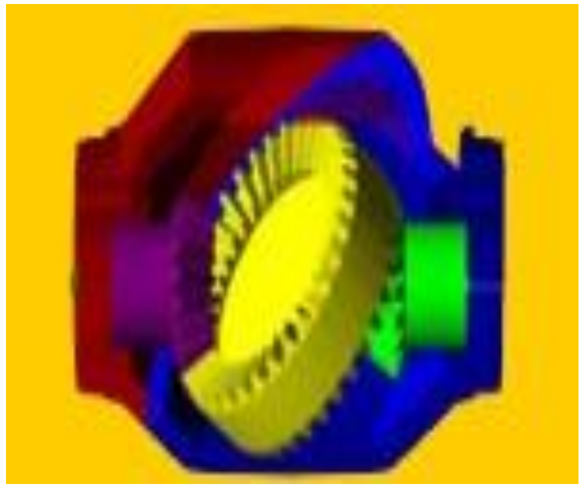


Figure 7 Orientation preserving [2]

US patent 3,288,202 describes a hydraulic actuator called “piston lever rotary actuator”. [3]. this invention provides a new and improved rotary actuator having a high torque in a small, compact and rugged unit. See figure 8.

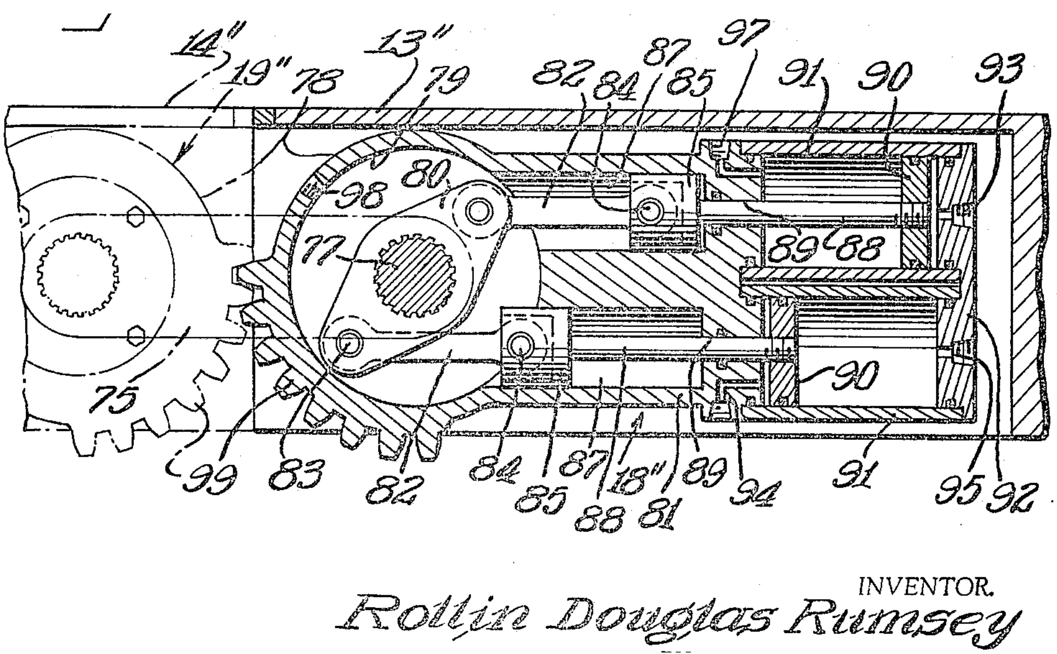


Figure 8, US patent 3,288,202. Piston lever rotary actuator [3]

US patent 2,946,320 describes "Rotary Hydraulic Servo Actuator". [4] . Rotary type hydraulic actuators are susceptible to high wear. This results in leakage problems. Converting linear motion of linear actuator in rotary motion is objectionable due to backlash. The actuator discussed in US patent 2,946,320 effectively overcomes the two problems in a novel way. See figure 9.

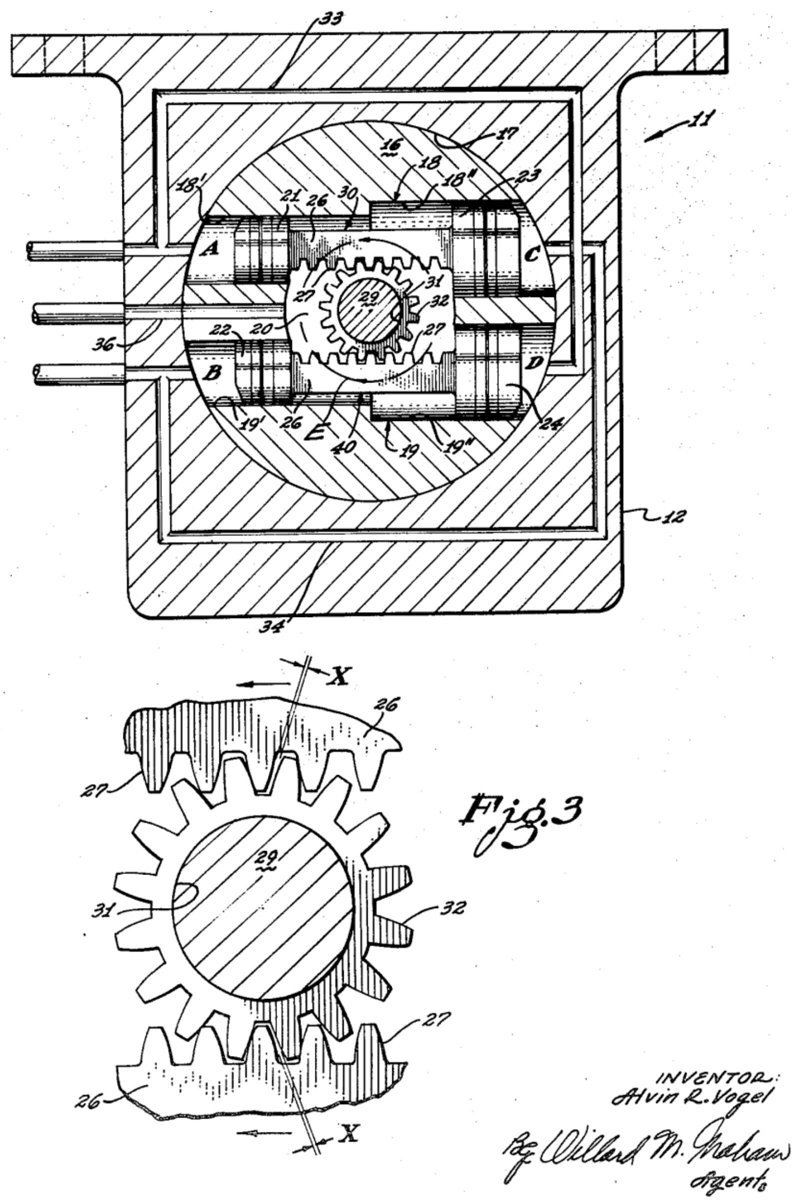


Figure 9, US patent 2, 946, 320, Rotary hydraulic servo actuator [4]

Rotary hydraulic vane actuators are important class of hydraulic actuators.[5] Such actuators are preferred in high performance robots where a high torque is required in a compact volume. Coulomb friction due to seals in such actuators is difficult to model from control point of view. Modeling and control of an industrial hydraulic rotary vane actuator using a piece wise linear model has been done.

An integrated joint actuator for serpentine robots using pneumatics has been developed. [6] Pneumatic actuators are less common but are an important class of conventional actuators. There are three main types of pneumatic actuators i.e Cylinders, bellows and pneumatic muscles. Force in pneumatic cylinders and bellows is developed in a quadratic proportion relative to their diameter. Moreover force decreases linearly relative to their length during expansion. On other hand pneumatic muscle produces a much larger force for same diameter compared to pneumatic cylinder and bellows. But a larger force also requires a larger length. One big disadvantage associated with pneumatic muscle is that force drops much more dramatically during contraction compared with its two counterparts. Therefore pneumatic bellows have been selected for the joint actuator. The design of the joint actuator is space efficient. See figure 10,11 and 12.

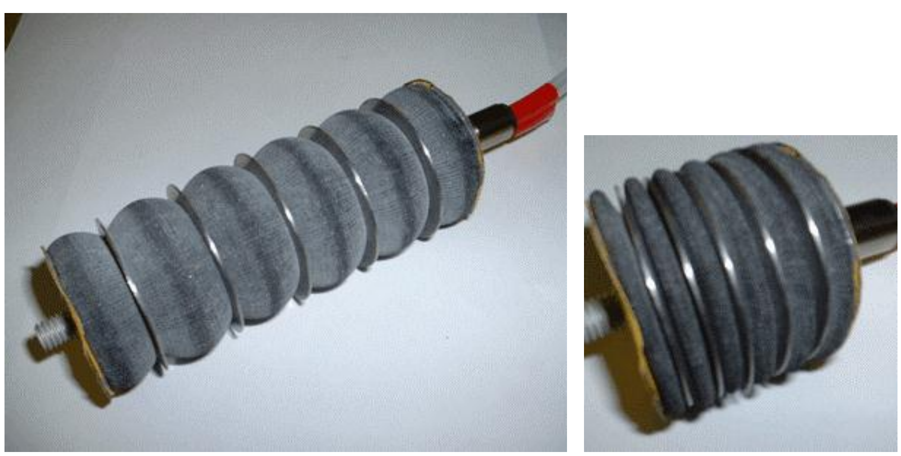


Figure 10, Pneumatic bellows[6]

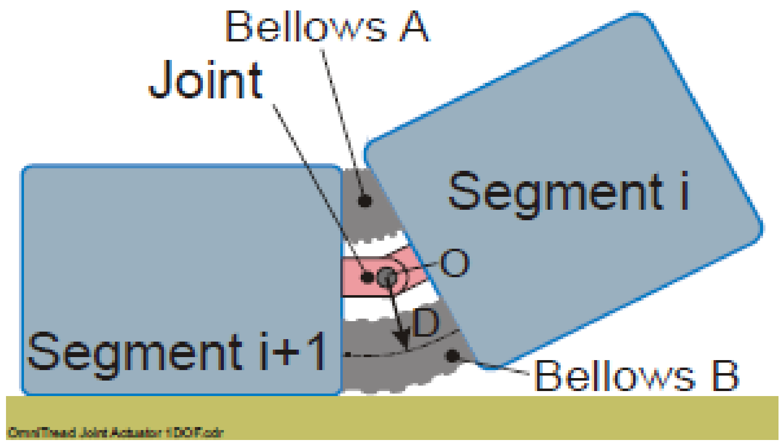


Figure 11, 1-DOF joint using pneumatic bellows [6]

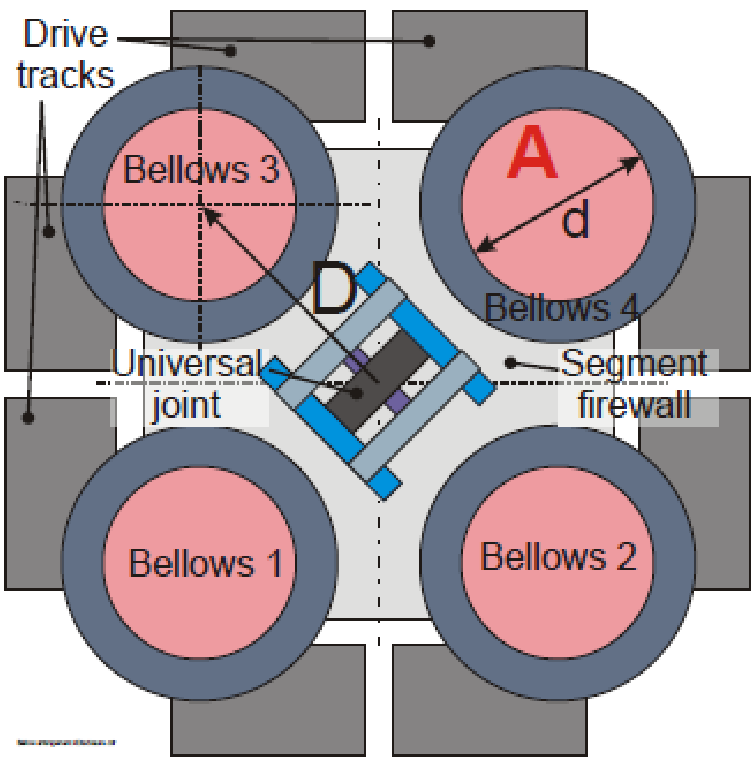


Figure 12, integrated joint actuator using pneumatic bellows [6]

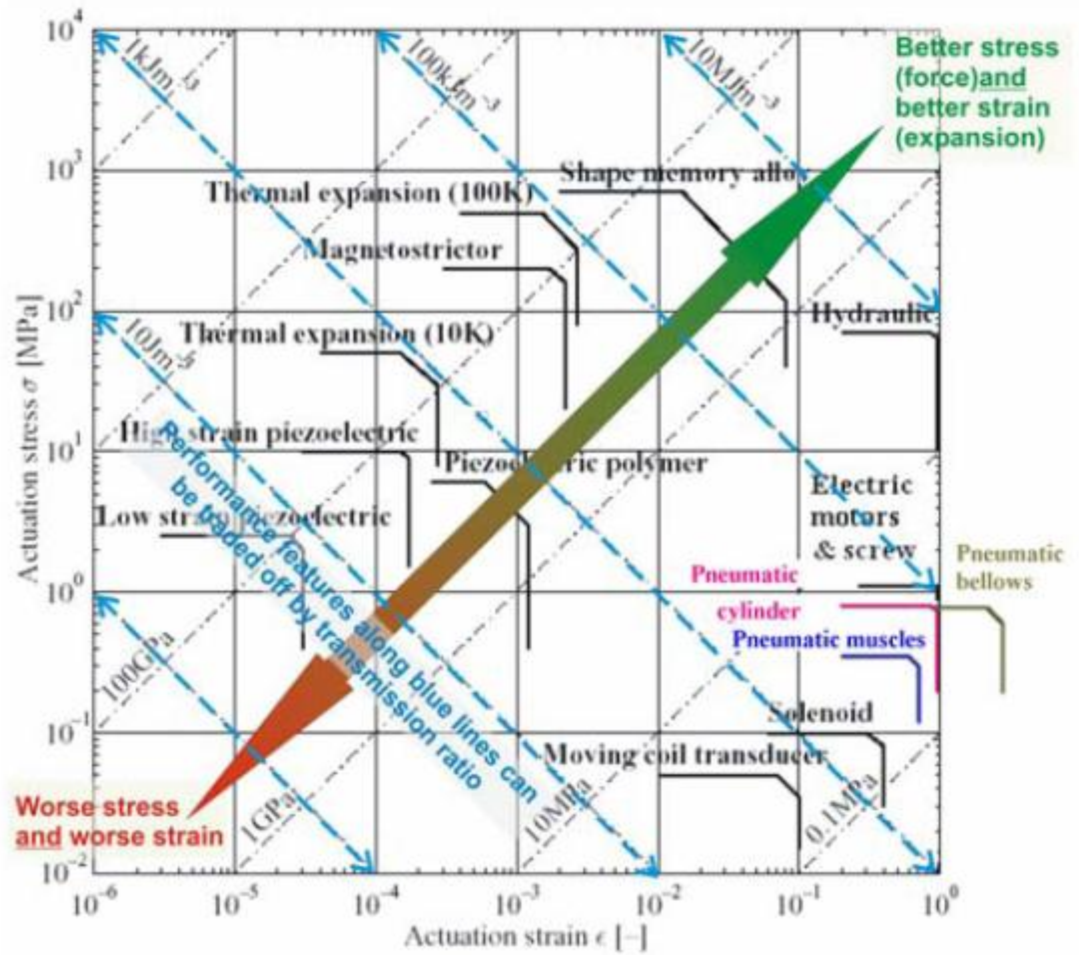


Figure 13, A comparison of different actuators [6]

Drive type performance compared	Electric	Hydraulic	Pneumatic
Efficiency* [%]	(<1) 50-55 (>90)	30-35	15-25
Power to weight ratio [W/kg]	25-150	650	300
Force to cross section area [N/cm2]	0.3-1.5	2000	100
Durability [cycles]	$5\text{-}9{\cdot}10^5$	$6{\cdot}10^6$	$>10^7$
Stiffness [kN/mm]	10-120	30	1
Overload ratio [%]	25	50	50-150
Linear movements ranges [m]	0.3 – 5	0.02 – 2	0.05 – 3
Linear velocity [m/s]	0.001 – 5	0.002 – 2	0.05 – 30
Positioning precision [mm]	0.005	0.1 – 0.05	0.1
Reliability (relative)	Normal	Worse	Better
Maintenance costs (relative)	Normal	Higher	Lower
Unfavorable features	Electric hazard, magnetic disturbances, heating	Leakages, difficulties with energy transmission	Noisy
Favorable features	Easy energy transmission and storage		Safety

Note: The efficiency value in this table already includes a "penalty" for producing pneumatic or hydraulic pressure from a rotary source of mechanical power.

Figure 14, A comparison of electric, hydraulic and pneumatic actuator [6]

A cable driven snake like robot arm (CDSLRA) has been designed. [7] It consists of a flexible back bone at the centre of an equilateral triangle with three cables for actuation at the vertex of the triangle. See figure 15 and 16.

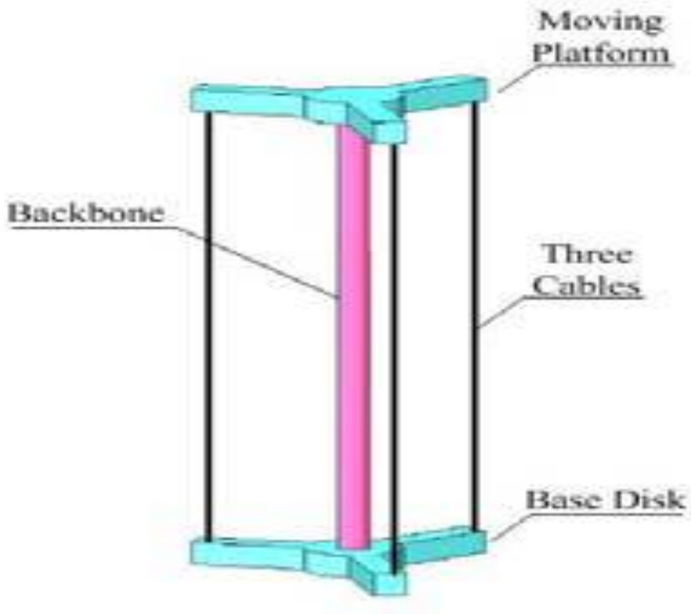


Figure 15, Cable driven snake like robot arm [7]

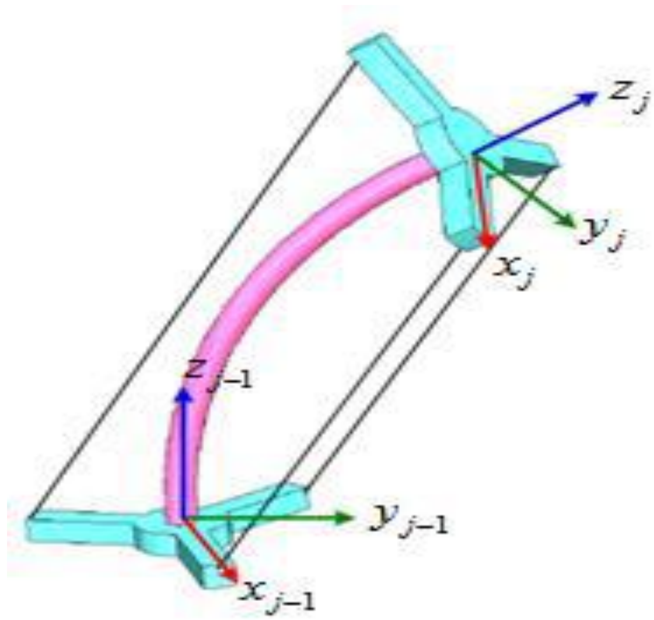


Figure 16, Cable driven snake like robot arm [7]

Shape Memory Alloys consist of a group of metals that have the ability to return to some previous defined shape when some appropriate thermal procedure is applied.[1] Shape memory alloys work on the principal of SME. This effect was discovered by a Swedish physicist Arne Olander. An alloy is plastically deformed when cool and return to its original shape when heated.SME is because of shift in material crystalline structure between two different phases called martensite and austenite. See figure .The main advantages of SMA in robot actuation are reduced size weight and complexity. The main disadvantages are low efficiency of less than 10%, a low band width, small absolute strains and difficulty in controlling of SMA actuators. See figure 17.

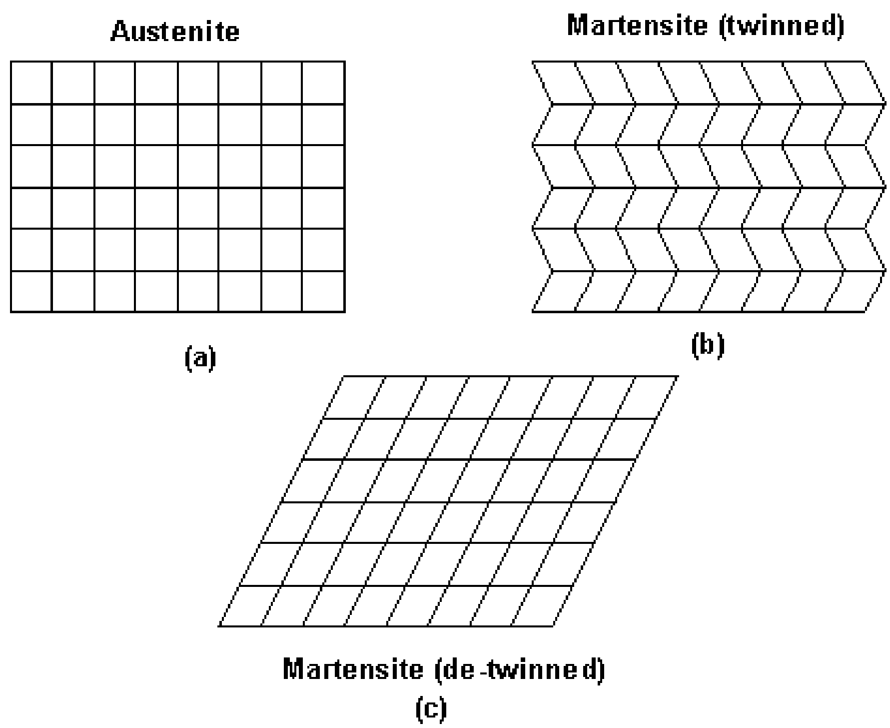


Figure 17, Crystal structure in SMA [1]

A novel in pipe worming robot based on SMA has been presented. [8] It consists of twelve linear SMA actuators and assumes the shape of cuboids. It can easily pass through ‘L’ and ‘T’ shape joints of a pipe. It demonstrates a novel way of solving access related problems. See figure 18 , 19 and 20.

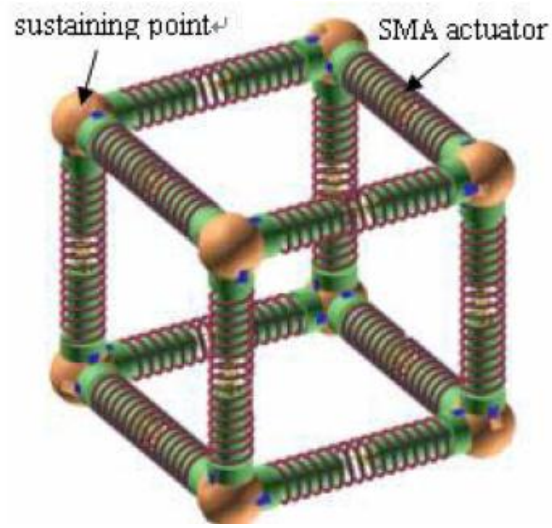


Figure 18, twelve linear SMA actuators making a cuboid [8]

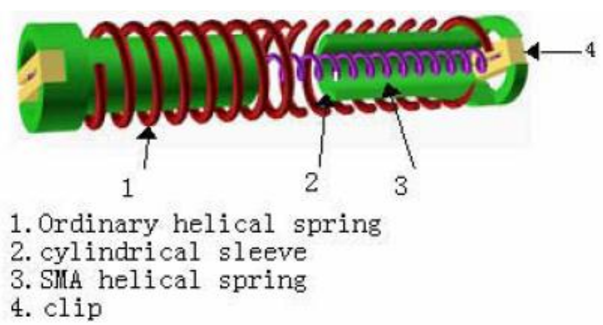


Figure 19, Design of linear SMA actuator [8]

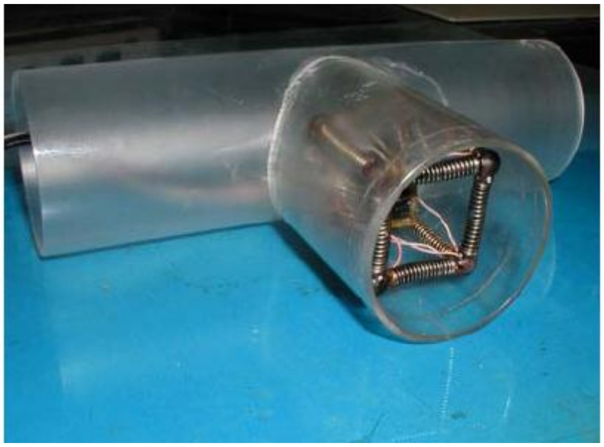


Figure 20, Robot passing through a 'T' pipe [8]

A micro gripper using smart piezoelectric actuator has been designed.[9] Piezoelectric are materials which produce strain in a specific axis when voltage is applied across it. The micro gripper uses two piezoelectric unimorphs which are analogues to a bimetallic strip. See figure 21.

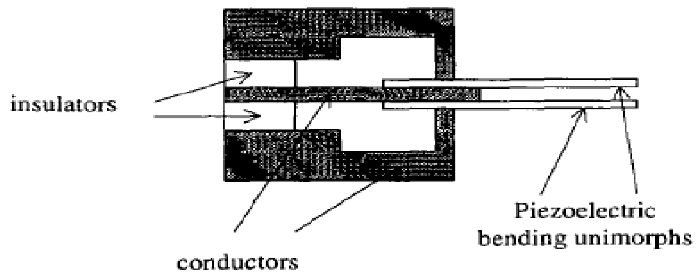


Figure 21 A micro gripper using piezoelectric bending unimorphs as actuators.[9]

Piezoelectric motors and piezoelectric linear actuators are commercially available. But they are only suited for applications requiring very low torque.

Natural muscle has some very attractive properties as an actuator. [10]It has a high energy density, quick response and a large work space. Research is being done to make an artificial muscle that closely resemble natural muscle or even surpass it in the properties of interest. Electrostrictive artificial muscle [EPAM] is one of the attractive output of the research. EPAM has a strain of 30% and pressure of 1.9 MPa. The measured specific energy for EPAM made of polyurethane and silicon is higher for piezoelectric, electromagnetic and electrostatic actuators. The basic design of an EPAM is shown in figure. A comparison of EPAMs made up of different materials is shown in figure. A spherical joint actuator has been designed which uses EPAM roll actuators. See figure 22, 23, 24 and 25.

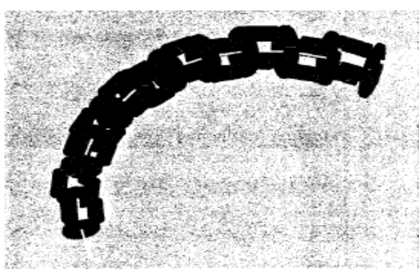


Figure 22, Kinematic Model of Serpentine Manipulator with Linked Spherical Joints [10]

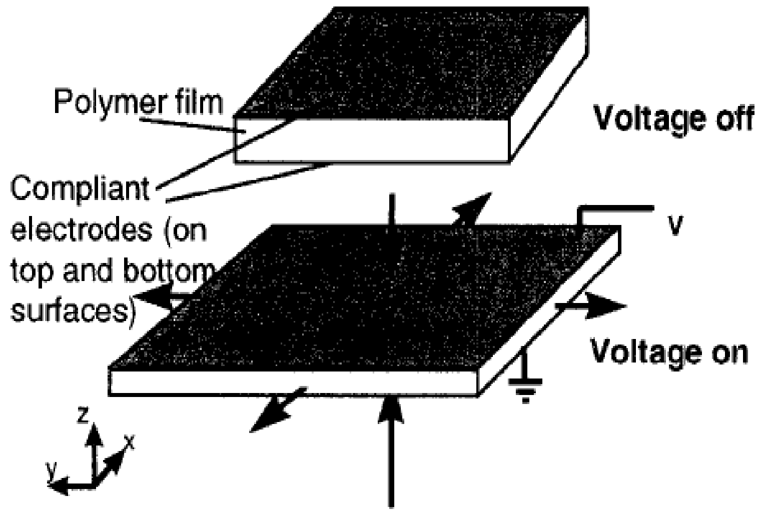


Figure 23 [10], EPAM DESIGN

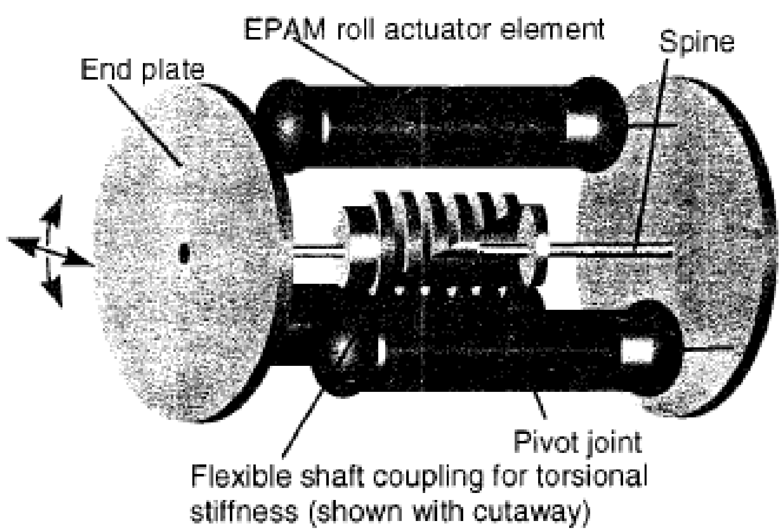


Figure 24, Spherical Joint Actuator for a Serpentine Manipulator [10]

Actuator Type (specific example)	Max Strain (%)	Max Pres-sure (MPa)	Max Energy Density (J/cm^3)	Max Efficiency (%)	Specific Density	Relative Speed (full cycle)
Electrostrictive Polymer Artificial Muscle[1]						
Silicone	32	0.21	0.034	90	1	Fast
Polyurethane	11	1.9	0.10	80	1	Fast
Electrostatic Devices (Integrated Force Array[2])	50	0.03	0.0015	>90	1	Fast
Electromagnetic (Voice Coil[3])	50	0.10	0.025	>90	8	Fast
Piezoelectric						
Ceramic PZT[4])	0.2	110	0.10	>90	7.7	Fast
Polymer(PVDF[5])	0.1	4.8	0.0024	90	1.8	Fast
Shape Memory Alloy (TiNi[6])	>5	>200	>5	<10	6.5	Slow
Shape Memory Polymer (Polyurethane[7])	100	4	2	<10	1	Slow
Thermal (Expansion[8])	1	78	0.4	<10	2.7	Slow
Electrochemo-mechanical Conducting Polymer (Polyaniline[9])	10	450	23	<1%	~1	Slow
Mechano-chemical Polymer/Gels (poly-electrolyte[10])	>40	0.3	0.06	30	~1	Slow
Magnetostrictive (Terfenol-D, Etrema Products[11])	0.2	70	0.025	60	9	Fast
Natural Muscle (Human Skeletal[12])	>40	0.35	0.07	>35	1	Med

1. Source: Pelrine, Kornbluh, and Joseph [1998].
2. Source: MCNC web site:
http://www.mcnc.org/HTML/ETD/EMAD/ifa/ifa.html
3. These values are based on an array of 0.01 m thick voice coils, 50% conductor, 50% permanent magnet, 1 T magnetic field, resistivity of 2 ohm-cm, and 40,000 W/m^2 power dissipation.
4. PZT B, at maximum electric field of 4 V/µm, using data from Moulson and Herbet [1990], p. 293.
5. PVDF, at maximum electric field of 30 V/µm. Source: AMP literature, AMP Inc. Valley Forge, Pennsylvania, USA
6. Source: Hunter et al. [1991].
7. Source: Tobushi, Hayashi, and Kojima [1992].
8. Aluminum, using a temperature change of 500°C.
9. Source: Baughman et al. [1990].
10. Source: Hunter and Lafontaine [1992].
11. Source: Edge Technologies literature, Edge Technologies, Ames Iowa, USA
12. Source: Hunter and Lafontaine. [1992.

Figure 25, Comparison of actuator technologies [10]

mechanical design

After detailed literature review it is concluded that newly developed technologies like SMA, piezoelectric, elastomers etc are not mature enough to be of practical importance for applications which require high torque and power density in a tight volume. Of the remaining options hydraulic actuators remains to be the most attractive choice.

1.4 CONCEPT AND MOTIVATION OF DESIGN.

1.4.1 Three DOF Omni wheel robot

A three DOF Omni wheel robot has three wheels placed at the vertex of a equilateral triangle. Such a robot exhibit XY planar motion and rotation about Z axis. See figure 26.

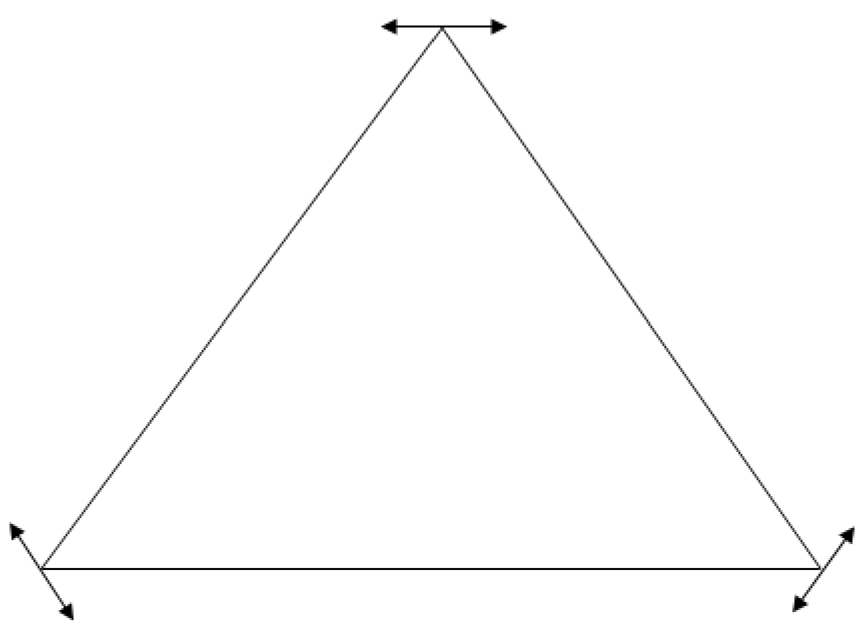


Figure 26, 3 DOF Omni wheel robots

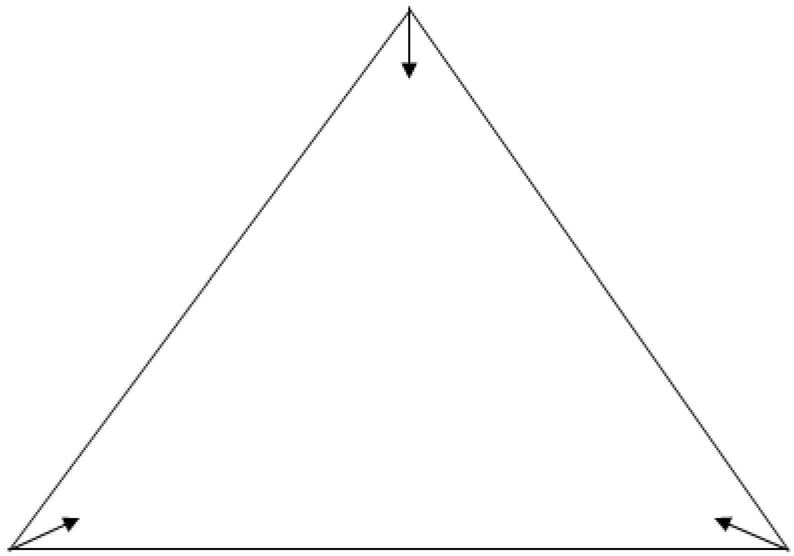


Figure 27, 2 DOF Omni wheel robots

1.4.2 Two DOF Omni wheel robot

A two DOF Omni wheel robot has three wheels placed at the vertex of a equilateral triangle. Such a robot exhibit XY planar motion only. The main concept of the actuator has been derived from this kind of Omni wheel robot. i.e We can achieve 2 DOF actuator by placing 1 DOF actuator at 120 ^{o} to each other. See figure 27.

1.4.3 Sphere joint.

A sphere joint is a unique joint having three DOF. See figure 28. If we restrict the motion of the sphere joint about z-axis it becomes an ideal snake robot joint having two DOF with axis of rotation of each DOF lying in the same plane. See figure 28.

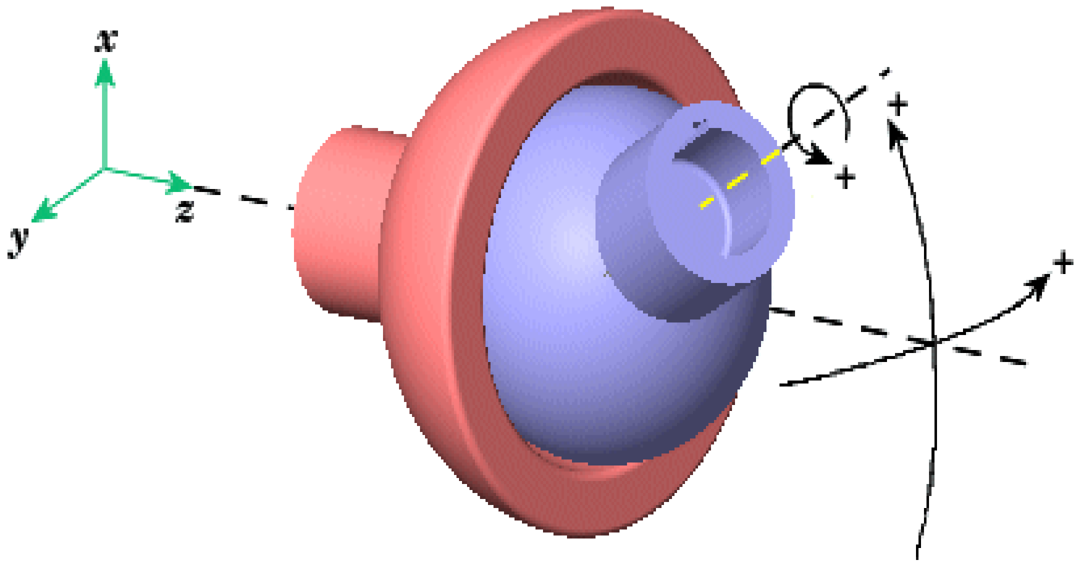


Figure 28, Spherical joint

1.4.4 Challenging part of design

The most challenging part of the design was to merge concept 2 and 3 in a single and highly compact module

1.5 BASIC DESIGN

A novel two DOF hydraulically actuated spherical shaped actuator is designed. It consists of following parts.

1.5.1 The sphere

This is the most important part of the actuator. It is a perfect sphere analogue to the ball of a spherical joint. It has three grooves cut at 120^o. Each grove has a depth ‘D’ and width ‘W’. The grove is a circular arc. The outer radius of the circular arc is equal to the radius of the sphere and inner radius is equal to radius of sphere - depth of grove. The plane in which the arc lies passes through the centre of the sphere. The depth and width of the grove decides the maximum arc length of the grove. See figure 29.

Following properties are worth noticing.

$$Area\ of\ grove = \ width\ of\ grove\ x\ depth\ of\ grove$$

$Ag\ = WxD$ (Approximately)

And

$$Torque\ of\ actuator\ \propto\ Ag$$

$$Joint\ space\ of\ actuator \propto\ Arc\ length\ of\ grove$$

$$Arc\ length\ of\ grove \propto 1/Ag$$

$$Js \propto 1/Ag$$

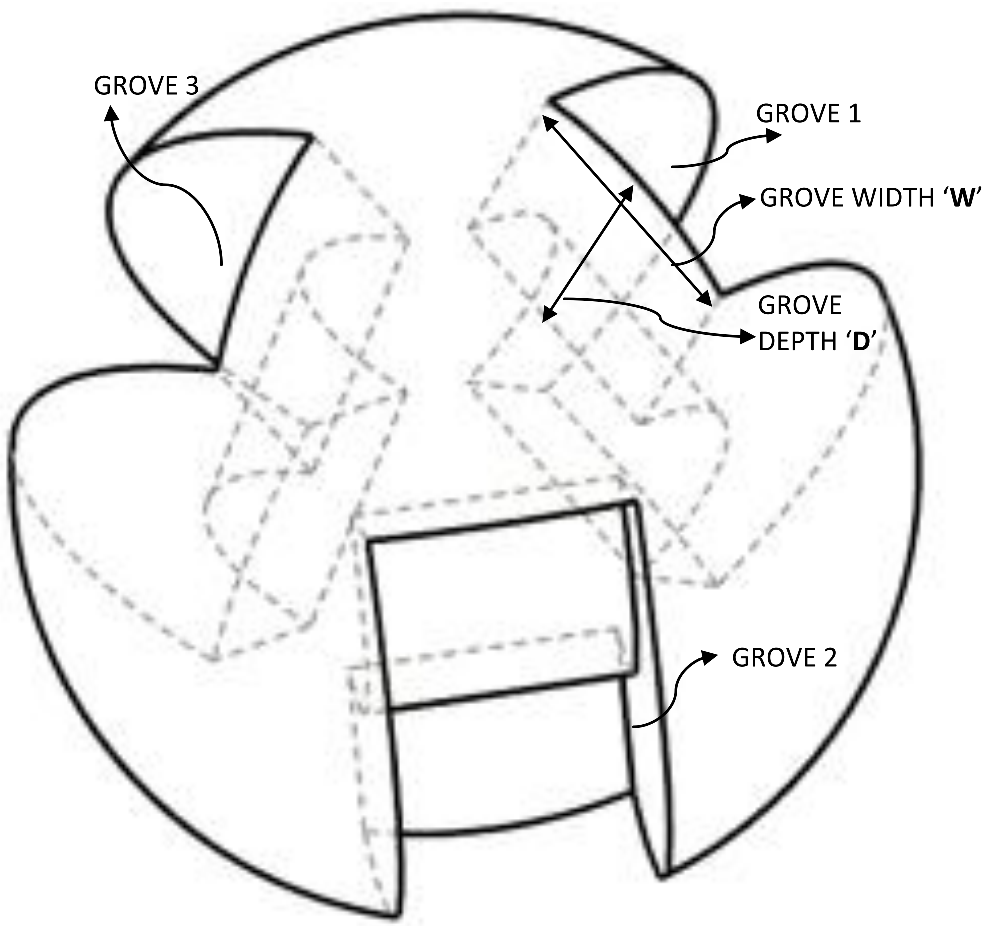


Figure 29, sphere with three grooves embedded at 120°

1.5.2 The cup

It is a hollow semi sphere. The inner radius of the hollow sphere of which it is made is equal to the radius of the sphere. This ensures that the cup fits the sphere air tight and perfectly. This further ensures that when the cup is fitted to the sphere, the centre of the sphere and the centre of the hollow sphere of which the cup is a part coincides with each other. In such an arrangement the cup can exhibit a three DOF motion about the centre of the sphere and is analogues to a spherical joint.

The cup has one hole and two slots. The lines passing through the centre of the slots and the hole lie in a plane which cuts into two equal parts, the hollow sphere of which the cup is made of. The hole and the slots are at 120 ^{o} to each other. The hole restricts the third DOF of the spherical joint. I.e. it resists rotation about z axis. The two slots accommodate the variable distance between the grooves. If the slots are replaced with holes, the mechanism will get jammed. See figure 30.

Figure 30, The cup

1.5.3 The piston & pin

The piston is resembles a small cube. The piston fits perfectly in the grove of the sphere and is capable to move in it. The motion exhibited by the piston in the grove is circular with axis of rotation passing through the centre of the sphere. The inner (smaller) portion of the piston has a circular shape with radius of curvature equal to radius of sphere-depth of grove. The outer (larger) portion has a spherical shape. The outer surface of the piston equals to a piece of outer surface of the sphere about which the cup rotates. See figure 31and 32.

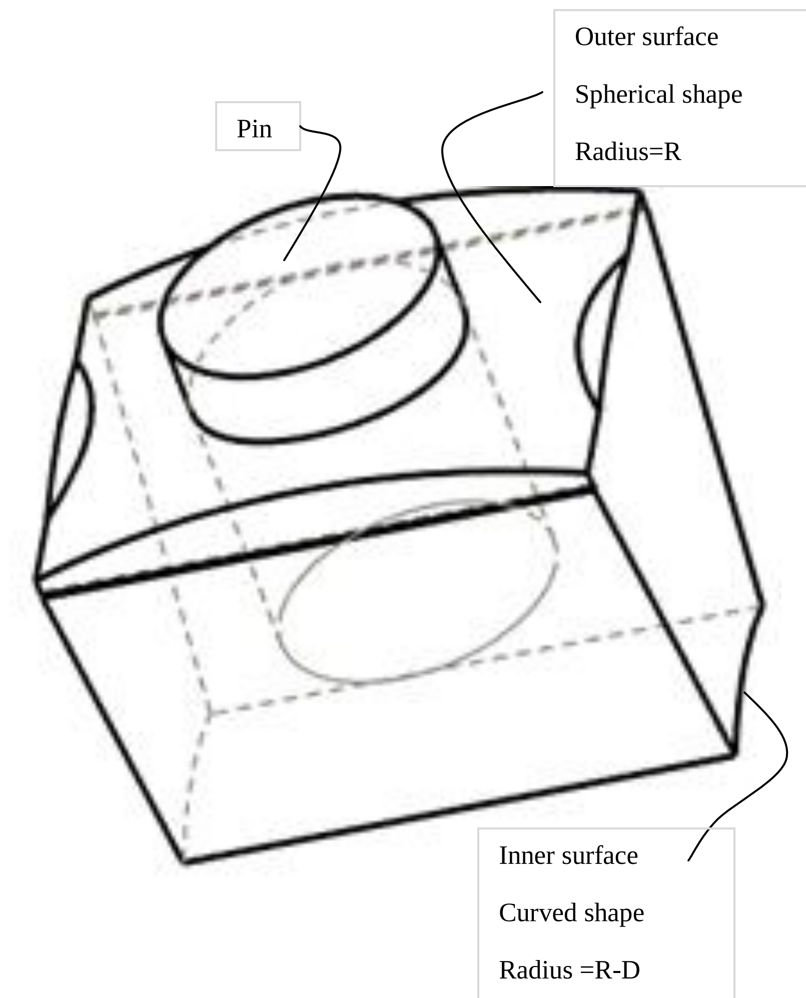


Figure 31, The piston and pin assembly

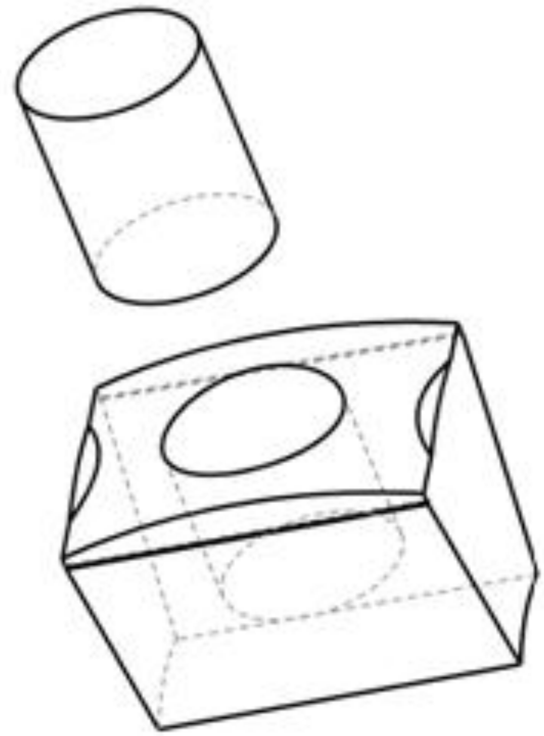


Figure 32, the piston and pin assembly

1.5.4 Assembling the parts

The actuator under consideration consists of mainly four parts. See figure xyz for reference. They are the sphere, pistons, the cup and the pins. They are represented by a, b, c and d. this alphabetical order represents the sequence in which the parts will be assembled. Moreover different parts of the sphere, the cup, the piston and the pins which closely related to each other have been given same numerical number. See figure 33.

The sequence of assembling of parts is following.

a. The pistons 2b, 3b and 4b are fitted to the groves 2a, 3a and 4a respectively.
b. Then the cup 1c is fitted to the sphere 1a.
c. At last the pins 2d, 3d and 4d are fitted.
d. The resultant assembly is shown in figure 34 and 35.

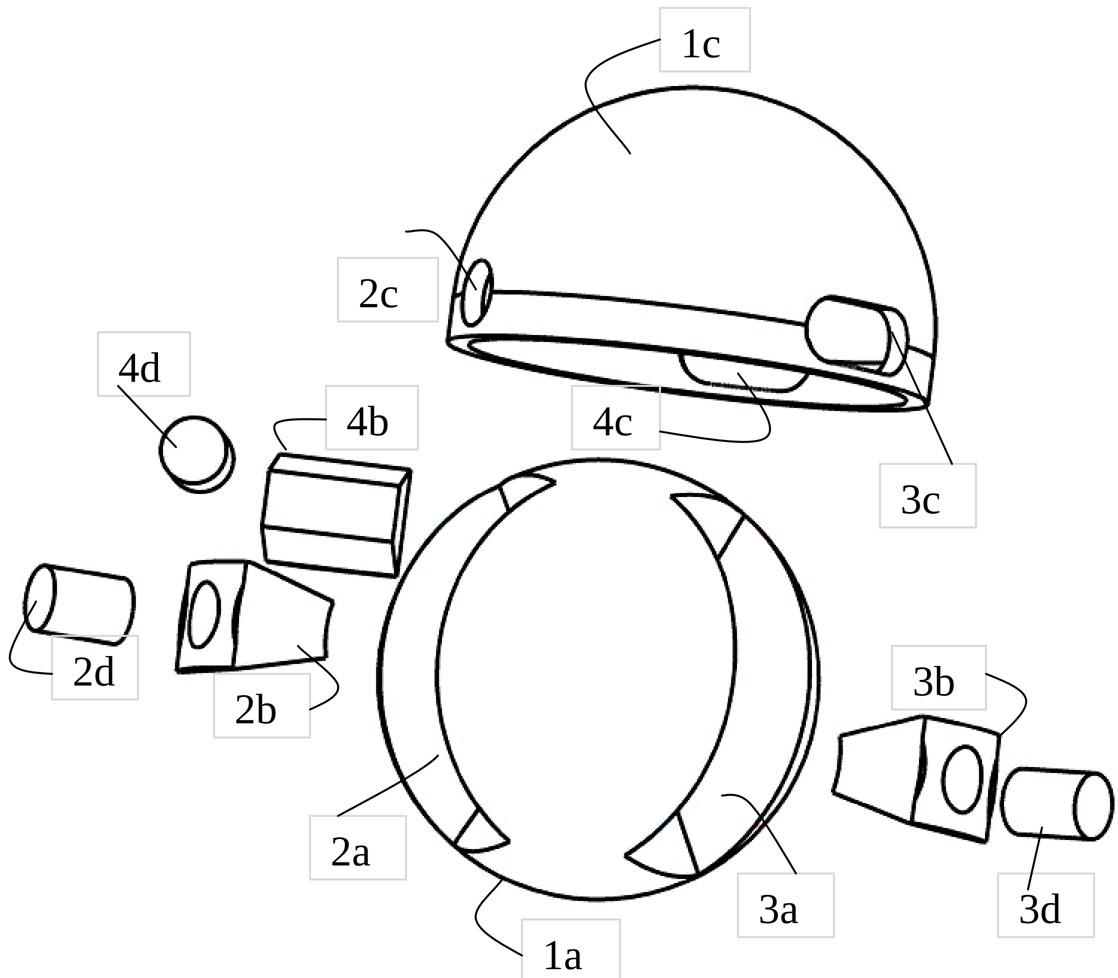


Figure 33, Exploded view of actuator assembly

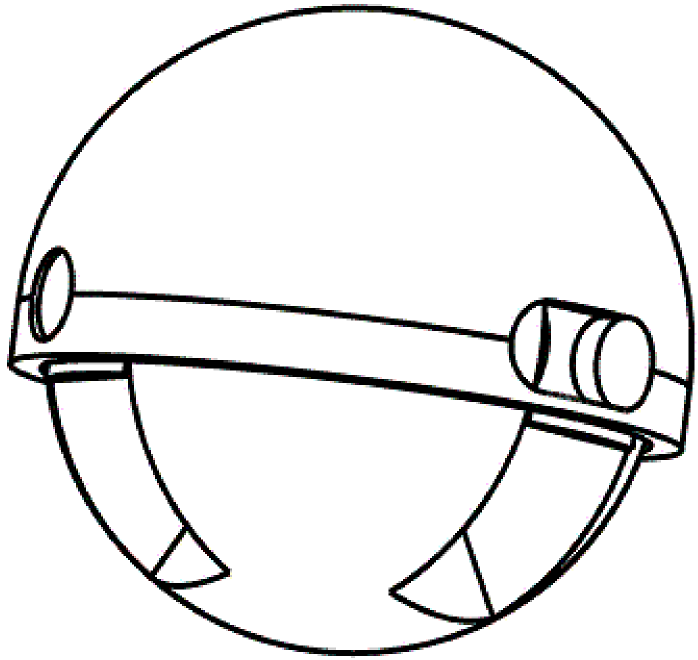


Figure 34, Isometric view of assembly

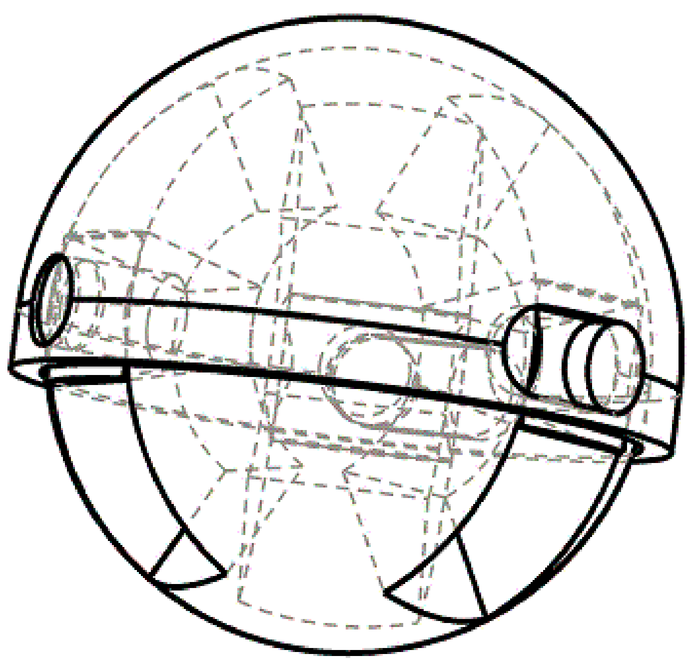


Figure 35, Isometric view of assembly with hidden lines

1.6 FLUID INJECTION MECHANISM

This actuator is hydraulically actuated. Therefore a good fluid injection mechanism is critical for its operation. A good fluid injection mechanism should have the following properties.

1. It should be simple
2. It should be reliable
3. It should not be effected by the motion of the actuator
4. Nor should it affect the motion of the actuator.
5. It should not affect the maneuverability of the actuator in tight space.

After recursive thinking the following design was achieved. See figure 36, 37 and 38. As per this design it is suggested that the fluid be routed to the grove through the pin and piston. This design provides the following advantages.

1. **Ease of connection to external hydraulic source.**

   Hydraulic pressure is mainly transmitted through pipes which are circular in shape. Only circular shape pipe can maintain its shape under high pressure. The pin is analogues to a circular pipe. Hence a circular hydraulic pressure pipe can be easily connected to the external tip of the pin.

2. **Ease of precise manufacturing**

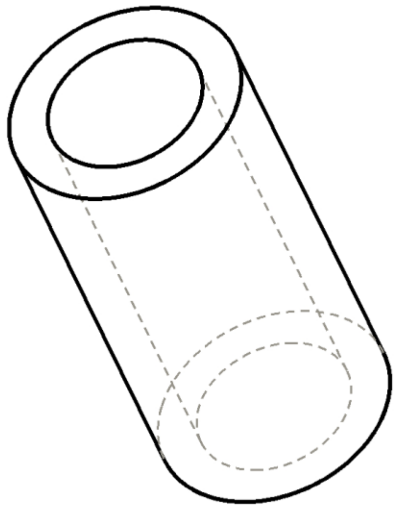
   The pin is circular in shape and can be made on a lathe machine with great ease and high accuracy. Similarly the passage in the piston can be easily made by using drill machine or preferably milling machine.

3. **Minimum possibility of leakage from pin and piston meshing area.**

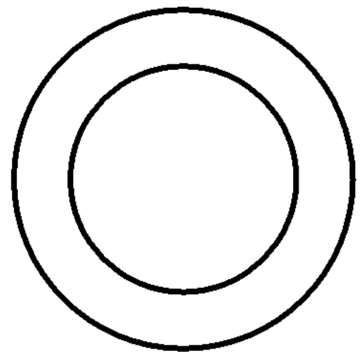
   Since pin and piston can be made easily and precisely. This results in minimized leakage possibility. In addition to it the circular design of pin allows us to tightly fit it into the hole of the piston. The contact surface between the pin and the piston is enough to cater for any possibility of leakage.

4. **Minimum hindrance to motion of the actuator**.

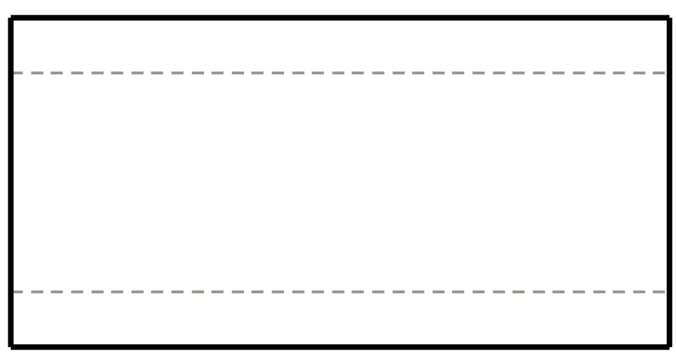
   The connecting pipes connecting the pins with the hydraulic source lie totally outside the workspace of all the moving parts of the actuator. Therefore the only hindrance from the pipes is because of its rigidity. Higher the flexibility of the connecting pipes lesser the hindrance to the motion of the actuator.



Isometric view



Top view



Side view

Figure 36, pin hollowed for fluid injection

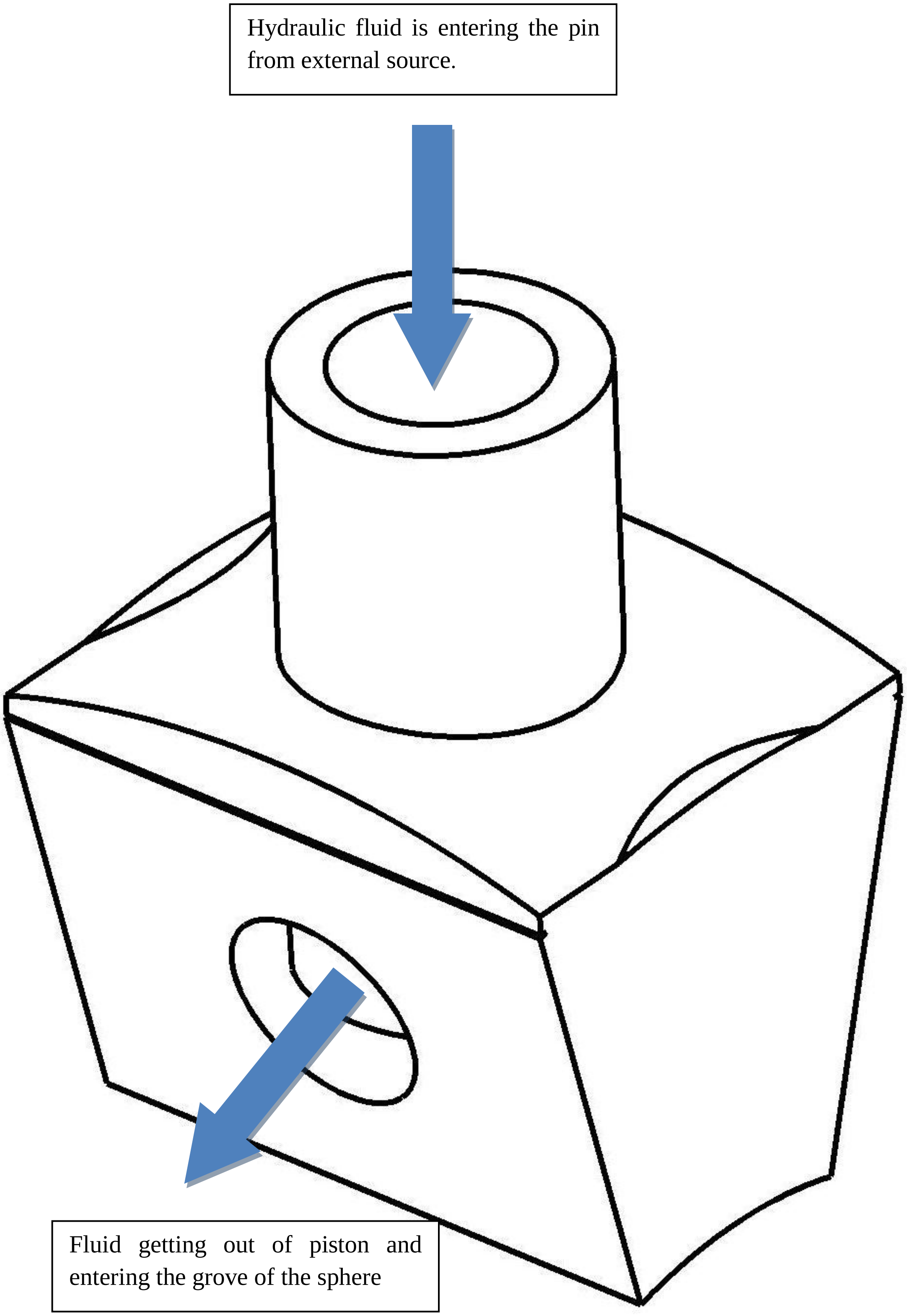


Figure 37, demonstrating fluid injection mechanism

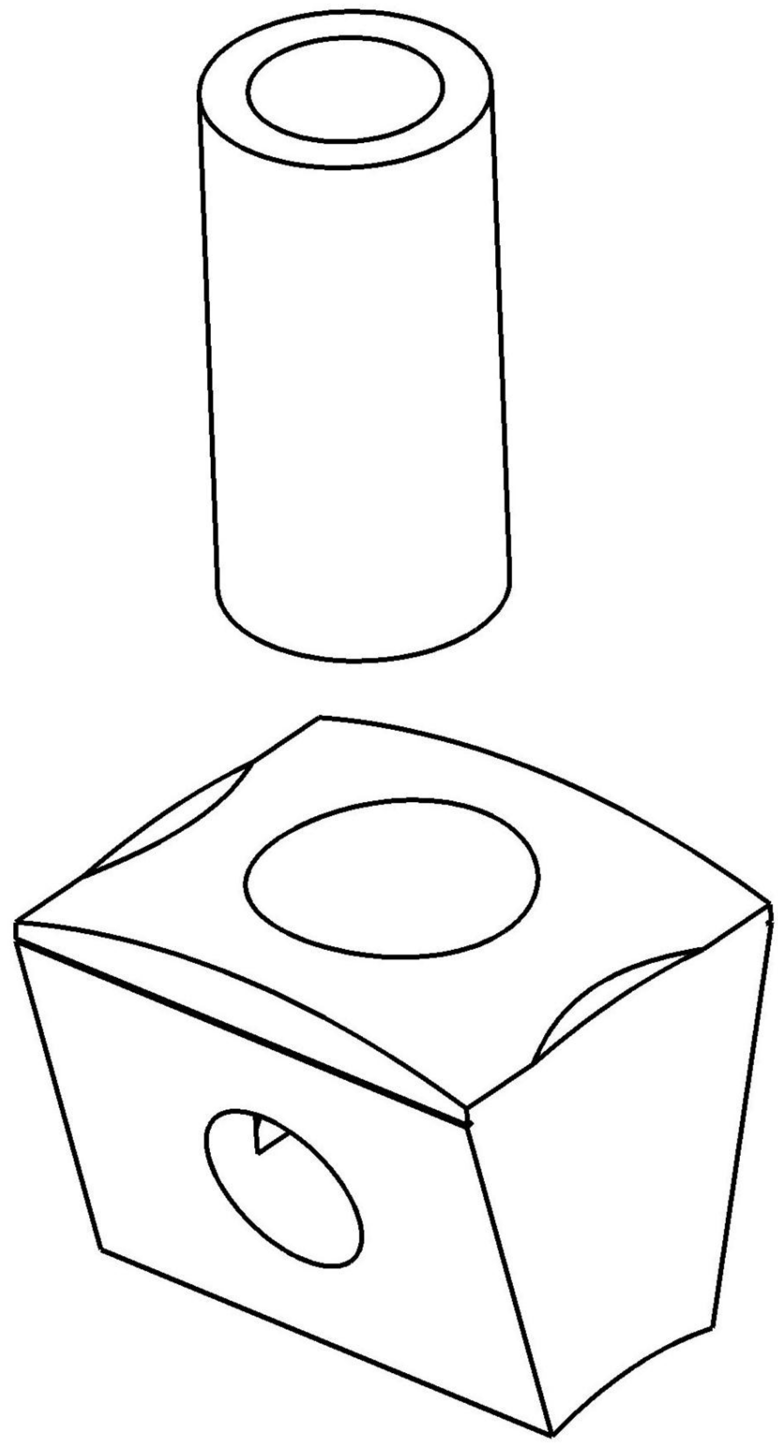


Figure 38, exploded view of fluid injection mechanism

1.7 SEALINGS

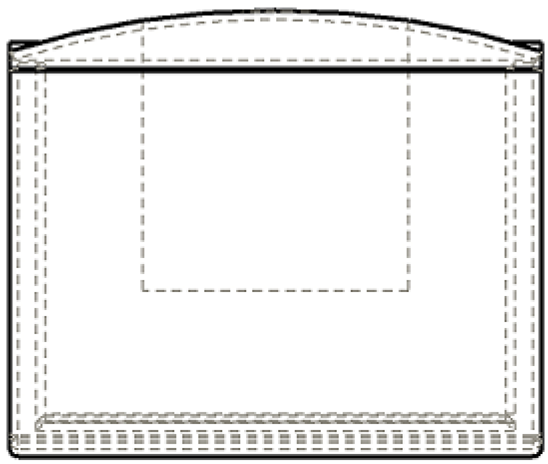
Leakage and contamination is a main problem in a hydraulic system. Leakage control is critically important for a hydraulic system in order to function properly. In a hydraulic system leakage is depends on following factors.

1. Directly proportional to operating pressure.
2. Improper machining leaving spaces between the moving parts.
3. Line contact between moving parts.
4. Metal-metal contact between moving parts.
5. Low viscosity of the operating fluid increase chances of leakage.

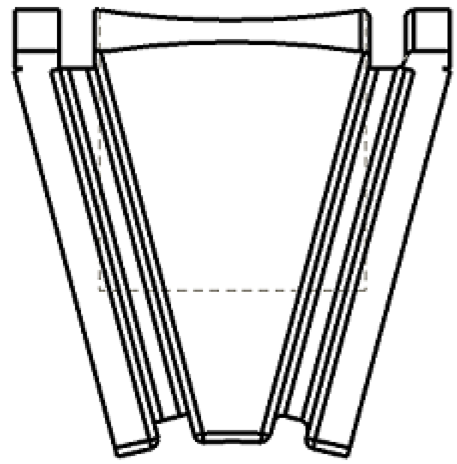
Following is a solution to control leakage in a hydraulic system with reference to abve mentioned factors.

1. Operating pressure cannot be decreased as it will directly affect working capability of the actuator.
2. Fine machining of areas where leakage may occur will reduce leakage issues.
3. Surface /area contact should be preferred between moving parts at locations where leakage may occur. At such areas line contact should be avoided.
4. Metal-Teflon or metal-rubber contacts should be preferred.
5. Viscosity of the fluid should not be increased as it will increase energy losses of the actuator.

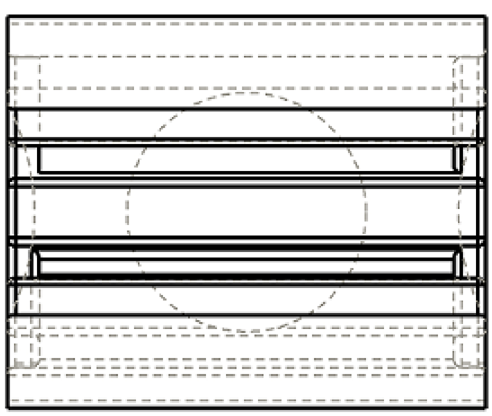
In actuator under consideration, a grove has been made in piston and along the border of the grooves of the sphere. A rubber ring will be placed in the grove. This will provide optimum sealing to the actuator. Figure 39, 40, 41, 42 and 43 illustrate the modifications done for sealing in detail.



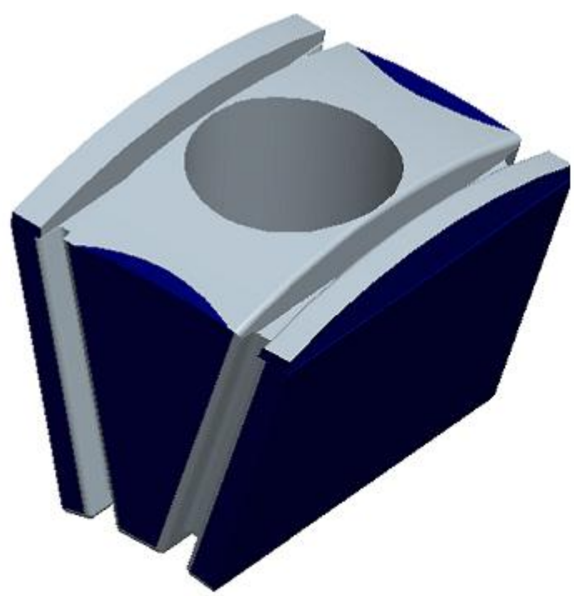
Front view



Side view



Top view



Isometric view

Figure 39, Different views of piston having groove for sealing

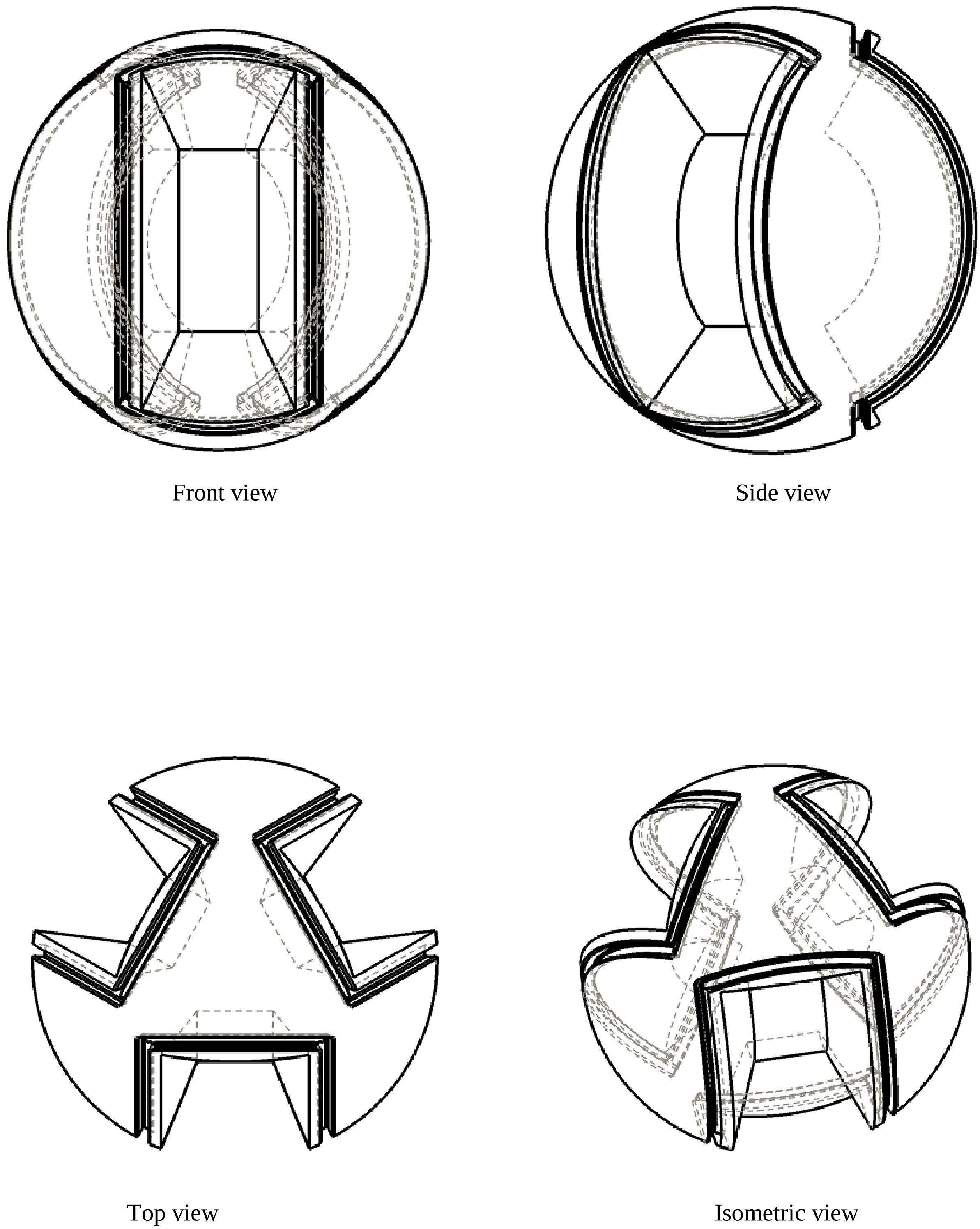
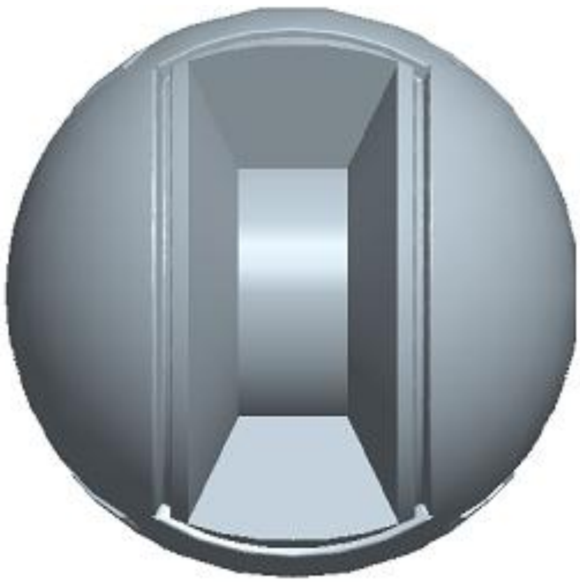
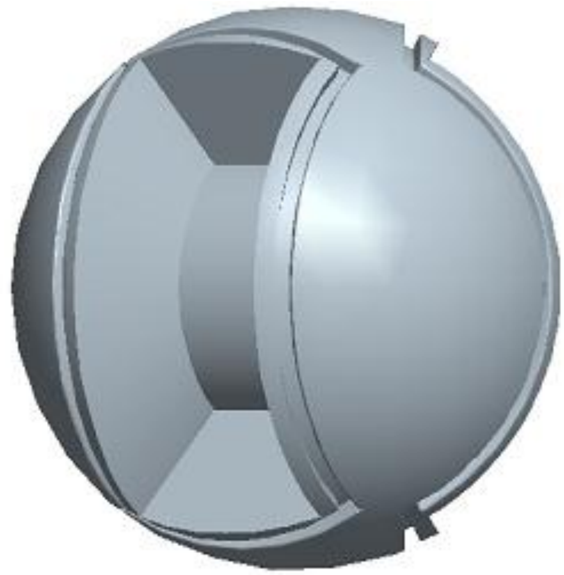


Figure 40 ,Different views of sphere having grooves for rubber sealing

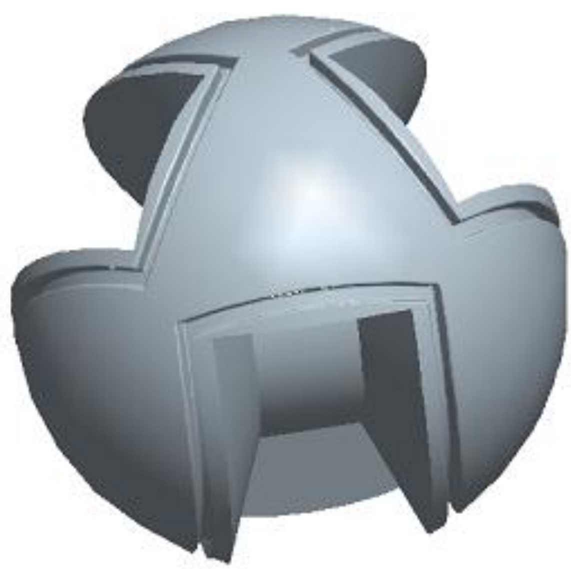


Front view



Side view

Top view



Isometric view

Figure 41, Different views of sphere having grooves for rubber sealing

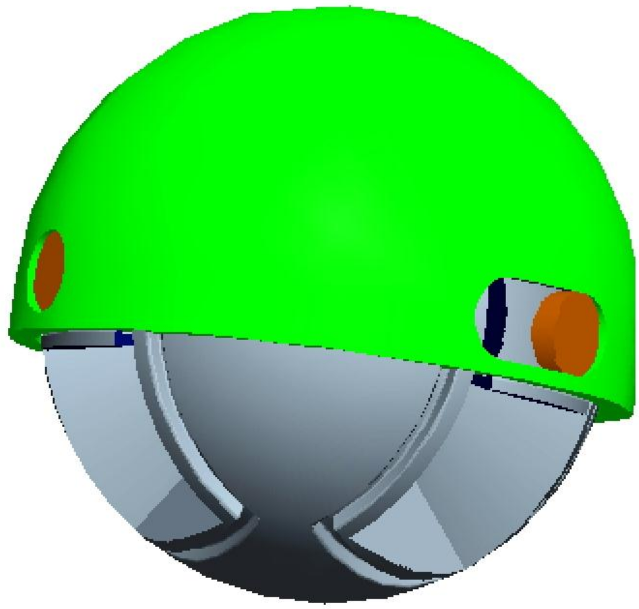


Figure 42, Assembly of the actuator having grooves for rubber sealing

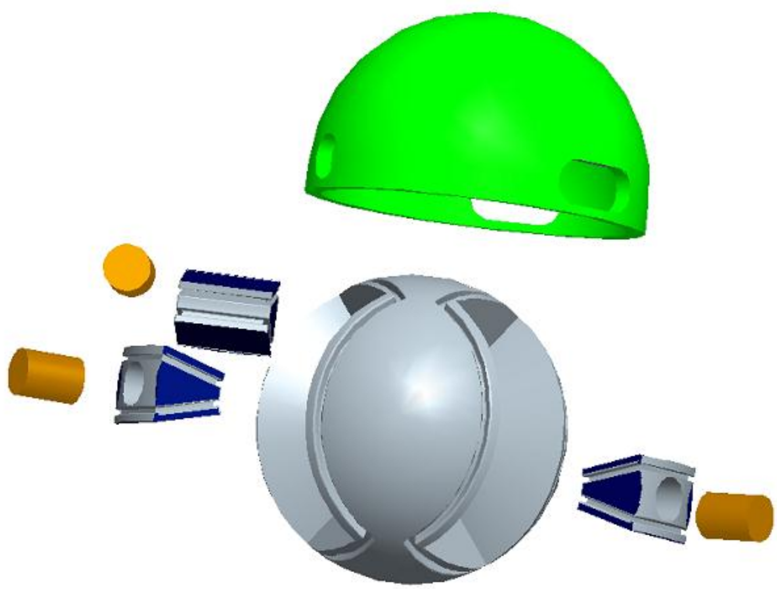


Figure 43, Exploded view of assembly of the actuator having grooves for rubber sealing

ANALYSIS

In order to understand the function and characteristic of the actuator system it is important to perform different types of analysis. A reference coordinate system is established. Important parameters for analysis have been identified with respect to the reference coordinate system. Important relations between these parameters have been identified.

1.8 REFERENCE COORDINATE SYSTEM.

The actuator system consists of parts that exhibit motion which is two dimensional in space. But the motion exhibited by these parts lie in different planes. There if the motion of all these parts is to be shown in a single coordinate system then it should be three dimensional in space. Moreover the motion exhibited by these parts is curved. Therefore spherical coordinate system is the most suitable coordinate system for the actuator system. See figure 44 , 45 and 53.

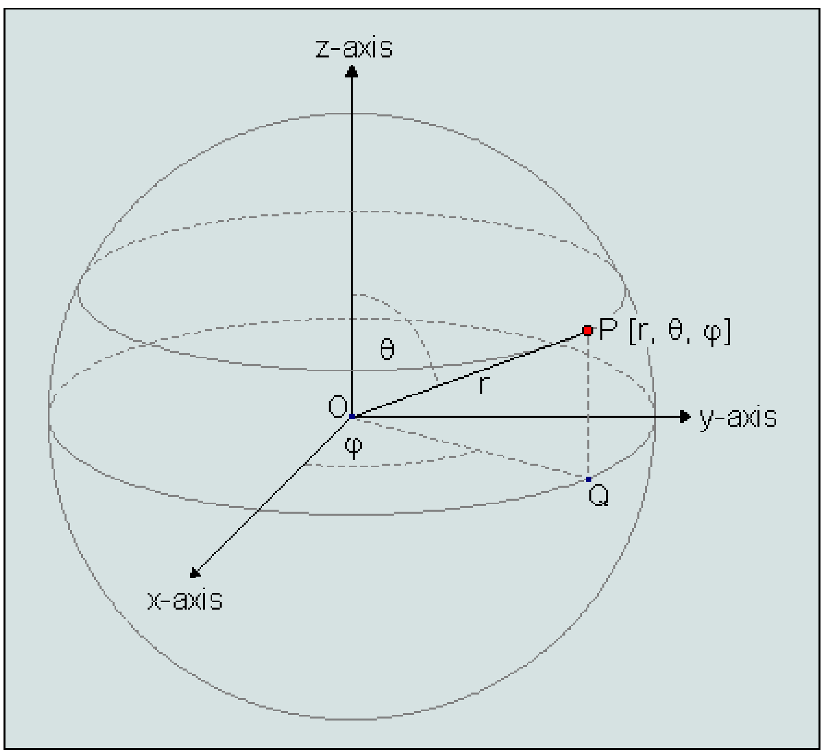


Figure 44, Spherical coordinate system

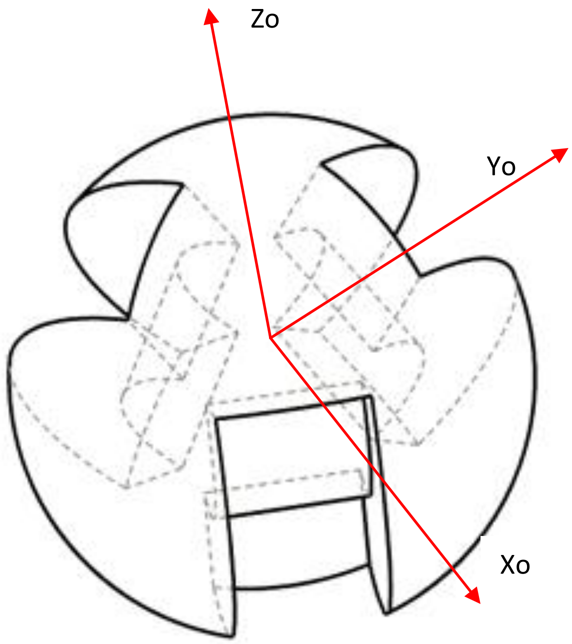


Figure 45, Reference coordinate system

1.9 IDENTIFICATION OF IMPORTANT PARAMETERS FOR ANALYSIS

1. **Radius of sphere**

   It is the distance from the centre of the sphere to the furthest points on the surface of the sphere. It is denoted by 'R'. See figure 48.

2. **Width and depth of grove.**

   The width of grove is represented by W and its depth is represented by D. see figure 47.

3. **Angle of grove**

   It is the angle made by the grove with the centre of the sphere. It is denoted by θ_{G1}, θ_{G2}, θ_{G3} respectively for the three groves. See figure 49.

4. **Reference plane.**

   The plane XoYo is the reference plane. This plane bisects θ_{G1}, θ_{G2}, θ_{G3}. It is denoted by PL_R.

5. **Cup plane**

Consider three lines L1,L2,L3. They are perpendicular to the surface of the cup and passes through the centroid of the three holes of the cup. Cup plane is the plane formed by L1, L2, and L3. It is denoted by $PL_{C.}$ See figure 46.

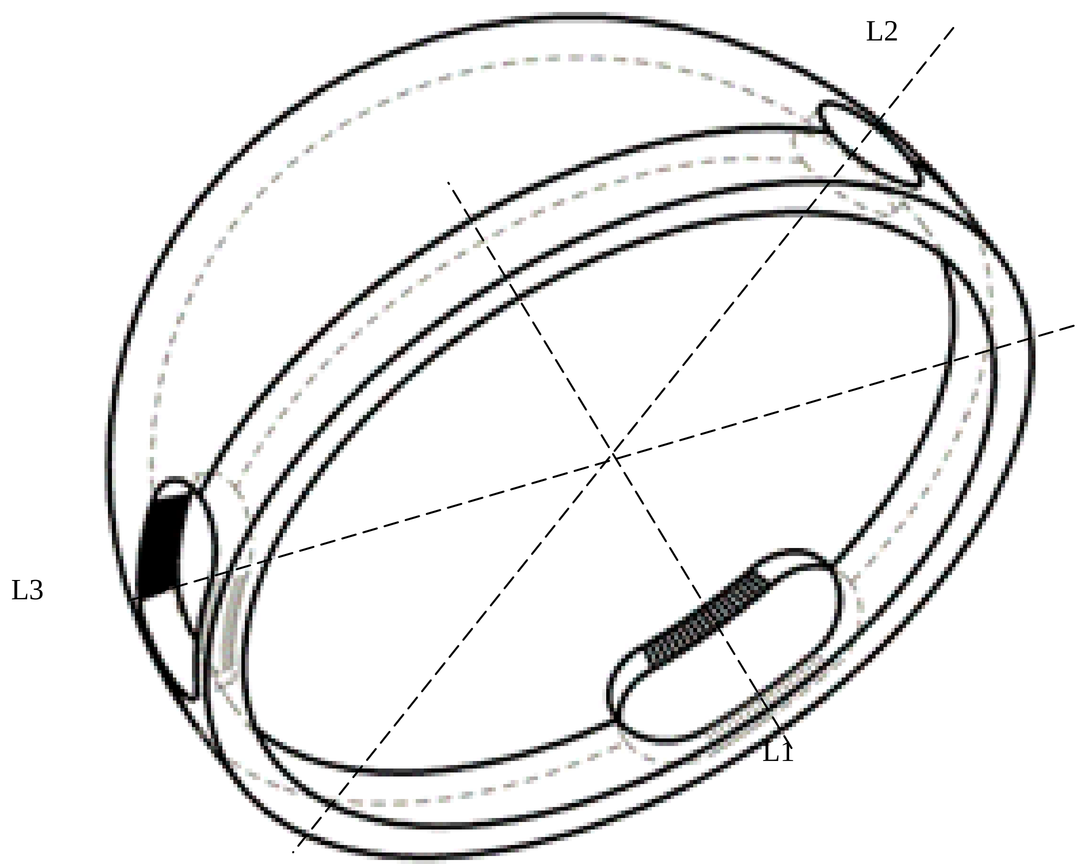


Figure 46, Figure 46, Cup plane defined by L1 L2 L3

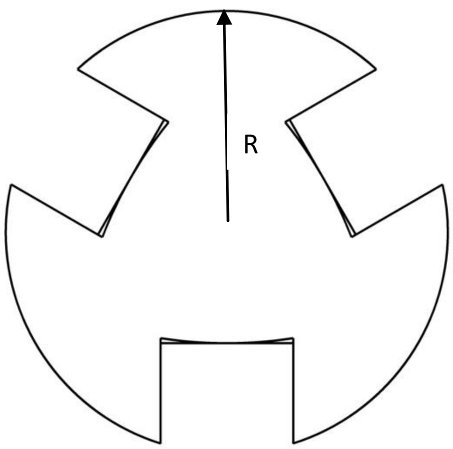


Figure 48, Radius of sphere

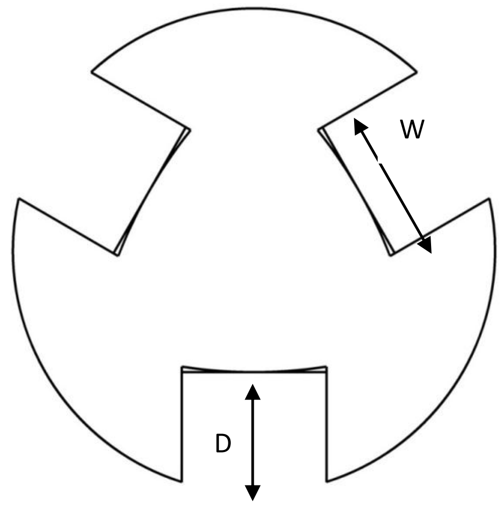


Figure 47, Depth and width of groove in sphere

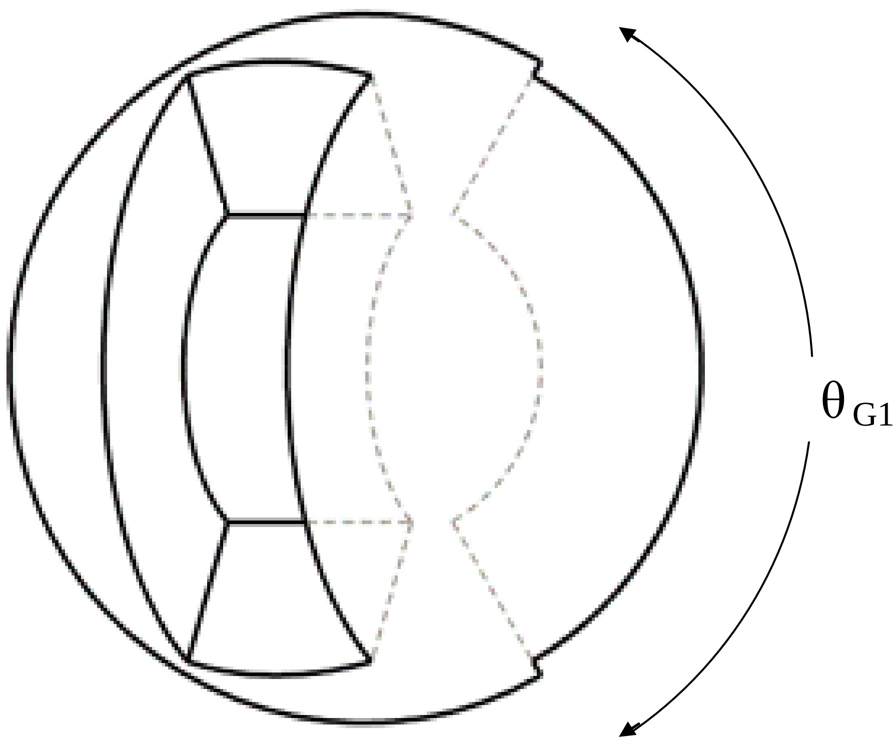


Figure 49, Groove represented by θ_{G1}

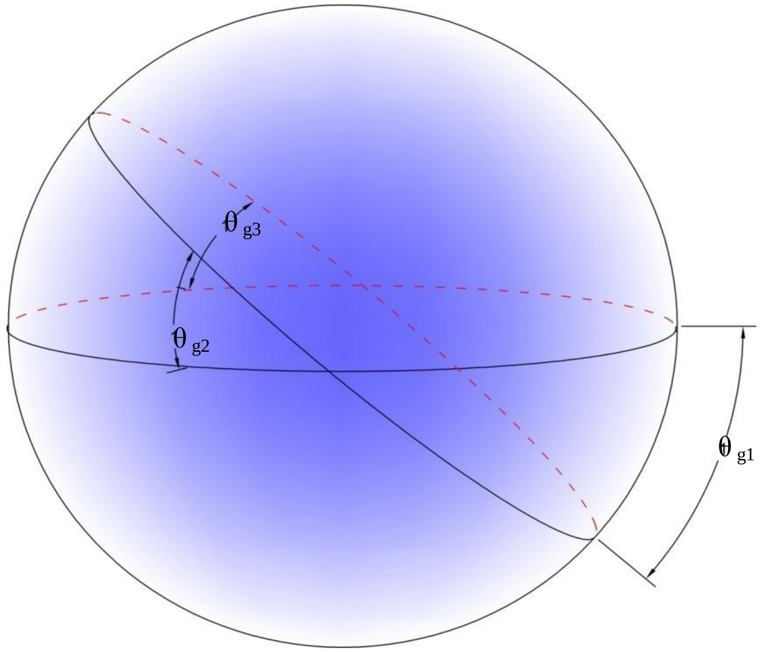


Figure 50, three dimensional view of θ g1, θ g1, θ g1

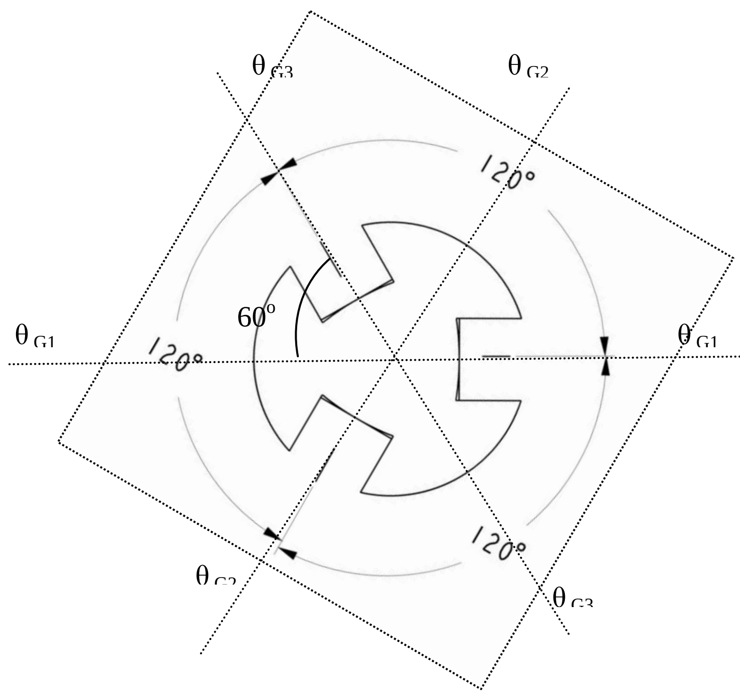


Figure 51, Top view of sphere representing angle between groves

6. Direction of joint.

Direction of joint is represented by vector n. n is normal to the surface of the cup and is normal to the cup plane PLc. The direction of P with respect to the reference plane is specified by two variable θ and φ. θ is the angle between vector n and Zo. Φ is the angle between projection of P on XoYo plane and Yo. See figure 52.

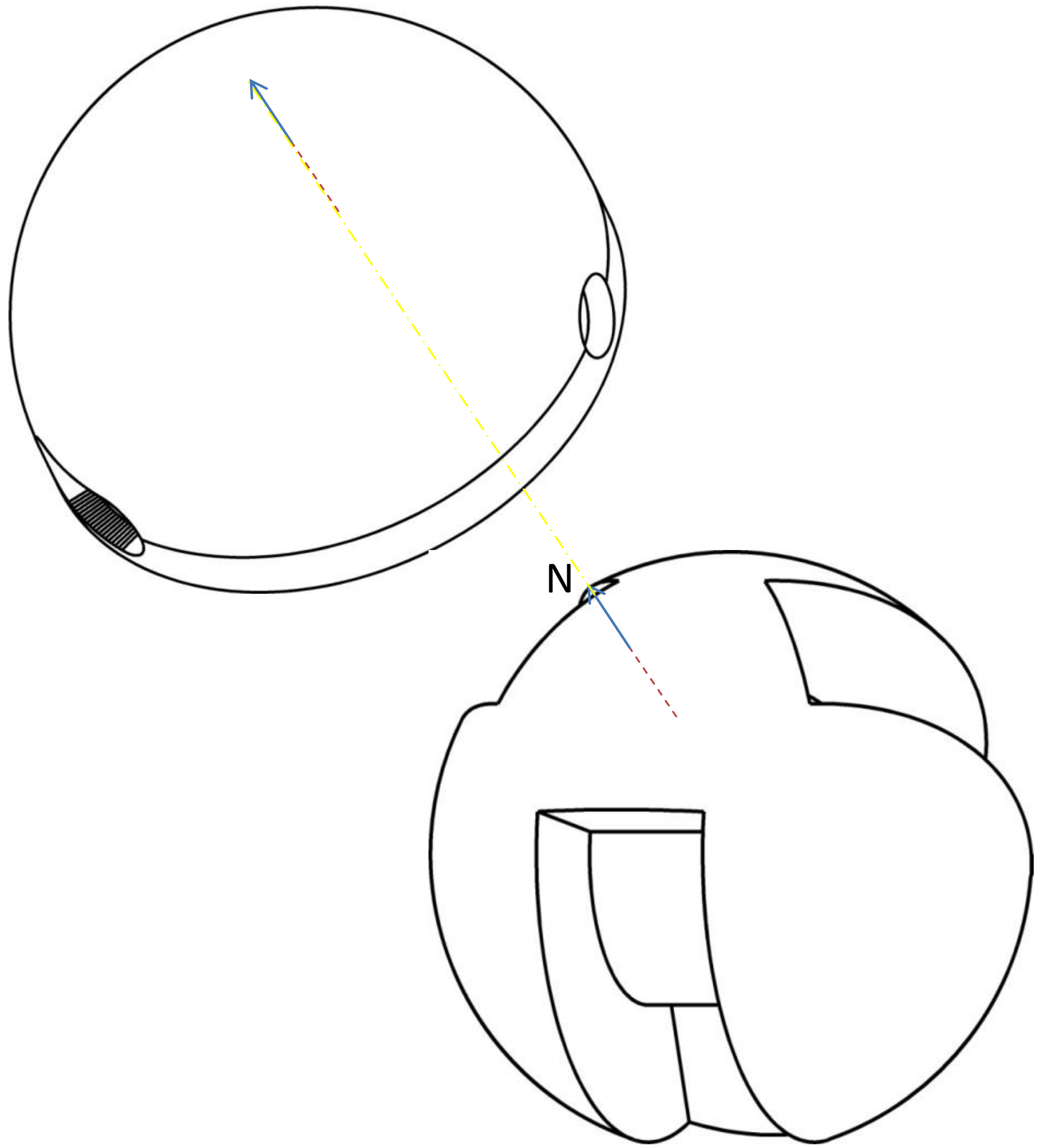


Figure 52, Direction of joint perpendicular to cup plane and passing through centre of sphere

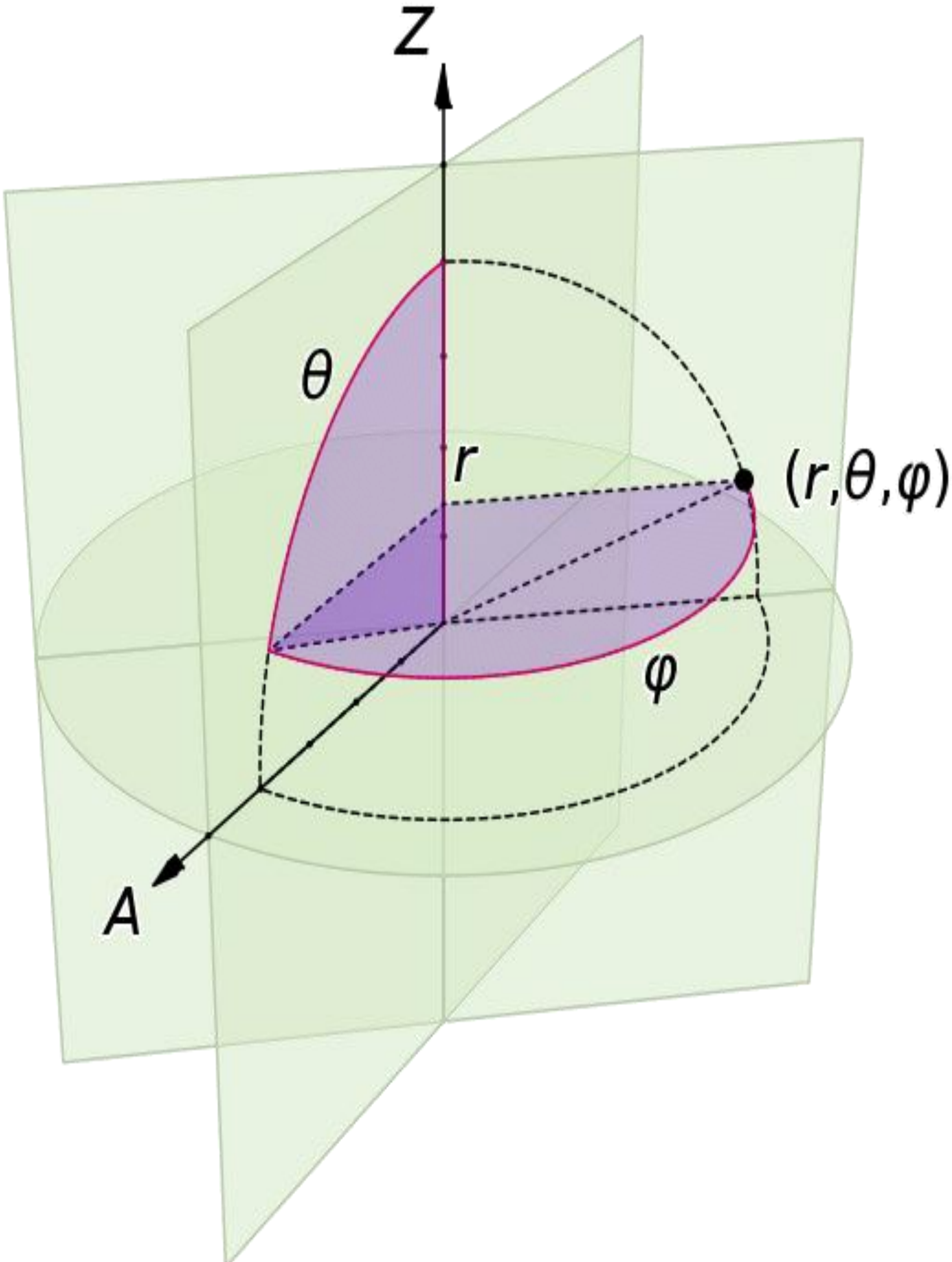


Figure 53, Spherical coordinate system

1.10 ANALYSIS OF IMPORTANT PARAMETERS

1.10.1 Resolution of position vectors of pistons.

Consider three vectors v1, v2, and v3 representing position vectors of the pistons moving in grove1 ,grove2 and grove3 respectively. These vectors are the position vectors of the centroid of the piston moving in the three groves of the sphere with respect to reference frame.

From figure we can write

$$V1x = V1cos90 = 0 \qquad 1$$

$$V1y = V1\cos\theta g1 \qquad 2$$

$$V1z = V1\sin\theta\, g1 \qquad 3$$

$$V2xy = V2\cos\theta\, g2 \qquad 4$$

$$V2x = V2xycos30$$

$$V2x = V2\cos\theta\, g2cos30$$

$$V2x = V2\cos\theta\, g2cos30 \qquad 5$$

$$V2y = V2xysin\,(-30)$$

$$V2y = -V2xysin30$$

$$V2y = -V2\cos\theta\, g2sin30 \qquad 6$$

$$V2z = V2\sin\theta\, g2 \qquad 7$$

$$V3xy = V3\cos\theta\, g3 \qquad 8$$

$$V3x = V3xycos(-150)$$

$$V3x = V3xycos(210)$$

$$V3x = V3xycos\,(180 + 30)$$

$$V3x = V3xycos\,(180)cos(30) - sin(180)sin(30)$$

$$V3x = V3xy\,(-1)cos(30) - 0$$

$$V3x = -V3xycos30$$

$$V3x = -V3cos\,\theta\,g3cos30 \qquad 9$$

$Similarly$

$$V3y = -V3xysin30$$

$$V3y = -V3cos\,\theta\,g3sin30 \qquad 10$$

$$V3z = V3sin\,\theta\,g3 \qquad 11$$

1.10.2 A proof that components of V2 and V3 are correctly derived

$We\ know\ that$

$$V^2 = Vx^2 + Vy^2 + Vz^2 \qquad 12$$

$Therefore$

$$V2^2 = V2x^2 + V2y^2 + V2z^2 \qquad 13$$

$$V3^2 = V3x^2 + V3y^2 + V3z^2 \qquad 14$$

$Putting\ values\ in\ equation\ 13\ from\ equation\ 5,6\ and\ 7$

$$V2^2 = (V2\cos\theta\,g2cos30)^2 + (-V2\cos\theta\,g2sin30)^2 + (V2\sin\theta\,g2)^2$$

$$= (V2^2\,cos2\,\theta\,g2cos^2\,30\,) + (V2^2cos^2\,\theta\,g2sin^2 30) + (V2^2sin^2\theta\,g2)$$

$$= V2^2(cos^2\,\theta\,g2cos^2\,30 + cos^2\,\theta\,g2\,sin^2 30 + sin^2\theta\,g2)$$

$$= V2^2(cos^2\,\theta\,g2(cos^2\,30 + sin^2 30) + sin^2\theta\,g2)$$

$$= V2^2(cos^2\,\theta\,g2\,(\,1) + sin^2\theta\,g2)$$

$$= V2^2(cos^2\,\theta g2 + \; sin^2\,\theta g2)$$

$$= \; V2^2(1)$$

$$V2^2 = \; V2^2 \quad Hence\ verified$$

Now putting values in equation 14 from equation 9, 10 and 11

$$V3^2 = (V3x)^2 + (V3y)^2 + (V3z)^2$$

$$= (-V3cos\,\theta g3cos30)2 + (-V3cos\,\theta g3sin30)2 + (\,V3sin\,\theta g3)2$$

$$= V3^2cos^2\theta g3\;cos^2 30 + V3^2cos^2\,\theta g3\;sin^2 30 + \; V3^2sin^2\,\theta g3$$

$$= \; V3^2\;(cos^2\,\theta g3cos230 + cos^2\theta g3sin^2 30 + \; sin^2\theta g3)$$

$$= \; V3^2\;(cos^2\theta g3\;(cos^2 30 + sin^2 30) + \; sin^2\theta g3)$$

$$= \; V3^2\;(cos^2\theta g3\;(1) + \; sin^2\theta g3)$$

$$= \; V3^2\;(cos^2\theta g3 + sin^2\,\theta g3)$$

$$= \; V3^2\;(1)$$

$$V3^2 = V3^2 \qquad Hence\ verified$$

1.10.3 Direction of joint as a function of θ_{g1}, θ_{g2}.

Since v1, v2 lie in cup plane PLc.Moreover the direction of joint n is normal to the cup plane PLc. Therefore the following relations hold true.

$$n = V2xV1 \qquad 15$$

And

$$V2xV1 = \; (-v1v2\sin\theta\;g1\cos\theta\;g2sin30 - v1v2\cos\theta\;g1\sin\theta\;g2)i$$

$$+(v1v2\sin\theta\;g1\;cos\theta g2cos30)j$$

$+ \ (v1v2cos\ \theta\ g1cos\ \theta\ g2cos30)\ k$

$V2xV1 = \ (-v1v2\ (\sin\theta\ g1\ \cos\theta\ g2sin30 + \ cos\theta\ g1\sin\theta\ g2)\ i$

$+ (v1v2 \sin\theta\ g1 \cos\theta\ g2cos30)j$

$+(v1v2\ \cos\theta\ g1\ \cos\theta\ g2\ cos30)k$ 16

$n = (-v1v2\ (\sin\theta\ g1\ \cos\theta\ g2sin30 + \ cos\theta\ g1\sin\theta\ g2)\ i$

$+ \ (v1v2 \sin\theta\ g1 \cos\theta\ g2cos30)j \ \ + (v1v2 \cos\theta\ g1 \cos\theta\ g2\ cos30)k$ 17

1.10.4 Direction of joint as a function of θ_{g2}, θ_{g3}.

Since $v2, v3$ *lie in cup plane PLc. Moreover the direction of joint n is normal to the cup plane PLc. Therefore the following relations hold true.*

$n = V3xV2$ 18

And

$V3xV2 = (-v2v3\ sin\ \theta\ g2\ cos\ \theta\ g3sin30 + v2v3\ cos\ \theta\ g2\ sin\theta\ g3sin30)\ i$

$+(-v2v3\ sin\ \theta\ g2\ cos\ \theta\ g3cos30 - v2v3\ cos\ \theta\ g2\ sin\ \theta\ g3cos30)\ j$

$+(v2v3\ cos\ \theta\ g2\ cos\ \theta\ g3sin30cos30 + v2v3\ cos\ \theta\ g2\ cos\ \theta\ g3sin30cos30)\ k$

$- -$ 19

1.10.5 θg3 as a function of θg2 and θg1

From equation 15 *and* 18

$V2xV1 = V3xV2$

⇨ $(V2xV1)_x = \ (V3xV2)_x$ 20

By putting values in equation 20 *from equation* 17 *and* 19 *we get*

⇨ $(-v1v2\ (\sin\theta g1\ \cos\theta g2sin30 + \ cos\theta g1\sin\theta g2)$

$= (-v2v3 \ sin\ \theta g2\ cos\ \theta g3sin30 + v2v3\ cos\ \theta g2\ sin\theta g3sin30)$

⇨ $(-v1v2\ (sin\ \theta g1\ cos\ \theta g2sin30 + \ cos\theta g1sin\ \theta g2)$

$= (v2v3\ (\ cos\ \theta g2\ sin\theta g3sin30 - \ sin\ \theta g2\ cos\ \theta g3sin30)$

$As\ |V1| = v1 = |V2| = v2 = |V3| = v3 = R - d$ 21

$Therefore\ v1v2 = v2v3$

⇨ $-(sin\ \theta g1\ cos\ \theta g2sin30 + \ cos\theta g1sin\ \theta g2)$

$= (\ cos\ \theta g2\ sin\theta g3sin30 - \ sin\ \theta g2\ cos\ \theta g3sin30)$ 22

$\theta g1\ and\ \theta g2\ are\ known\ and\ \theta g3\ is\ unknown$

$Let\ - \ (sin\ \theta g1\ cos\ \theta g2sin30 + \ cos\theta g1sin\ \theta g2) = c$ 23

$cos\ \theta\ g2sin30 = b$ 24

$-sin\ \theta\ g2sin30 = a$ 25

$\theta\ g3\ = x$ 26

$Putting\ values\ of\ equation\ 24{,}25{,}26\ in\ equation\ 22\ \ we\ get$

$acos(x)\ +\ b\ sin(x)\ =\ c$ 27

1.10.6 Solution of equation of form $\mathbf{a\ cos(x) + \ b\ sin(x) = \ c}$

$Consider\ the\ expression\ Rcos(x - \alpha)$

$This\ expression\ can\ be\ extended\ as\ follows$

$R\cos(x - \alpha) = \ R(cosxcos\alpha + sinxsin\alpha)$

$= Rcosxcos\alpha + Rsinxsin\alpha$

$= (Rcos\alpha)cosx + (Rsin\alpha)sinx$ 28

$Let\quad Rcos\alpha = a$ 29

$Rsin\alpha = b$ 30

$Putting\ values\ of\ equation\ 29\ ,30\ in\ 28\ we\ get$

$R\cos(x - \alpha) = acosx + bsinx$ 31

$Squaring\ and\ adding\ equation\ 28\ ,29\ we\ get$

$a^2 + b^2 = R^2cos^2\alpha + R^2sin2\alpha$

$= R^2(cos^2\alpha + sin^2\alpha)$

$= R^2(1)$

$a^2 + b^2 = R^2$ 32

⇨ $R = (a^2 + b^2)^\wedge(1/2)$ 33

Now

$\frac{Rsin\alpha}{Rcos\alpha} = \frac{b}{a} = tan\alpha$ 34

Summarizing the procedure

⇨ $a\, cos(x) + b\, sin(x) = cos\,(x - \alpha) = c \quad (from\ equation\ 31)$

⇨ $Cos(x - \alpha) = \frac{c}{R}$

⇨ $x - \alpha = cos - 1\left(\frac{c}{R}\right) = cos - 1(c/R) + \alpha$ 35

1.10.7 Relation between θ g1 , θ g2 and θ , Φ .

we can write

$n_{xy} = ncos(90 - \theta)$ 36

$n_x = n_{xy}sin(\Phi)$

$= n\,[cos\,(90)\,cos\,(\theta) + sin\,(90)\,sin\,(\theta)]\,sin\,(\Phi)$

$= n\,[0 + 1.sin\,(\theta)]\,sin\,(\Phi)$

$= n\,[sin\,(\theta)]\,sin\,(\Phi)$

$= n\,sin\,(\theta\,)\,sin\,(\Phi)$ 37

similarly

$n_y = n\,sin(\theta)\,cos(\Phi)$ 38

$n_z = n\,sin(90 - \theta)$

$= n\,[sin(90)\,cos(\theta\,) - cos(90)\,sin(\theta\,)]$

$= n[1.cos(\theta\,) - 0]$

$= n\,cos\,\theta$ 39

From equation 17 and 37 we can write

$$(-v1v2\,(sin\,\theta\,g1\,cos\,\theta\,g2sin30 + cos\theta\,g1sin\,\theta\,g2) = n\,sin\,(\theta\,)\,sin\,(\Phi)$$

$$-\,(sin\,\theta\,g1\,cos\,\theta\,g2sin30 + cos\theta\,g1sin\,\theta\,g2) = sin\,(\theta\,)\,sin\,(\Phi) \qquad 40$$

And

$$+\,(v1v2\,sin\,\theta\,g1\,cos\,\theta\,g2cos30) = n\,sin\,(\theta)\,cos\,(\Phi)$$

$$sin\,\theta\,g1\,cos\,\theta\,g2cos30 = sin\,(\theta)\,cos\,(\Phi) \qquad 41$$

$Dividing\ equation\ 40\ by\ 41\ we\ get$

$$\frac{-\sin\theta\,g1\cos\theta\,g2sin30}{\sin\theta\,g1\cos\theta\,g2cos30} - \frac{cos\theta\,g1sin\,\theta\,g2}{\sin\theta\,g1\cos\theta\,g2cos30} = \frac{sin\,(\theta\,)\,sin\,(\Phi)}{sin\,(\theta)\,cos\,(\Phi)}$$

$$\left(\frac{-sin30}{cos30}\right) - \left(\frac{cos\theta\,g1sin\,\theta\,g2}{sin\,\theta\,g1\,cos\,\theta\,g2cos30}\right) = \frac{\sin(\Phi)}{\cos(\Phi)}$$

$$-tan30 - \left(\frac{cos\theta\,g1sin\,\theta\,g2}{sin\,\theta\,g1\,cos\,\theta\,g2cos30}\right) = \tan(\Phi)$$

$$\Phi = Tan^{-1}\left(-tan30 - \left(\frac{cos\theta\,g1sin\,\theta\,g2}{sin\,\theta\,g1\,cos\,\theta\,g2cos30}\right)\right) \qquad 42$$

$From\ equation\ 4.40\ we\ can\ write$

$$-\,(sin\,\theta\,g1\,cos\,\theta\,g2sin30 + cos\theta\,g1sin\,\theta\,g2) = sin\,(\theta\,)\,sin\,(\Phi)$$

$$\theta = Sin^{-1}\left(\frac{-\,(\sin\theta\,g1\cos\theta\,g2sin30 + cos\theta\,g1\sin\theta\,g2)}{\sin(\Phi)}\right) \qquad 43$$

1.10.8 Torque of the actuator

Torque is defined as product of force and moment arm. In case of the actuator under consideration it can be divided into two types.

a. Applied torque
b. Resisting torque

1. **Applied torque**

When fluid is injected in the groves of the actuator it produces pressure in the enclosed chambers. The pressure applies force on the corresponding pistons. This results in a torque about the axis of rotation of the corresponding pistons. *The sum of the torques produced by the pistons about their axis of rotation is the applied torque.* See figure 54 and 55.

2. **Calculating applied torque**

Since most of the parameters of the actuator are defined with respect to the reference coordinate system $X_oY_oZ_o$ so it will be convenient to calculate the applied torque with respect to the reference coordinate system.

Let

$F1 = force\ applied\ on\ piston1$

$F2 = force\ applied\ on\ piston2$

$F3 = force\ applied\ on\ piston3$

And

$r1 = r2 = r3 = r = moment\ arm = radius\ of\ sphere - (depth\ of\ grove)/2$

$then$

$\tau1 = rxF1$ 44

$\tau2 = rxF2$ 45

$\tau3 = rxF3$ 46

$Now\ resolving\ \tau1, \tau2\ and\ \tau3\ into\ their\ xy\ components.$

$\tau1x = rF1$ 47

$\tau1y = 0$ 48

$\tau2x = -\tau2cos60^o$

$= -rF2cos60^o$ 49

$\tau2y = -t2sin60^o$

$= -rF2sin60$ 50

$\tau3x = -\tau3sin30^o$

$= -rF3sin30^o$ 51

$$\tau 3y = \tau 3cos30^o$$
$$= rF3cos30^o \quad 52$$

$$Tx = \tau 1x + \tau 2x + \tau 3x$$
$$= rF1 + (-rF2cos60) + (-rF3sin30)$$
$$= rF1 - rF2cos60 - rF3sin30$$
$$= r(F1 - F2cos60 - F3sin30) \quad 53$$

$$Ty = \tau 1y + \tau 2y + \tau 3y$$
$$= 0 + (-rF2sin60) + (rF3cos30)$$
$$= -rF2sin60 + rF3cos30$$
$$= r(F3cos30 - F2sin60) \quad 54$$

$$Tz = 0 \quad 55$$

3. Resisting torque

Torque produced due to force/load applied on the outer center of the cup as shown in figure 56.

4. Calculating resisting torque

Let P=moment arm=position vector in direction of joint with magnitude equal to radius of sphere. Moreover from equation 17 we can write

$$P = -R\ (sin\ \theta\ g1\ cos\ \theta\ g2sin30 + cos\theta\ g1sin\ \theta\ g2)\ i$$
$$+ R\ (sin\ \theta\ g1\ cos\ \theta\ g2cos30)\ j$$
$$+R\ (cos\ \theta\ g1\ cos\ \theta\ g2\ cos30)k \text{ ------------------- } \quad 56$$

$$Let\ load = F = Fxi + Fyj + Fzk$$

⇨ $Tr = PxF$

$$= \quad +((R\ sin\ \theta\ g1\ cos\ \theta\ g2cos30)Fz - (\ R\ cos\ \theta\ g1\ cos\ \theta\ g2\ cos30)Fy)\ i$$

$$+(-R(sin\ \theta\ g1\ cos\ \theta\ g2sin30 + \ cos\theta\ g1sin\ \theta\ g2)Fz -$$
$$R(cos\ \theta\ g1\ cos\ \theta\ g2\ cos30)Fx)\ j$$

$$+(-R(sin\ \theta\ g1\ cos\ \theta\ g2sin30 + \ cos\theta\ g1sin\ \theta\ g2)Fy -$$
$$(\ Rsin\ \theta\ g1\ cos\ \theta\ g2cos30)Fx)\ k$$

$$= \quad +R\ ((sin\ \theta\ g1\ cos\ \theta\ g2cos30)Fz - (\ \ cos\ \theta\ g1\ cos\ \theta\ g2\ cos30)Fy)\ i$$

$$+R\ (-(sin\ \theta\ g1\ cos\ \theta\ g2sin30 + \ cos\theta\ g1sin\ \theta\ g2)Fz -$$
$$(cos\ \theta\ g1\ cos\ \theta\ g2\ cos30)Fx)\ j$$

$$+R\ (-(sin\ \theta\ g1\ cos\ \theta\ g2sin30 + \ cos\theta\ g1sin\ \theta\ g2)Fy -$$
$$(sin\ \theta\ g1\ cos\ \theta\ g2cos30)Fx)\ k$$

$$= \quad R[\ ((\ sin\ \theta\ g1\ cos\ \theta\ g2cos30)Fz - (\ \ cos\ \theta\ g1\ cos\ \theta\ g2\ cos30)Fy)\ i$$

$$(-(sin\ \theta\ g1\ cos\ \theta\ g2sin30 + \ cos\theta\ g1sin\ \theta\ g2)Fz -$$
$$(cos\ \theta\ g1\ cos\ \theta\ g2\ cos30)Fx)\ j$$

$$(-(sin\ \theta\ g1\ cos\ \theta\ g2sin30 + \ cos\theta\ g1sin\ \theta\ g2)Fy -$$
$$(\ sin\ \theta\ g1\ cos\ \theta\ g2cos30)Fx)\ k]$$ --- 57

$$Let \quad A = \ sin\ \theta\ g1\ cos\ \theta\ g2cos30$$

$$B = \ cos\ \theta\ g1\ cos\ \theta\ g2\ cos30$$

$$C = \ sin\ \theta\ g1\ cos\ \theta\ g2sin30 + \ cos\theta\ g1sin\ \theta\ g2$$

$Then\ we\ can\ write\ the\ above\ equation\ as$

$$= \ R[\ (\ A\ Fz - \ B\ Fy)\ i \qquad (-\ CFz - \ B\ Fx)\ j \qquad (-CFy - \ AFx)\ k] \qquad 58$$

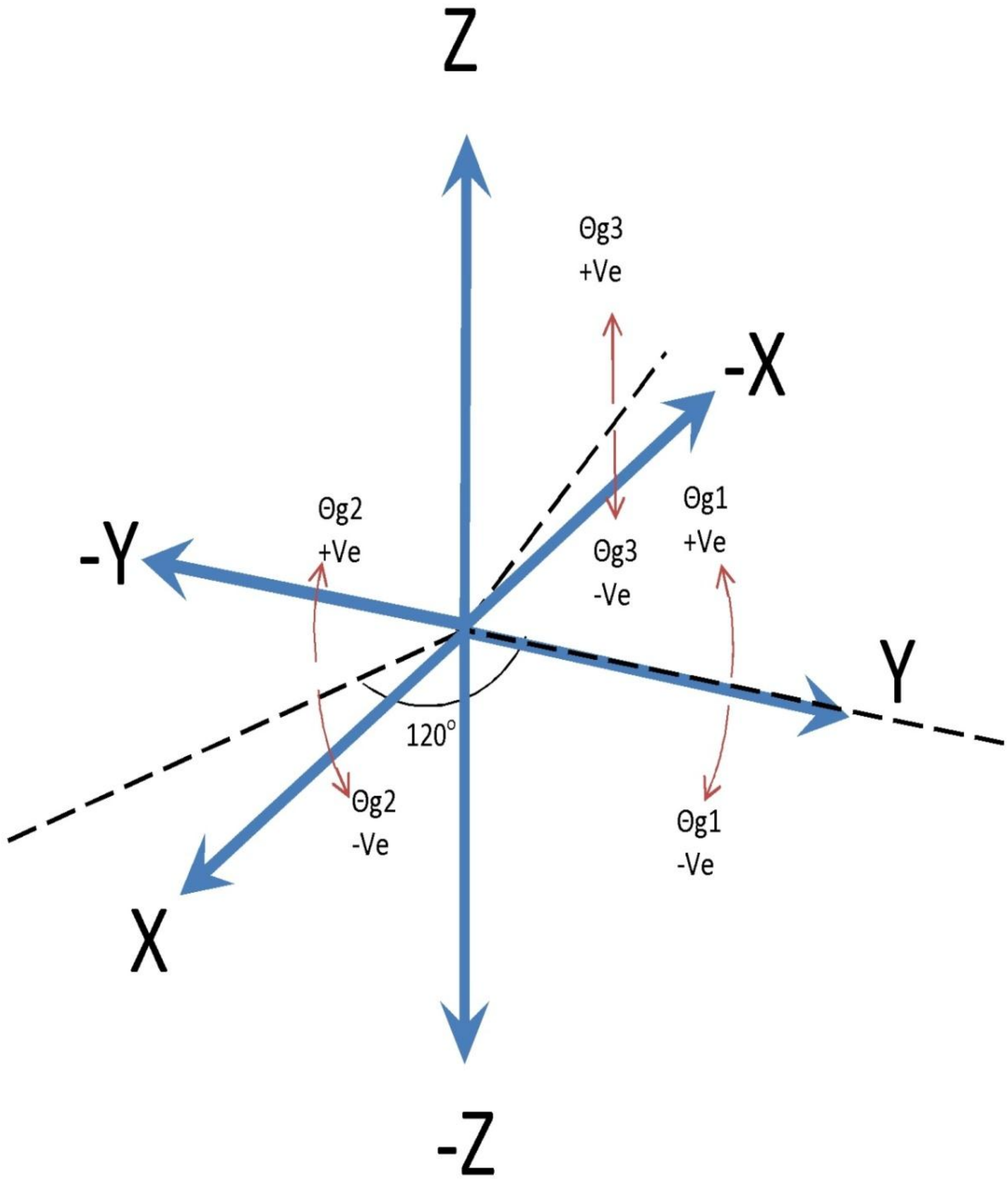


Figure 54, signs and planes of movement of θ_{g1} θ_{g2} θ_{g3}

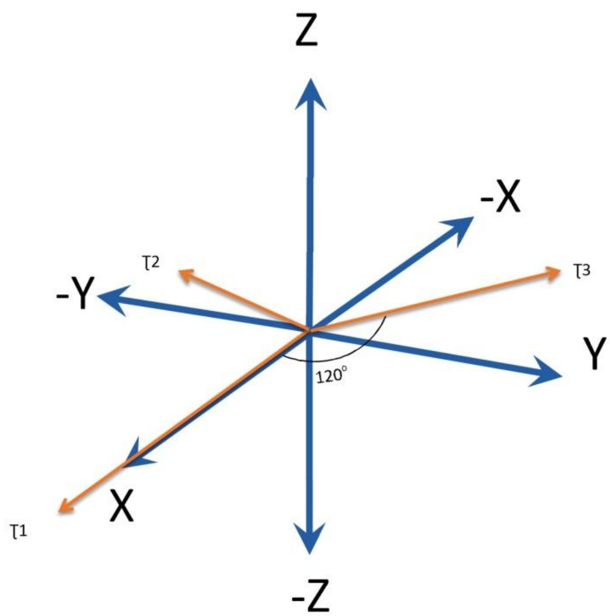


Figure 55, Direction of torques due to pressure in each grove

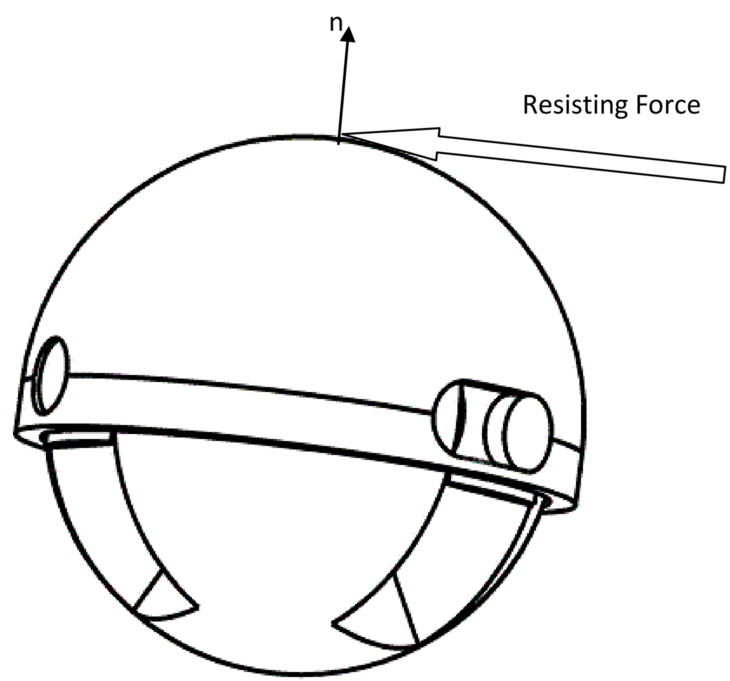


Figure 56, Resisting force and direction of joint

1.10.9 DOF of the actuator

Although the actuator apparently seems to be a simple part but actually its different parts exhibit a complex set of interdependent motions. The actuator can be subdivided into three main structural parts.

a. The sphere

b. The cup

c. The three pistons

We proceed by finding DOF of each part with respect to the other.

1) DOF of pistons with respect to sphere

There are three grooves in the sphere and three pistons can move in it. Each piston exhibits a rotary motion about an axis that passes through the centre of the sphere. Thus the motion of each piston is single DOF The motion of the three pistons with respect to the sphere is three DOF. See figure 57 and 58.

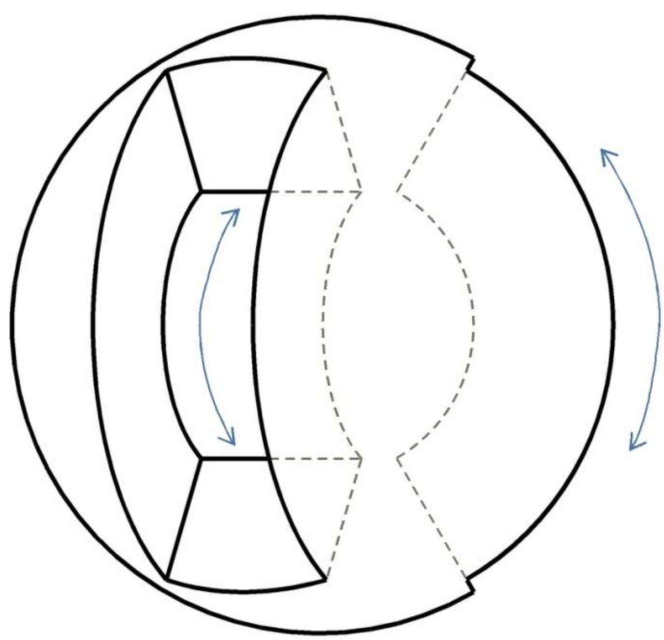


Figure 57, DOF of piston W.R.T sphere

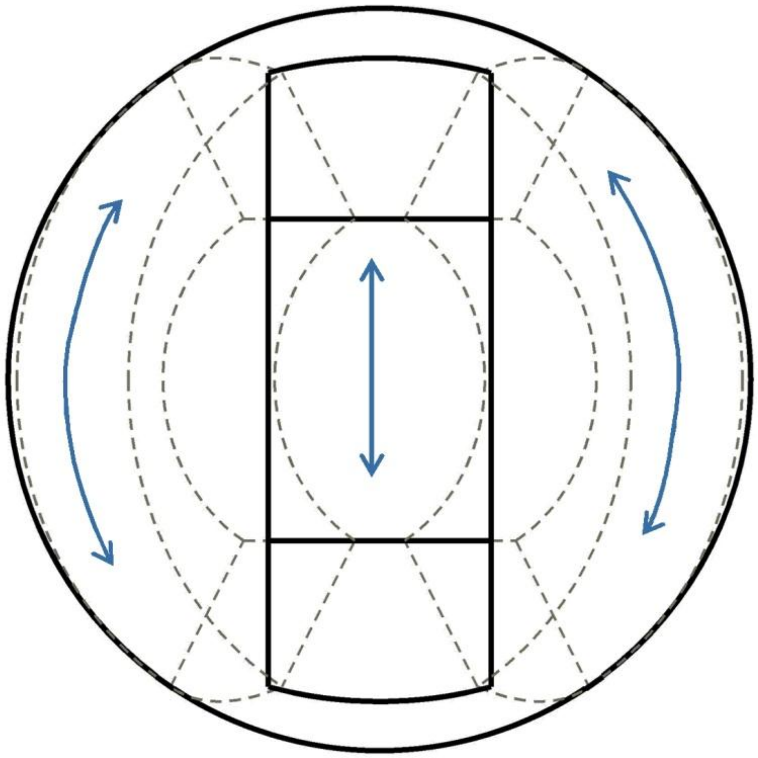


Figure 58, DOF of piston W.R.T sphere

2) DOF of pistons with respect to cup

There are two grooves and a hole in the cup. A piston exhibit two DOF of motion in each grove and a single DOF in a hole. This results in a five DOF motion of pistons with respect to the cup. See figure59.

3) DOF of cup with respect to sphere

The cup and sphere are analogues to a spherical joint with one DOF constrained. A spherical joint has three DOF. A spherical joint rotates about all three axis. The present actuator the cup can only rotate about the x and y axis of the reference frames whose origin lie at the centre of the sphere. See figure 60.

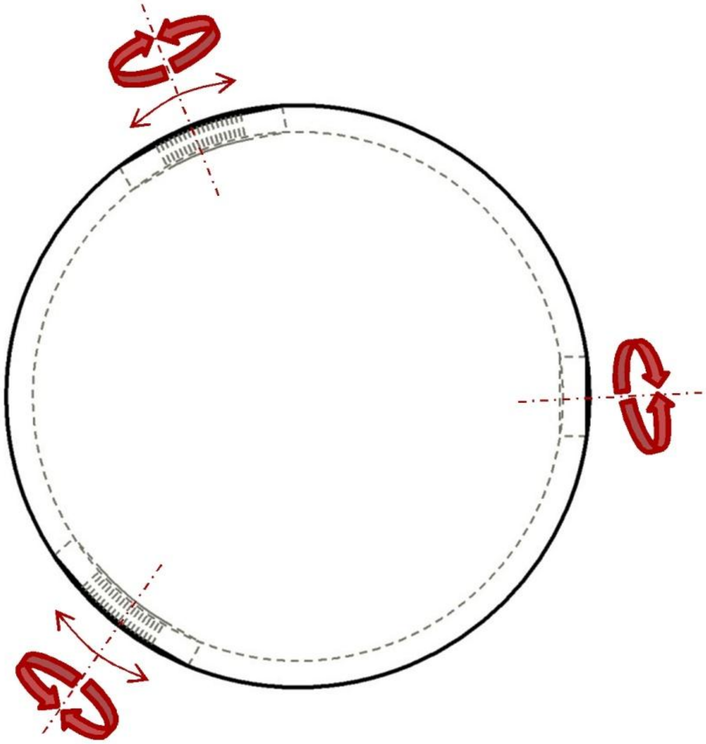


Figure 59, DOF of pistons W.R.T cup

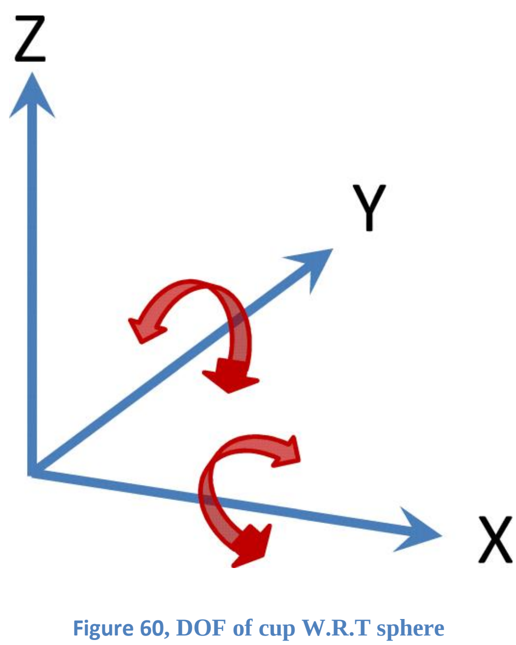


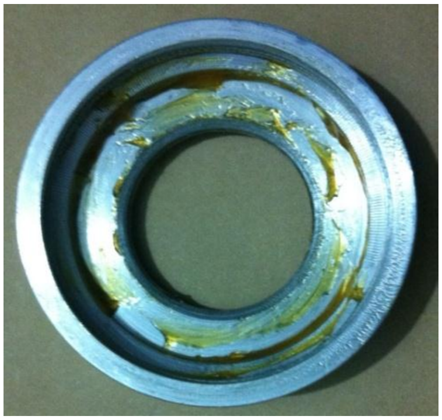
Figure 60, DOF of cup W.R.T sphere

PROTOTYPE OF MODEL

Prototype of model has been manufactured. This is not an exact prototype of the designed actuator. This only demonstrates that the actuator successfully performs two DOF motion with out jamming throughout its work space. The pictures of the prototype are given below.

The sphere

Piston & pin



The cup

Assembly

Figure 61, Pictures of prototype

AN IMPROVED MODEL WITH REDUCED WEIGHT

1.11 EFFECT OF WEIGHT REDUCTION ON PERFORMANCE OF ACTUATOR.

Reducing the weight of the actuator has positive effects on the performance of the actuator in general and the performance of the snake-arm robot made of the actuator in specific.

A light weight actuator will consume less energy. Moreover it will require less energy and torque for self actuation. Frictional losses are also reduced specifically under no load condition during self actuation.

The impact of weight reduction of the actuator on the performance of the snake arm robot is very high and is of great importance. The weight of the actuator is directly effects cantilever length of the snake arm robot. And cantilever length of snake arm robot directly affects the accessibility of the snake arm robot.

1.12 DESIGN OF SPHERE WITH REDUCED WEIGHT

Material from certain portion of the sphere can be removed without affecting its strength. Figure 62, 63, 64 and 65 shows how this can be done.

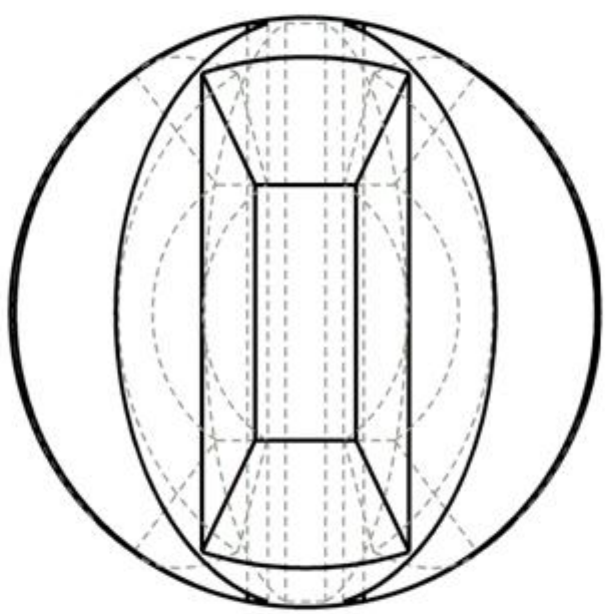


Figure 62, Front view of sphere with improved design for weight reduction

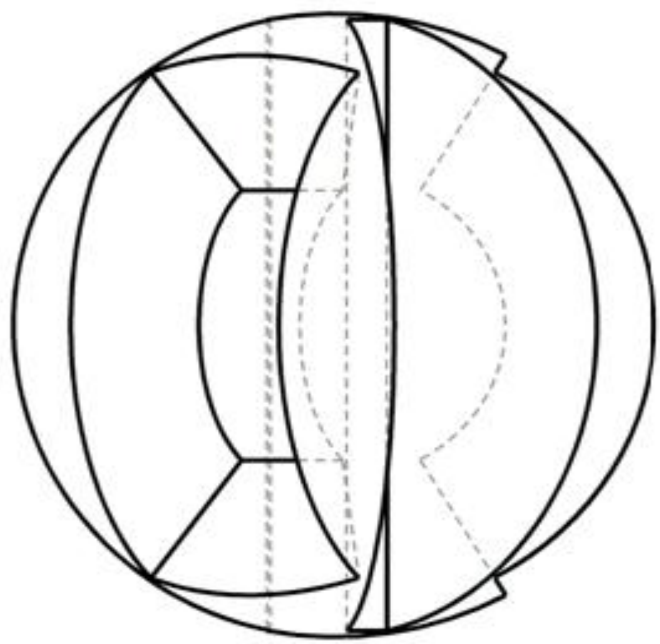


Figure 63, Side view of sphere with improved design for weight reduction

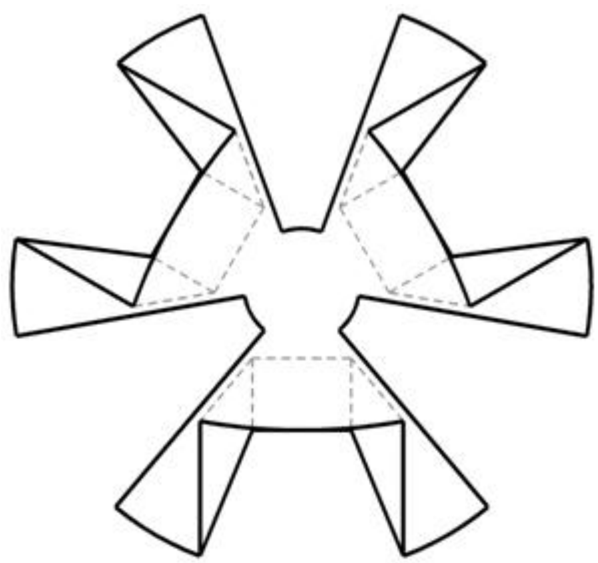


Figure 64, top view of sphere with improved design for weight reduction

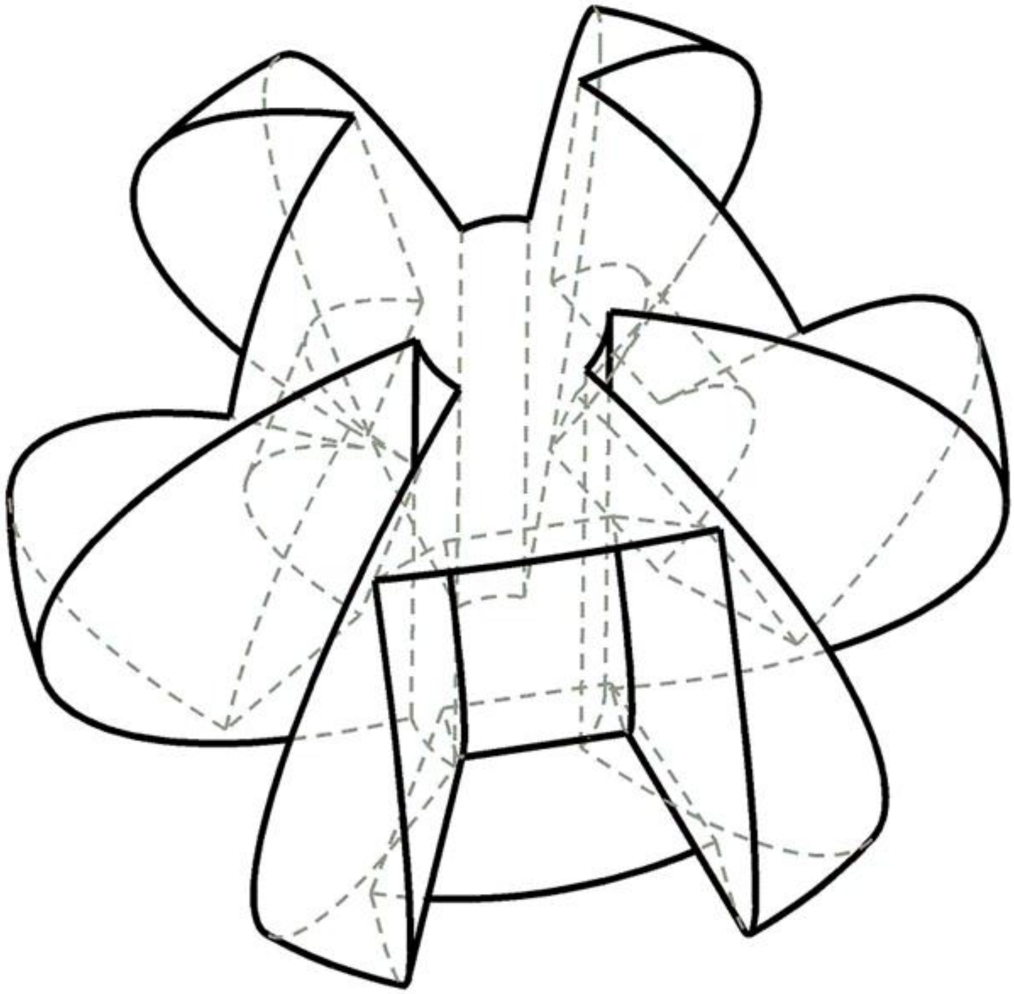


Figure 65, Isometric view of sphere with improved design for weight reduction

CONCLUSIONS

The following conclusions can be drawn from the research work done in the preceding chapters.

1. Hydraulic actuators have very high energy density and are highly suitable for snake-arm robots actuators
2. For optimum compactness, a sphere shape is ideal for two and three DOF rotary motion actuators. When a sphere is subjected to a two or three DOF rotary motion , the set of points in space which lie outside the boundary of the sphere always remains the same
3. For high pressure transmission, a unidirectional transmission is preferred. Therefore it was used in the actuator.
4. Leakage could be a potential problem in the actuator
5. Fine machining and proper sealing is important.
6. The actuator designed is the first ever spherical shaped hydraulically actuated actuator.
7. Two DOF hydraulic actuators are formed by cascading two one DOF hydraulic actuators in a serial manner. This is first ever hydraulic actuator with two DOF without cascading one DOF actuators in serial manner.

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