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Design and development of a Multipurpose, Programmable Humanoid Robot

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ABSTRACT - A wide range of applications can be found for humanoid robots. They can be utilized for medical research purposes, such as the development of various types of prostheses and the study of different human joints and motions. Additionally, they have applications in fields like disaster management, mine work, serving as human assistants in various professions, and providing emotional support.

In this project, a low-cost humanoid robot is being designed and built, capable of performing basic human movements such as walking, self-balancing, and pick-and-drop operations. The parts are being designed using the SolidWorks platform. Simulations and analyses will be carried out using software like MATLAB. The manufacturing of the robot will be performed using the 3D printer available in our lab. The assembly process will involve integrating all the parts along with the electronic components. This will enable the robot to detect and pick objects, avoid obstacles, and communicate with people.

At the end of the research project, a humanoid robot with at least 21 degrees of freedom (DOFs) will be designed, featuring smooth and dexterous motions. The robot will possess the ability to sense its environment and interact with it, making it highly useful in various applications.

Key Words: Humanoid robot, Low-cost, Basic human movements, SolidWorks, Simulation and analysis, 3D printing, Degrees of freedom (DOFs), Sensing and interaction

I. INTRODUCTION

Robotics is an emerging field of science in which robots are fabricated and programmed to perform varied tasks. In this field, humanoid robots are sophisticated robots that are designed to resemble the human body and are capable of performing tasks similar to humans and interacting with them.

A humanoid robot is a robot with a body shape that is built to resemble that of the human body. In general, humanoid robots have a torso, a head, two arms, and two legs. Additionally, some humanoid robots may have heads designed to replicate human facial features, such as eyes and a mouth.

A humanoid design may serve functional purposes, such as interacting with human tools and environments, or experimental purposes, such as studying bipedal locomotion. It may also be used for other purposes. The attempt to simulate the human body contributes to a better understanding of it and aids in the development of computational models of human behaviour. Human cognition, which focuses on how humans learn from sensory information to acquire perceptual and motor skills, is a field of study that benefits from humanoid robots. The effective and anthropomorphic design of humanoid robots is a critical phase in their development.

II. PROBLEM STATEMENT

The aim of this research is to design and develop a multipurpose, programmable humanoid robot that can perform a wide range of tasks and interact with humans effectively. The robot should be capable of executing basic human movements. Furthermore, the robot should be programmable, allowing for flexibility and adaptability in task execution. The challenge lies in achieving an optimal design that balances structural integrity, mechanical efficiency, and realistic human-like appearance, while ensuring cost-effectiveness and manufacturability. This research aims to address these challenges and contribute to the advancement of multipurpose humanoid robot technology."

2.1. Objectives

The main objective of the project is to build humanoid robot and perform various motions like walking, balancing and pick and dropping. This task can be divided into following sub objectives.

1. Study of human gait, motion and current humanoids.
2. Fixing Degrees of Freedoms and their locations.
3. CAD modelling of various parts and joints.
4. Kinematic and Structural analysis.
5. Motion Generation
6. Electronic component selection & Circuit designing
6. Interfacing and coding framework
7. Manufacturing by FDM 3D Printer
8. To enable Asteroid to perform various human activities like:

I. Walking
II. Balancing
III. Pick and dropping

III. METHODOLOGY

Fig 1: Methodology of the project

3.1. Literature Review

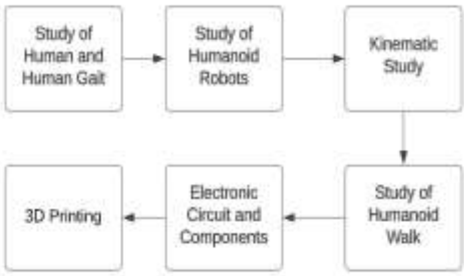

Fig 2: Literature Review Steps

3.1.1. Study of Human and Human Gait

The human body is the structure of a human being. The human body has four limbs (two arms and two legs), a head and a neck which connect to the torso. The body's shape is determined by a strong skeleton made of bone and cartilage, surrounded by fat, muscle, connective tissue, organs, and other structures. [1] Which inspired our 2-stage structure of humanoid i.e. Stronger Skeleton and casing which will consist of our organs (electronic Power and controlling units).

Human body has 244 degrees of freedom. Basically, free motion is work of joints and ligaments present in the body. The number of joints is 230. Many of them having single DOF and some have more than one. [2] Studding this We decided necessary DOFs of human which are necessary to perform desired task and included them in our Humanoid.

Human Gait

Human gait refers to locomotion achieved through the movement of human limbs. Human gait is defined as bipedal, biphasic forward propulsion of center of gravity of the human body. [3] Different gait patterns are characterized by differences in limb-movement patterns, overall velocity, forces and changes in the contact with the surface (ground, floor, etc.)

Types of Human Gait

Human gaits are the various ways in which a human can move, either naturally or as a result of specialized training. The so-called natural gaits, in increasing order of speed, are the walk, jog, skip, run, and sprint. All-natural gaits are designed to propel a person forward, but can also be adapted for lateral movement. Walk is most important gait in our project point of view.

Walk

Walking involves having at least one foot in contact with the ground at all times. There is also a period of time within the gait cycle where both feet are simultaneously in contact with the ground. When a foot is lifted off the ground, that limb is in the swing phase of gait. When a foot is in contact with the ground, that limb is in the stance phase of gait. A mature walking pattern is characterized by approximately 60% of the gait cycle being the stance phase of gait while 40% in swing phase.

double limb stance

when both feet are in contact with the ground and the center of mass is within a person's base of support polygon i.e. region formed by enclosing all the contact points between the feet and the ground by using a convex shape.

Single Limb Stance

Only one foot is in contact with the ground and the center of mass is in front of that foot and moving towards the leg that is in the swing phase.

As single Limb Stance end Center of mass travels from one limb to another limb in Double Limb Stance. Then Single Limb Stance of other limb Starts and this cycle continues.

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3.1.2. Study of Humanoid Robots

This chapter is overview of the various humanoid robot we studied, Humanoid robot still a new technology with many challenges. Only few humanoid robots are commercially available, often at high cost. This is a very important aspect; researches had been done in the field of Robotics and AI for humanoid until recent years [5]. We also study the human structure and behavior to build humanoid robot. The realistic looks of humanoid robot are all inspired from the human body structure and having it's of functional purpose. The study of humanoid robot includes the many of humanoid robot which helps us in this project.

Leonardo da Vinci designs a humanoid automaton that looks like an armoured knight knows as Leonardo's robot (1495) ,there are many such human like robots design automation mentioned in the history but world's first full-scale humanoid robot with artificial mouth was initiated by Waseda University(Japan) in 1967 project name- WABOT-1(1972) [6][7].In addition this project WABOT-2 humanoid was devolved as the advanced version of aWABOT-1 in addition to basic human gait motions it has the artistic activity of in playing keyboard instruments .

Honda developed many humanoid robots the seven series of robots named as Experimental model E0 to E6 which all has the basic android design structure and performed the basic human gait motion this series devolved 1986-1993. The Prototype Model series P1, P2 and P3 an evolution from E series, with upper limbs (1997) [8].

The 11th bipedal humanoid robot 'ASIMO (Advanced Step in Innovative mobility)'in 2000, able to run, 130cm tall and weighs 54kg with operating time one-hour. It has ability to recognize moving object and face recognition ASIMO respond to sound and it is named in the world's most advanced humanoid robots. The name ASIMO was chosen in honor of Isaac Asimov [9].

NAO (2008) is one of best commercial humanoids in the research, education and entertainment sector. NAO is an open source humanoid robot which has very attractive mechanical design frame with 25 degree of freedom [10][11].

Poppy humanoid robot (2013) first open source 3D-printed humanoid robot in the world It is a 25-degrees of freedom humanoid robot with a fully actuated vertebral column with 83cm tall and weighs 5.3kg. It is used for education, research (walk, human-robot interaction) or art (dance, performances). From a single arm to the complete humanoid, this platform is actively used in labs, engineering schools, and artistic projects. ABS material is used in 3d printed manufacturing for its mechanical frame. Dynamixel motors are used as actuators. As Poppy humanoid project is available in our college's PI lab, we study many aspects of humanoid robot with basic functioning and the complex mechanical structural design and gain hands of experience of the working of the Poppy humanoid robot. After studying POPPY, we observed some of the drawbacks such as-the hand(palm) of the poppy is having zero degree of freedom as its do not have gripping function, also due high DOF it is hard to balance its C.G. and control its bipedal motion [13][14].

There are also some advanced robots we studied –ATLAS (Boston dynamics2013) it is use to do many difficult activities like climb ladder, a double flipped jump, drive utility vehicle at site.

SOPHIA developed by Hanson Robotics; it is most advanced AI implemented humanoid robot which has ability to display 60 facial expressions. Sophia is conceptually similar to the computer program ELIZA which was one of the first attempt at simulating human conversations. Sophia is able to have conversation using natural language subsystem. In 2018 Sophia was upgraded with functional leg [15].

We also studied two made in India humanoid robots MANAV (2014) a 2 ft tall and weight 2kg is India's first humanoid manufactured by 3d printed technology made up of Acrylonitrile butadiene styrene plastic (ABS) with total 21 DOF. The robot comes with lithium polymer battery also equipped with Wi-Fi and Bluetooth connectivity [18][19].

RASHMI one of the most advanced AI implemented humanoid robot with 83 facial expressions with its unique 6 axis neck movement. Facial recognition ,3d mapping and OCR. Rashmi used to speak 4 different language English, Hindi, Marathi, Bhojpuri, etc. Rashmi has also a functional hand with finger movement, she doesn't have legs motion at present. Rashmi will be used in ISROs Gaganyaan2022 space mission.

3.1.3. Kinematic Study

3.1.3.1. Kinematics

Kinematics is field of study that describes the motion of points, bodies (objects), and systems of bodies (groups of objects) without considering the forces that cause them to move. In this report we have performed Kinematic study on single foot and arm for motion programming and analysis [21].

Coordinate Systems

First task is to clearly define the position and orientation of each part of the robot. To do this we define a special point on every link of robot, considering this point as origin we define a coordinate system for each link.

Global Coordinate System

It is fixed coordinate system located on base link of robot and it is used for determining location of any point in space with reference to fixed base. Positions defined using World Coordinates are called Absolute Positions.

Local Coordinate System

Every link of robot is assigned with its own local coordinate system so we can relate any link to base link via transformation matrix. Any position of point on link defined using local coordinates is called relative position.

Homogeneous Transformation Matrix

We can represent link local coordinate system (B) with respect to fixed global coordinate system (S) by specifying position of B in S coordinates i.e. P vector and also orientation of B in S coordinate i.e. R matrix. We gather this together in 4x4 matrix, called homogeneous transformation matrix or transformation matrix [22].

$$T = \begin{bmatrix} R & P \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{13} & P_x \\ R_{21} & R_{22} & R_{23} & P_y \\ R_{31} & R_{32} & R_{33} & P_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Chain Rule

What we described above in Homogeneous transformation matrix can be generalized. Let us assume we have a mechanism which connects the local coordinates S_1 through S_n. If we have a Homogeneous Transformation which describes next local coordinates S_i and S_{i+1} as,

$$i+\,^{i}_{1}T$$

by reiterating through the above process, we get the following equation,

$$^{1}_{n}T = \,^{1}_{2}T * \,^{2}_{3}T \ldots * \,^{n-1}_{n}T$$

Here $^{1}_{n}T$ is a homogeneous transformation that describes the position and attitude of the Nth joint. To add another link to the end of this joint we need to multiply it with the homogeneous transformation matrix from the right This method of multiplying the homogeneous transformation in order to calculate the coordinate transform matrix is called the chain rule. The chain rule enables us to calculate the kinematics of an arm with multiple joints without too much complication.

For example,

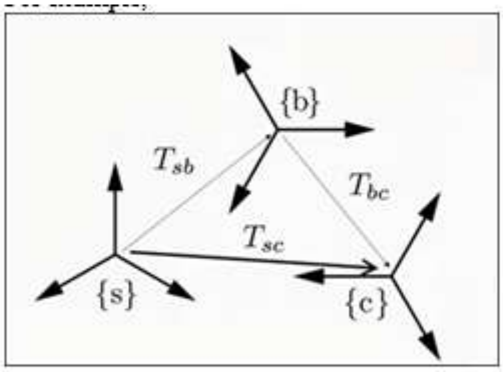

Fig 3: Transformation Matrices

For above system, Final homogeneous transformation matrix is,

$$T_{sc} = T_{sb} * T_{bc}$$

Like this we can assign coordinate systems on every link of robot and define every link with respect to other mathematically.

3.1.3.2. Forward Kinematics

Forward kinematics refers to the use of the kinematic equations of a robot to compute the position of the end-effector from specified values for the joint parameters (Joint angle). For forward kinematics we generally begin with fixed base link and find transformation matrix for each link and combine them to find final transformation matrix. If we put our joint parameters (i.e. joint angles) in transformation matrix we can find position and orientation of end effector for those particular parameters.

Workspace of a Robot (Manipulator)

Workspace analysis of serial manipulators is of great interest since the workspace geometry can be considered not only a fundamental issue for manipulator design but for robot placement in a working environment and trajectory planning.

It is defined as the set of points that can be reached by its end-effector considering type of joints and physical constraint on them.

We can find out workspace using manual graphical analysis or by iteration method in MATLAB.

3.1.3.3. Inverse Kinematics

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Inverse kinematics makes use of the kinematics equations to determine the joint parameters that provide a desired position for each of the robot's end effectors. When we compare final transformation matrix (4x4 matrix) with position and orientation (4x4 matrix) we need, we can solve those simultaneous equations to find out joint parameters.

Denavit Hartenberg Representation

While it is possible to carry out all of the forward kinematics using an arbitrary frame (Coordinate systems) attached to each link of the robot, it is helpful to be systematic in the choice of these frames. A commonly used convention for selecting frames of reference in robotic applications is the Denavit-Hartenberg, or D-H convention. In this convention, coordinate systems are assigned using certain rules such that any link can be described using only four parameters. Whereas normal 3-Dimensional system every link may have 6 degrees of freedom and might require 6 parameters to describe link/transformation of link.
Rules for assigning coordinate system to $link_i$ in D-H notations are as follows:

i) Z_i is an axis about which the rotation is considered or along which the translation takes place.
ii) If Z_{i-1} and Z_i axes are parallel to each other, X axis will be directed from Z_{i-1} to Z_i along their common normal.
iii) If Z_{i-1} and Z_i axes intersect each other, X axis can be selected along either of two remaining directions.
iv) Z_{i-1} and Z_i axes act along a straight line, X axis can be selected anywhere in a plane perpendicular to them.
v) Y axis is decided as Y = ZxX.

After assigning coordinate system we can find out DH parameters for each which are as follows:

Link Parameters

Length of $link_i$ (a_i): It is the mutual perpendicular distance between $Axis_{i-1}$ and $Axis_i$ Angle of twist of $link_i$ (α_i): It is defined as the angle between $Axis_{i-1}$ and $Axis_i$.

Joint Parameters

Offset of $link_i$ (d_i): It is the distance measured from a point where a_{i-1} intersects the $Axis_{i-1}$ to the point where a_i intersects the $Axis_{i-1}$ measured along the said axis.
Joint Angle (θ_i): It is defined as the angle between the extension of ai-1 and ai measured about the $Axis_{i-1}$.[23]

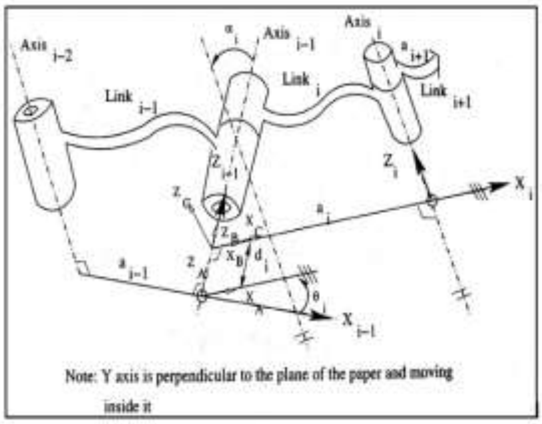

Fig 4: Denavit-Hartenberg Parameters

Now for given DH parameters transformation matrix can be found out as follows:

$$ {}^{i-1}_{i}T = {}^{i-1}_{A}T\,{}^{A}_{B}T\,{}^{B}_{C}T\,{}^{C}_{i}T $$

$$ = ROT(Z,\theta_i)TRANS(Z,d_i)ROT(X,\alpha_i)TRANS(X,a_i) $$

$$ = Screw_Z Screw_X $$

This transformation matrices makes forward kinematic calculations much easier than normal.

3.1.4. Study of Humanoid Walk

Humanoids walking is moving along at a straight line with moderate pace by lifting up and putting down each foot in turn, so that one foot is on the ground while the other is being lifted and center of mass is always in equilibrium [4].

There exist two kind of walking, namely, static walking and dynamic walking. In "static walking", the projection of the center of mass never leaves the support polygon during the walking. In "dynamic walking", there exist periods when the projection of the center of mass leaves the support polygon.

Static walking is comparatively stable waling pattern which can be used without any uses of stabilizers. But also, it results in Slower walking speeds. Whereas Dynamic walking is relatively unstable walking pattern and may cause Humanoid to fall while walking. To prevent this, it might require special system called as stabilizers.

Stabilizers is type of program, which modifies the walking pattern by using gyros, accelerometers, force sensors or other devices to tolerate for any imbalance. Dynamic Walking with combination of stabilizer may result in faster walking pattern.

3.1.4.1. Static Walking

The center of gravity of the robot is always within the area bounded by the feet that are touching the ground. There exist 2 stages of walking, namely, Single Support Phase (SSP) and Dual Support Phase (DSP). In SSP only one leg is touching the ground and CG is balanced above that leg. In DSP both feet are touching the ground and CG can move within support polygon i.e. from one leg to another. Walking Pattern is generated such that CG is always above supporting Phase.

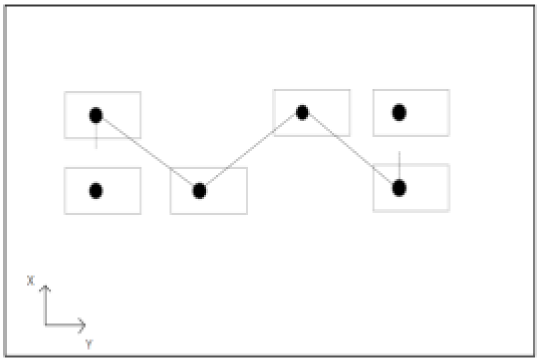

Fig 5: Walking Pattern for static walking

3.1.4.2. Dynamic Walking

There are few Dynamic walking pattern generation methods. The most known of which is Inverse pendulum method for Dynamic Walking.

Inverse Pendulum method

It is very complex to Dynamic study humanoid considering every joint and mass. So inverted pendulum method makes 3 assumptions which simplifies dynamic calculations of Humanoid. These assumptions are as follows:

i) We assume that all the mass of the robot is concentrated at its center of mass (CoM).
ii) We assume that the robot has massless legs, whose tips contact the ground at single rotating joints.
iii) We assume the robot motion is constrained to the sagittal plane and

defined by the axis of walking direction and vertical axis.

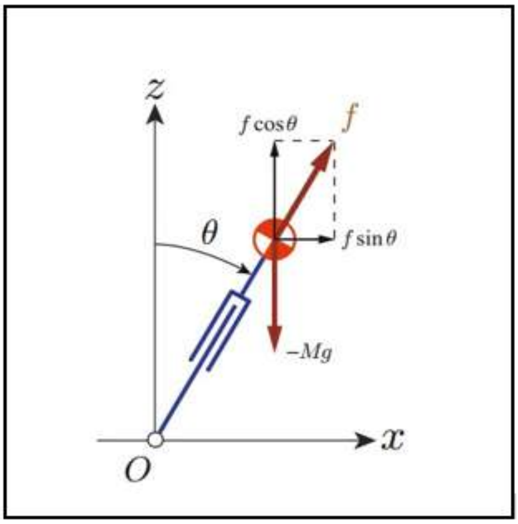

Fig 6: Inverse pendulum model

The inputs of the pendulum are the torque τ at the pivot and the kick force f at the prismatic joint along the leg. One of the important limitations is we cannot use big torque τ since the feet of biped robot is very small. If a walking robot has a point contact like a stilt, we have τ = 0.

In this case, the pendulum will almost always fall down, unless the CoM is located precisely above the pivot. Even with such a simple pendulum, we have a variety of falling patterns corresponding to different kick forces, f.

For Kick Force, f = (mg/cosθ), we get gravitational force balanced by kick force and CoM travels horizontally. Intuitively, we can say the pendulum is keeping the CoM height by extending its leg as fast as it is falling. We call this the Linear Inverted Pendulum.

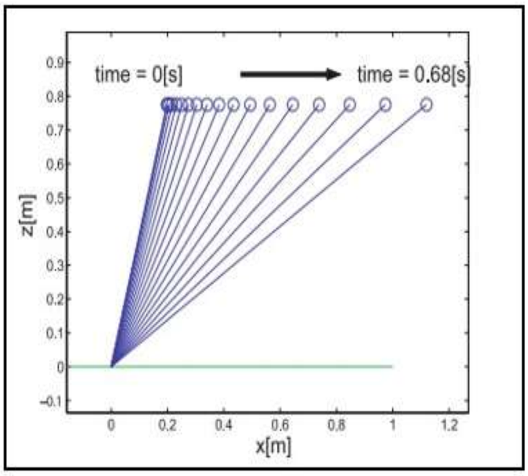

Fig 7: Horizontal Motion in LIP

3.1.5. Electronics Circuit and Components

3.1.5.1. MX28AT

The MX-28T Dynamixel Robot Servo Actuator is the newest generation of Robotis Dynamixel actuator; equipped with an onboard 32bit 72mhz Cortex M3, a contact-less magnetic encoder with 4x the resolution over the AX/RX series, and up to 3mpbs using the new TTL 2.0 bus. Each servo has the ability to track its speed, temperature, shaft position, voltage, and load. The newly implemented PID control algorithm is used to maintain shaft position can be adjusted individually for each servo, allowing controlling the speed and strength of the motor's response [24].

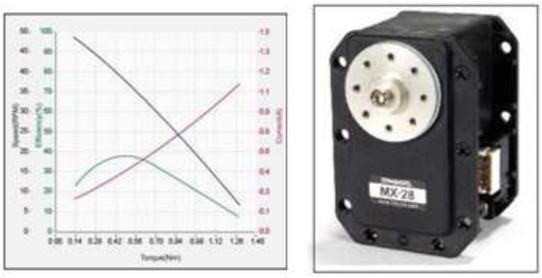

Fig 7: Performance Graph of (MX28AT)

3.1.5.2. MX64AT

The MX-64T Dynamixel Robot Servo Actuator is the newest generation of Robotis Dynamixel actuator. Each servo has the ability to track its speed, temperature, shaft position, voltage, and load. The newly implemented PID control algorithm used to maintain shaft position can be adjusted individually for each servo, allowing controlling the speed and strength of the motor's response. All MX Series servos use 12v nominal voltage, so MX Dynamixels can be mixed without having to worry about separate power supplies. All of the sensor management and position control is handled by the servo's built-in microcontroller. This distributed approach leaves your main controller free to perform other functions [25].

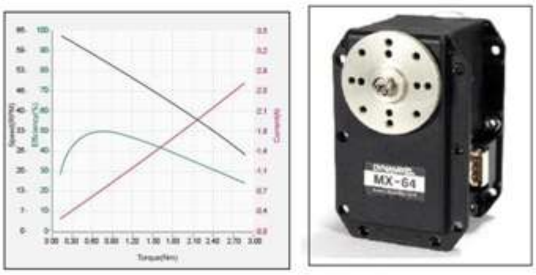

Fig 8: Performance graph (MX64AT)

3.1.5.3. AX12

The AX-12A servo actuator from Robotis is the most advanced actuator on the market in this price range. The AX-12A robot servo has the ability to track its speed, temperature, shaft position, voltage, and load. As if this weren't enough, the control algorithm used to maintain shaft position on the ax-12 actuator can be adjusted individually for each servo, allowing you to control the speed and strength of the motor's response. All of the sensor management and position control is handled by the servo's built-in microcontroller. This distributed approach leaves your main controller free to perform other functions [26].

Fig 8: Servo AX 12

3.1.5.4. SG 90 Servo

A servo motor is a rotary actuator or a motor that allows for a precise control in terms of the angular position, acceleration, and velocity. Basically, it has certain capabilities that a regular motor does not have. Consequently, it makes use of a regular motor and pairs it with a sensor for position feedback. It is a self-contained electrical device that rotates parts of machine with high efficiency and great precision. The Tower Pro SG90 9g Mini Servo is 180° rotation servo. It equips sophisticated internal circuitry that provides good torque, holding power, and faster updates in response to external forces.

Advantages: Sg90 servo motor has good speed control characteristics, smooth control in the entire speed range, almost no oscillation, high efficiency, low heat generation, high speed control, and high precision position control [27].

Fig 10: Servo SG 90

3.1.5.5. U2D2

U2D2 is a small size USB communication converter that enables to control and operate DYNAMIXEL with PC.

U2D2 can be connected to the USB port of the PC with the enclosed USB cable. It supports both 3Pin TTL connector and 4Pin RS-485 connector to link up with various Dynamixel. U2D2 does not supply power to Dynamixel; therefore, an external power supply should provide power to Dynamixel[28].

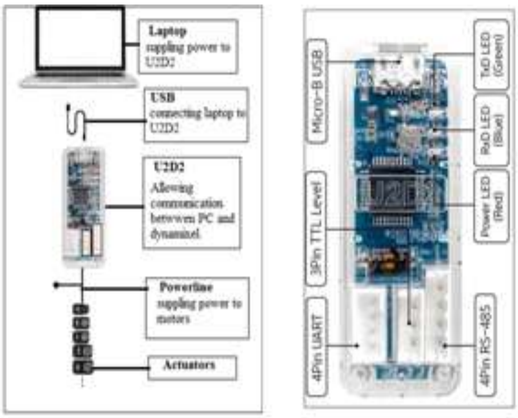

Fig 11: Components and Layout of U2D2

3.1.5.6. MPS2Dynamixel

Following are some of the important features of SMPS2Dynamixel.

I. This device provides power from the SMPS to the DYNAMIXEL.

II. Connect the SMPS to the DC terminal and connect the DYNAMIXEL using the cable.

III. 3P connector for AX series and 4P connector for DX/RX/EX series are mounted on the SMPS2Dynamixel. The power and communication line are all connected making it possible to play the role of the DYNAMIXEL expansion bus.

IV. When controlling the DYNAMIXEL with the USB2Dynamixel, power can be easily supplied to the DYNAMIXEL.

V. Can be used by connecting to a proper DC terminal. Can be used according to the proper voltage of the DYNAMIXEL.

VI. A shrink tube is used to cover the circuit part to protect it from short circuit from metal substances [29].

Fig 12: SMPS2Dynamixel

3.1.5.7. SMPS

To provide power supply to the humanoid robot, three SMPS are required. Two 5V, 5A SMPS units will be used to supply power to the robot's legs, while a 10A SMPS unit will be connected to the mid-body supply near the MX-64AT motor. This configuration ensures appropriate power distribution for optimal performance.

Fig 13: SMPS

3.1.6. 3D Printing

Fused deposition modelling (FDM), as one of the most commonly used low-cost three- dimensional (3D) printing technologies, has been a significant method to realize the transformation from conceptualization to the products. The parts can be manufactured rapidly and directly from computer aided design (CAD) model without geometry limitation and specific tooling and with high material utilization.

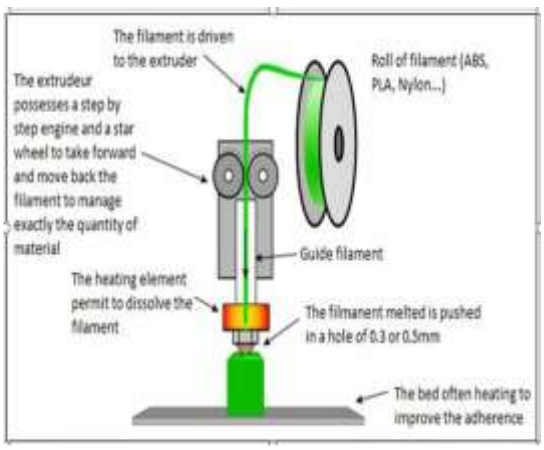

Fig 14: Working of FDM (Fused deposition modelling) process

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The above figure shows working of FDM, In the FDM process, the polymeric filament is continuously fed into the nozzle and heated to a semi liquid state, and then the thermoplastic material is extruded onto the previous layer along the cross-section contour and the filling trajectory. At the same time, the extruded material rapidly solidifies and adheres with the surrounding material to accumulate the required complex plastic parts. Hence, in comparison with the conventional fabrication process of composites characterized by impregnation and solidification of the matrix, FDM provides a possibility for manufacturing complex functional and structural parts with CFRTPCs (Continuous fiber reinforced thermoplastic composites).

3.2. Design of Humanoid

Mechanical structure of humanoid robot is an important task in the development of humanoid robot. The main objective is to design humanoid structure that can easily manipulate and capable imitate equivalent human motion. Stiffness and compliance consist with humanoid decide the flexibility of structure. Human dimension is considered as reference because their proportion allow for stable walking and optimal distribution of forces actuating while a human is walking. Biomechanics gives us the relation between human height and length of each link and in the same way for the mass. Design of humanoid robot should be Compact in size and light weight. The actuators of the Humanoid Robot used are Dynamixel Robot Servo Actuator. The design parameters include dimension aspect ratio, design of link, types of joint, forces on each joint, degree of freedom of each link, mass and height of body and mimic shape of human.

DESIGN OF HUMANOID			
ASPECT RATIO	DOF (DEGREE OF FREEDOM)	CAD MODELING	STRUCTURAL ANALYSIS

Fig 15: Building Blocks (Design of Humanoid)

3.2.1. Aspect Ratio

We study the human body and its motion to help in the development of humanoid robot Human body has 244 degrees of freedom (acronym is: DOF) Basically, free motion is work of joints and ligaments present in the body the number of joints are 230 many of them having single DOF and some have more than one. Consider weight and balancing of robot we decided to restrict height of robot up to 70cm [33]. Accordingly, ratios are taken.

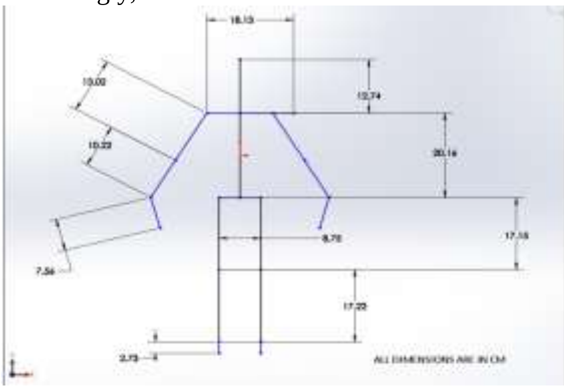

Fig 16: Aspect Ratio

3.2.2. Degrees of Freedom

The mechanical structure plays an important role in the humanoid's performance. DOF of mechanical system is the number of independent parameters that defines its configuration or state. Besides providing the general support to the main passive inactive subsystems of the humanoid, imitating the role of the human skeleton, it comprises a set of simple kinematics joints mimicking the most important degrees of freedom (DOF) of the human body.

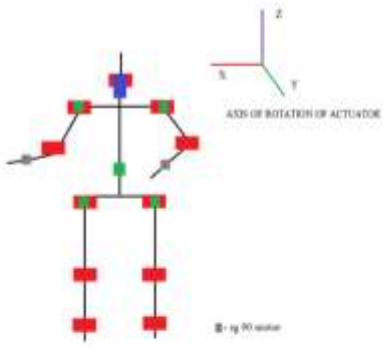

Fig 17: Motor location in Mechanical Design

ARM	SHOULDER(PITCH/ROLL)	2DOF×2=4DOF
	ELBOW(PITCH)	1DOF×2=2DOF
HAND	GRIPPER(GRASP/PINCH/GRIP)	3DOF×2=6DOF
TORSO	WAIST(ROLL)	1DOF
LEG	HIP(PITCH/ROLL)	2DOF×2=4DOF
	KNEE(PITCH)	1DOF×2=2DOF
	ANKEL(ROLL)	1DOF×2=2DOF
TOTAL		=21DOF

Table 1: Degree of freedom of humanoid robot

The mass of our humanoid is considered as 2kg and height is 70 cm. It has total 21 degree of freedom. Waist has 1 degree of freedom. Each leg has 4 degree of freedom and each arm has 3 degree of freedom and 3DOF of gripper for grasp or hold the objects. First degree of freedom of leg is inside the waist which contributes in balancing the robot while walking. The total height of our humanoid is 70 cm so according to biomechanics the length of each part is calculated.

3.2.3. CAD (Computer-Aided Design) Modelling

CAD modelling is use to create conceptual design, product layout, strength and kinematic analysis of assembly and the manufacturing processes themselves, produce detailed engineering designs through 3D and 2D drawings of the physical components of manufactured products. In order to design the humanoid robot, Solidworks software is used to draw the 3D model. The location and orientation of the motor is defined and embedded into the design. The design process has been repeatedly improved to obtain the best output. We use SOLIDWORKS 2017 edition software for CAD modelling.
Cad modelling is done by considering all above-mentioned parameter and following:

I. Aspect ratio and Degree of freedom of humanoid Robot.
II. Manufacturing process –Additive manufacturing by 3D printing technology (FDM- Fluid Deposition Modelling).
III. Considering above parameters, we decided that modelling should be done in 2 stages

3.2.3.1 Skeleton

Skeleton is the core of our humanoid which consists of motor holders, clamps and rigid links. The main power house of humanoid robot 'Battery' also at the section of skeleton along with wires and connectors. And main purpose of this Skeleton stage is to try to maintain Center of Mass (COM) of humanoid at the middle of body which is base of stable bipedal walking. The links will bear most of the forces and stresses which leads to high resistance and more stiffness. It also modelled such that it will be easier to 3D print these Parts. These are main load bearing parts of Humanoid.

Fig 18: 3D CAD of Full Skeleton structure of Humanoid Robot

3.2.3.2 Casing

Casing will consist of loosely attached parts that will mostly cover all joints and will act as protection and shock absorber for Skeleton. It will give aesthetic look to our humanoid. To make humanoid design more likely to human shape and for safety of the internal core skeleton structure this stage of aesthetic look is attached over a skeleton structure which includes the head also.

Fig 19: Casing of Humanoid

3.2.3.3. Clamp and Holder

For joining one component of Skelton structure with another and to hold the Actuators of the humanoid robot Clam and Holder system used. This allows relative movement with two of the joining components. This system allows the joints to move in a rotary motion along the axis of the dc motor actuator

Used. It is the most important part of the skeleton structure. There actuators used are- MX-28AT Dynamixel Robot Servo Actuator and MX-64AT Dynamixel Robot Servo Actuator, Tower pro sg90. The actuator sg90 is assembled in the cavity section of hand. But both the MX-28AT and MX- 64AT Dynamixel Robot Servo Actuator requires clamp holder system. Nut (M 2.5) and Bolt (wrench bolt M2.5*6) are used to assemble actuator and clamp-holder.

Fig. 20: Clamp and Holder Assembly

3.3.3.4. Complete CAD Assembly of humanoid Robot

Parts of skeleton structure like Thigh, Calf, Forearm, etc. are having shape of Rounded square to give more strength to structure makes humanoid deign safe and stable to and helps to manage bear a consider stress COM at center. The CAD model is made by considering the manufacturing process used -3d printing technology and properties of the Polylactic Acid Polymer plastic used.

The Assembly are divided into main parts as given below:

3.3.3.4.1 Upper Body Assembly

Fig 21: Upper Body Assembly (Isometric View)

3.3.3.4.2 Trunk Assembly

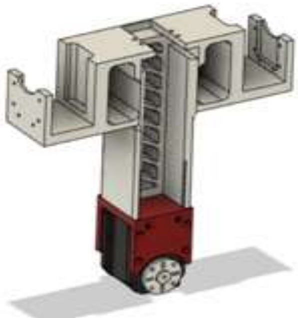

Fig 22: Trunk Assembly (Isometric View)

3.3.3.4.3 Lower Body Assembly

Fig 23: Leg Assembly (Isometric View)

3.3.3.5. Design of Gripper

The gripper has been designed as a 3D-printed component, emphasizing its significance within the humanoid's overall design. The design choice for the gripper entails a fully symmetrical three-fingered hand, enabling it to grasp objects of various shapes and sizes effortlessly, regardless of their orientation. To enhance its degrees of freedom and flexibility, the decision was made to independently drive each finger using three SG 90 Servo motors.

As an added feature, the mechanism incorporates a flexible tendon in the form of a 3D-printed spring. This integration further enhances the gripper's gripping capability and overall flexibility. With a total of three fingers per hand, the gripper provides three degrees of freedom (DOF), enabling it to perform intricate grasping maneuvers.

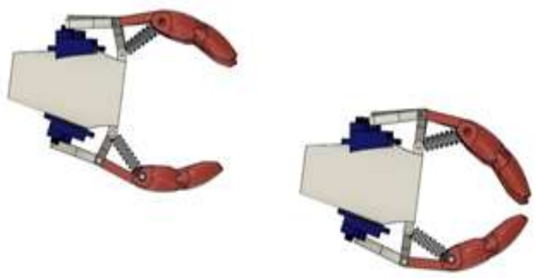

Fig 24: Flexion and Extension of Arm

For extension or release purpose spring will be used to extend fingers when servo pull is no longer in effect. When servo will return to its extension position spring force will force finger to extend and achieve extension position.

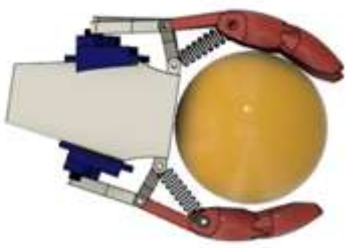

Fig 25: Variety of Objects Gripped by Arm

3.3. Simulations

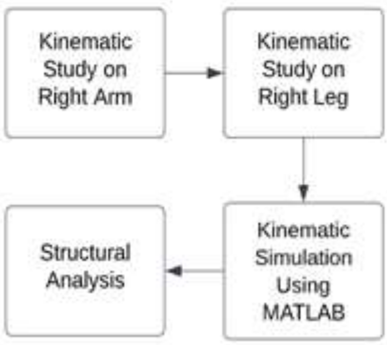

Fig 26: Simulation Performed on humanoid

3.3.1. Kinematic Study on Right Arm

As we are going to use our hands for pick, drop and various other application it is necessary to perform kinematic analysis on arm so we can use that framework in programming to automatically move hand to required end positions of hand.

Our arm is 3 revolute joint system (RRR). It has three revolute joints, 2at shoulder and 1at elbow joint. Due to revolute joint every joint angle (θi) is variable and taken as θ1, θ2, θ3 respectively.

Further Coordinate systems where assigned according to Denavit-Hartenberg notations. After assigning coordinate system to all links we can find all Denavit-Hartenberg parameters i.e. link and joint parameters [34]

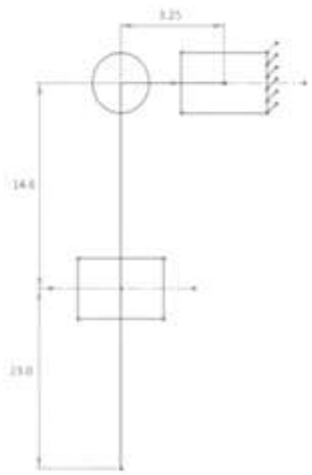

Fig 27: Kinematic Diagram of Right Arm

Link	θ_i	d_i	α_i	a_i
1	θ_1	3.125	90	0
2	θ_2	0	90	14.6
3	θ_3	0	90	23

Table 2: Denavit-Hartenberg Parameters for Right Arm

3.3.1.1. Forward Kinematics

$${}^{Base}_{3}T = {}^{Base}_{1}T * {}^{1}_{2}T * {}^{2}_{3}T$$

$${}^{Base}_{1}T = Ro(\bar{Z},\theta_1)\ Trans(\bar{Z},3.125)\ Rot(\bar{X}90)$$

$$= \begin{bmatrix} C_1 & 0 & S_1 & 0 \\ S_1 & 0 & -C_1 & 0 \\ 0 & 1 & 0 & 25/8 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^{1}_{2}T = Ro(\bar{Z},\theta_2)\ Trans(\bar{X}14.6)\ Rot(\bar{X}90)$$

$$= \begin{bmatrix} C_2 & 0 & S_2 & (73 * C_2)/5 \\ S_2 & 0 & -C_2 & (73 * S_2)/5 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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$${}^{2}_{3}T = Ro\,(\bar{Z}, \theta_3)\; Trans\,(\bar{X}23)\; Rot\,(\bar{X}90)$$

$$= \begin{bmatrix} C_3 & 0 & S_3 & 23 * C_3 \\ S_3 & 0 & -C_3 & 23 * S_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$${}^{Base}_{3}T = {}^{Base}_{1}T * {}^{1}_{2}T * {}^{2}_{3}T$$

F S_1 S_3+ C_1 C_2 C_3	$C_1 S_2$	C_1 C_2 S_3 - C_3S_1	73*_____C_1C_2/5 + 23*S_1S_3+23* C_1 C_2 C_3
C_1 C_3 S_1 -C_3 S_1	S_3 S_1	C_2 C_1 + C_2 S_1 S_3	73 * C_2S_1/5-23*C_1 S_3 +23* C_2 C_3 S_1
C_3S_2	$-C_2$	S_2S_3	73 * $S2$/5 +23* C_3S_2 + 25/8
0	0	0	1

This is final equation for forward Kinematics of position and orientation of hand corresponding to the Shoulder joint.

3.3.1.2. Inverse Kinematics

$${}^{Base}_{3}T = \begin{bmatrix} R_{11} & R_{12} & R_{13} & q_x \\ R_{21} & R_{22} & R_{23} & q_y \\ R_{31} & R_{32} & R_{33} & q_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$q_x = \frac{73 * C_1C_2}{5} + 23 * S_1S_3 + 23 * C_1C_2C_3$$

$$q_y = \frac{73 * C_2S_1}{5} - 23 * C_1S_3 + 23 * C_2C_3S_1$$

$$q_z = \frac{73 * S_2}{5} + 23 * C_3S_2 + 25/8$$

By solving above equations simultaneously we can find values of θ1, θ2, θ3 for required coordinates qx, qy, qz as follows.

$$\theta_1 = cos^{-1}\left(\frac{14.6^2 + 23^2 - q_x^2 - q_y^2 - (q_z - 3.125)^2}{2 * 14.6 * 23}\right)$$

$$\theta_2 = sin^{-1}\left(\frac{q_z - 3.125}{14.6 + 23 * co(\theta_3)}\right)$$

$$\theta_1 = tan^{-1}\left(\frac{q_y}{q}\right) - tan^{-1}\left(\frac{23 * sin(\theta_3)}{cos(\theta_2) * (14.6 + 23 * cos(\theta_3))}\right)$$

We can use above values of θ1, θ2, θ3 for required coordinates qx, qy, qz.

3.3.2. Kinematic Study on Right Leg

As we know legs are important part of a humanoid robot to make it mobile and capable to perform various assigned tasks, performing kinematic study on leg will provide us necessary parameters for path generation.

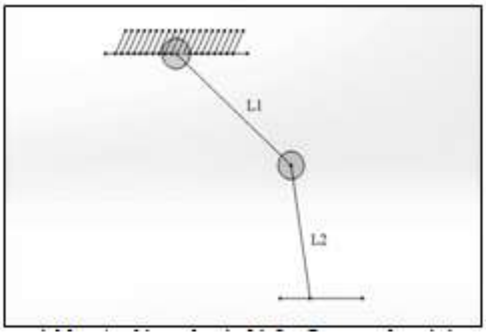

Fig 28: Kinematic Diagram of Right Leg

Here in this leg Assembly, Due to revolute joints Joint angle (θi) is variable. And its value is θ1 for first revolute joint. And θ2 for second Revolute Joint. Further Coordinate systems where assigned according to Denavit-Hartenberg notations.
Now parameter Table For given assembly are:

Frame	θi	di	αi	ai
1	θ1	0	0	0.17
2	θ2	0	0	0.16

Table 3: DH Parameters for Leg

3.3.2.1. Forward Kinematics

$$^{Base}_{2}T = {}^{Base}_{1}T \cdot {}^{1}_{2}T$$

$$^{Base}_{1}T = Ro(\bar{Z}, \theta_1)\, Trans(\bar{X}, .17)$$

$$= \begin{bmatrix} C_1 & -S_1 & 0 & .17 * C_1 \\ S_1 & C_1 & 0 & .17 * S_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{1}_{2}T = Ro(\bar{Z}, \theta_2)\, Trans(\bar{X}, .16)$$

$$= \begin{bmatrix} C_2 & -S_2 & 0 & .16 * C_2 \\ S_2 & C_2 & 0 & .16 * S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^{Base}_{2}T = {}^{Base}_{1}T \cdot {}^{1}_{2}T$$

$$= \begin{bmatrix} C_{12} & -S_{12} & 0 & .17 * C_1 + .16 * C_{12} \\ S_{12} & C_{12} & 0 & .17 * S_1 + .16 * S_{12} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This is final equation for forward Kinematics of position of foot corresponding to the Hip joint.

3.3.2.2. Inverse Kinematics

$$^{Base}_{2}T = \begin{bmatrix} C_\phi & -S_\phi & 0 & q_x \\ S_\phi & C_\phi & 0 & q_y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$q_x = .17C_1 + .16C_{12}$$

$$q_y = .17S_1 + .16S_{12}$$

$$C_2 = \frac{q_x^2 + q_y^2 - .17^2 - .16^2}{2 * .17 * .16}$$

$$C_2 = \frac{q_x^2 + q_y^2 - .0545}{0.0544}$$

Taking Inverse, we get,

$$\theta_2 = \arccos\left(\frac{q_x^2 + q_y^2 - .0545}{0.0544}\right)$$

This is the value of θ2.
Now,

$$q_x = .17C_1 + .16C_1C_2 - .16S_1S_2$$

$$= C_1(.17 + .16C_2) - S_1(.16S_2)$$

$$\rho = \sqrt{(.17 + .16C_2)^2 + (.16S_2)^2}$$

$$T = \arctan\left(\frac{.17 + .16C_2}{.16S_2}\right)$$

Therefore,

$$q_x = \rho C_1 sinT - \rho S_1 cosT = \rho \sin(T - \theta_1)$$

Hence,

$$\theta_1 = T - \arctan\left(\frac{q_x}{q_y}\right)$$

By this equation we can find value of θ1.

Using Equations of θ1& θ2 from Inverse kinematics, we can find orientation of link 1 and link 2 for given position of foot.

3.3.3. Kinematic Simulation Using MATLAB

As we can see, equations of kinematics are very complicated and requires a lot of calculations in terms of matrices. So Numerical computing software (MATLAB) was used to perform kinematics.

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3.3.3.1 Modeling of Arm

```
%Program to plot and model of right armstartup_rvc

dh=[
    0 3.125 0 1.571
    0 0 14.6 1.571
     0 0 23 1.571
    ]
k = SerialLink(dh,'name','Right arm'); k.plot([0 0
0],'tilesize',1,'basecolor',[1 1
1],'linkcolor',[0 0 0],'basewidth',1)
view([0 1 0]); k.teach;
```

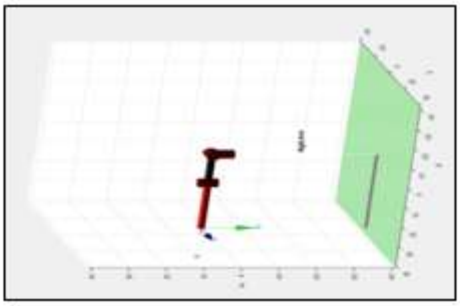

Fig 29: Modelling of Arm in MATLAB

3.3.3.2. Transformation matrix of dh parameters function

```
%transformation matrix for dh notations where theta is
variable and should be of syms data type.
function [matrix]=Trans_mat(theta_deg,d,a,alpha_deg)
theta=theta_deg*pi/180;   %to convert degree into radians

alpha=alpha_deg*pi/180;    %to convert degree into radians

matrix=[cos(theta) -sin(theta)*cos(alpha) sin(theta)
a*cos(theta)
    sin(theta) cos(theta)*cos(alpha) -
cos(theta)*sin(alpha) a*sin(theta)
    0 sin(alpha) cos(alpha) d0
    0 0 1];
end
```

3.3.3.3. Forward Kinematics

As we know matrix calculations are easier on MATLAB so, we wrote a MATLAB program to find final transformation matrix in forward kinematics to know final position of end effector for given set of values of θi this is program for finding out Final transformation matrix of forward kinematics of arm of humanoid.

```
%Program for finding out final transformation matrix of
forward kinematics
clc
symstheta1;
assume(in(theta1,'real') & theta1>(-pi) & theta1<pi);
symstheta2;
assume(in(theta2,'real') & theta2>(-pi) & theta2<pi);
symstheta3;
assume(in(theta3,'real') & theta3>(-pi) & theta3<pi);
t1=Trans_mat(theta1,3.125,0,90)
t2=Trans_mat(theta2,0,14.6,90)
t3=Trans_mat(theta3,0,23,90)
t=t1*t2*t3       %final transformation matrix
```

3.3.3.4. Inverse Kinematics Program

```
%program to find values theta1 theta2 theta3 for aparticular value
of x y %z coordinates
clc symstheta1;
assume(in(theta1,'real') & theta1>(-180) & theta1<180);
symstheta2;
assume(in(theta2,'real') & theta2>(-180) & theta2<180);
symstheta3;
assume(in(theta3,'real') & theta3>(-180) & theta3<180);

t1=Trans_mat(theta1,3.125,0,90)
t2=Trans_mat(theta2,0,14.6,90)
t3=Trans_mat(theta3,0,23,90) t=t1*t2*t3
x=35;  %X co-ordinate y=5;  %Y
co-ordinate z=3.25;    %Z co-
ordinate equ_for_x = t(1,4)== x
equ_for_y = t(2,4)== y equ_for_z
= t(3,4)== z
sol=solve([equ_for_x,equ_for_y,equ_for_z],[theta1,theta2,theta3]);
sol
```

this solution gives all possible combination values of θ1, θ2, θ3 for particular position of end effector.

3.3.3.5. Workspace Calculations

Workspace is important criteria for inspecting effectiveness of Robot (Manipulator). We have done workspace analysis on arm of robot to know which region is accessible for manipulator to perform pick and drop motion. Knowing workspace is important so that robot can autonomously decide whether the object is within reachable zone or not.

Normally, workspace is calculated by manually considering inner most and outermost regions in 2d views. But in this case, we found it difficult to find workspace just using 2d views as hand consists 3 degrees of freedom for motion in 3 dimensions [35].

So instead of general manual method we decided to find workspace using iterative method. In this method, we used transformation matrix of arm and using random values of θ1, θ2, θ3 so that we can see point which can be reached by our arm. We iterated this process thousands of time so that we can find approximate volume which can be swept by arm[36].

```
%program to find workspace using iterative method
clc;
clear;
startup_rvc
dh=[
    0 3.125 0 1.571
    0 0 14.6 1.571
     0 0 23 1.571
    ]
k = SerialLink(dh,'name','Right Arm')
k.plot([0 0 0],'tilesize',1,'basecolor',[1 1 1],'linkcolor',[0 0
0],'basewidth',1)
hold on
k.teach
hold  on
syms theta1;
assume(in(theta1,'real') & theta1>(-pi) & theta1<pi);
syms theta2;
assume(in(theta2,'real') & theta2>(-pi) & theta2<pi);
syms theta3;
assume(in(theta3,'real') & theta3>(-pi) & theta3<pi);
t1=Trans_mat(theta1,3.125,8)
t2=Trans_mat(theta2,0,14.6)
t3=Trans_mat(theta3,0,23)
t=t1*t2*t3
x = t(1,4);
y = t(2,4);
z = t(3,4);
th1_min=(-pi);
th1_max=pi;
th2_min=0;
th2_max=(pi);
th3_min=(-pi/2);
th3_max=(pi/2);
iteration=0;
total_itr=5000;
for i=1:1:2000
    th1=th1_min+rand*(th1_max-th1_min);
    th2=th2_min+rand*(th2_max-th2_min);
    th3=th3_min+rand*(th3_max-th3_min);
    theta1=th1;
    theta2=th2;
    theta3=th3;
    xplot=subs(x);
    yplot=subs(y);
    zplot=subs(z);
    scatter3(xplot,yplot,zplot,50,'MarkerFaceColor',[1
0],'MarkerEdgeColor','k');
    hold on
    iteration=iteration+1;
    fprintf('iteration %8.2f out of %8.2f \n',iteration,total_itr);
end
```

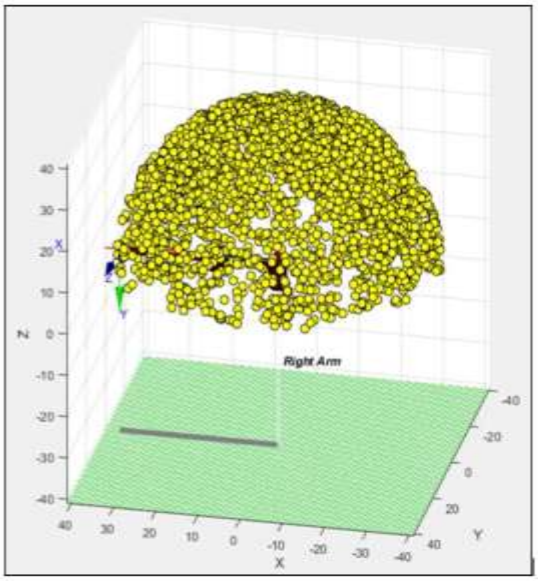

Fig 30: Workspace using Iterative Method in MATLAB

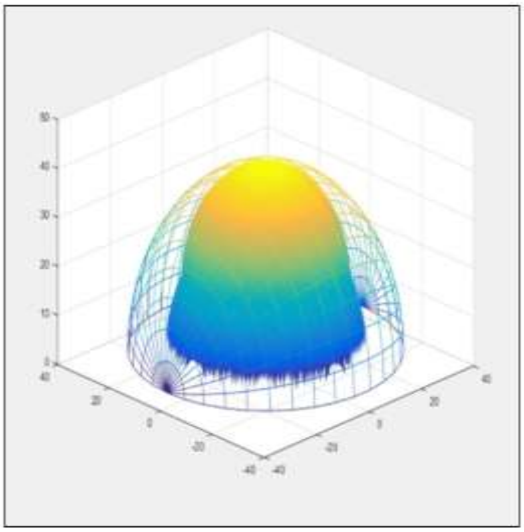

Fig 30: Workspace in MATLAB: Outer limit (Lined region) and Inner limit (Solid region)

3.3.4. Structural Analysis

After designing Humanoid Part, we performed mechanical structural simulation on various parts. 3d Printed parts are not single piece of material but a layer by layer deposition of plastic. Due to this, it exhibits different mechanical properties for different orientation, Shell thickness, Fill density, and fill structure. So, it is Difficult to find exact strength of 3d printed parts. Also, there is possibility of manufacturing defects and errors in 3d printing which also could result in less strength so we decided to keep huge factor of safety for those parts. We had different types of parts to be 3D printed in our project, so we used different types of setting to manufacture those parts. Also, we kept orientation such

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that Force on Part was perpendicular to the layers of 3d printing. As it will have more strength [37].

Mostly we divide our parts in two different categories according to their structure. First is Skeleton Joints and other is skeleton Bones. Skeleton joints were Complex parts with very thin cross section and less cross section area. Skeleton bones were comparatively simple structures with large cross section areas.

3.3.4.1. Topological Optimization and Static Structural Analysis of Shin

Iteration 1:

In the first iteration, the focus was on the structural analysis of the leg bone, which is one of the bones with the lowest weight in the entire body. To ensure safety, a compressive force of 30N was applied on the upper side of the bone, which transmits force onto the body. The lower part of the bone was fixed to simulate real-world conditions.

To perform the analysis, the material properties of ABS (Acrylonitrile Butadiene Styrene) were considered, as ABS is commonly used in 3D printing. A fill density of 20% was applied due to the large cross sections of the bone, along with a shell thickness of 0.5 mm. This resulted in an approximate fill density of 20%.

The compressive strength of ABS 3D printed parts with a 20% fill density was determined to be 20 MPa, which served as the basis for the analysis.

The results of the structural analysis provided insights into the bone's behavior under the applied compressive force. Parameters such as stress distribution, deflection, and overall stability were evaluated. These results helped identify potential areas of improvement and guided the subsequent iterations.

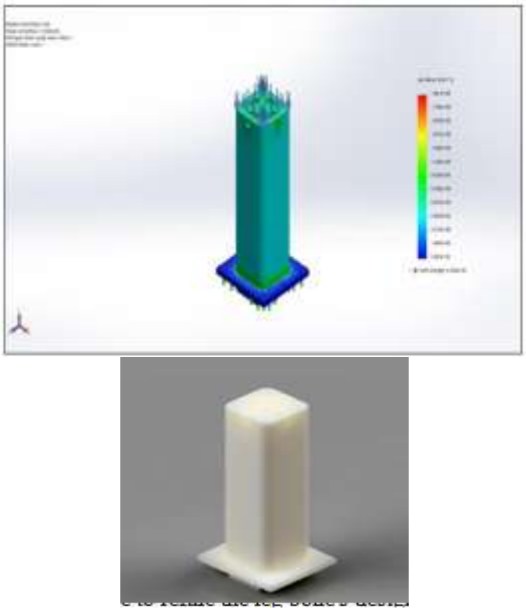

Fig 31: Iteration 1 Result (Shin Optimization)

Maximum stress was found to be 8 MPa which is much lower than permissible strength

Iteration 2:

In the second iteration, the key criteria of the humanoid's weight and strength were prioritized. Building upon the findings of the previous iteration, a topological optimization process was carried out to further enhance the leg bone's design.

Topological optimization involves optimizing the material distribution within a given structure to achieve a balance between weight reduction and structural integrity. This process aims to remove unnecessary material in non-critical areas while reinforcing regions that experience higher stress or load concentrations.

By applying topological optimization techniques, the engineers were able to refine the leg bone's design to reduce weight without compromising its strength. The results of the topologically optimized part exhibited significant improvements in terms of weight reduction while maintaining the required structural integrity.

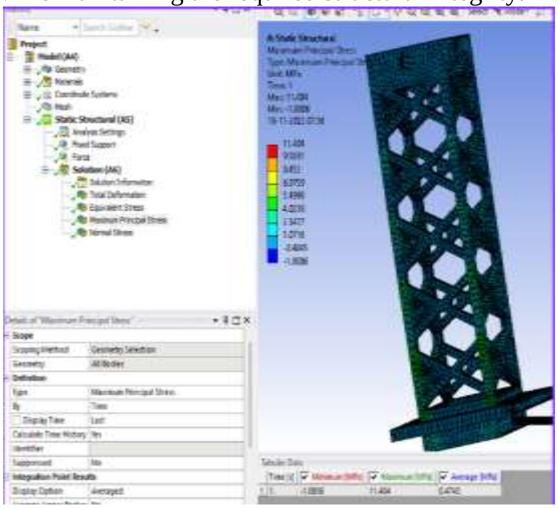

Fig 32: Iteration 2 Result (Shin Optimization)

Maximum stress was found to be 11 MPa which is lower than permissible strength. Even now the Maximum stress is greater than previous iteration's results, in iteration 2 67% less Material is used.

Therefore, the optimized design showcased a more efficient use of materials, eliminating excess material in non-critical regions. This resulted in a lighter leg bone that could still withstand the expected compressive forces and contribute to the overall functionality and performance of the humanoid.

The findings from this iteration provided valuable insights into the leg bone's structural efficiency and further informed the design process for subsequent iterations.

Fig 33: Iteration 1 vs Iteration 2 Design Comparison

IV. CONCLUSION

I. After studying the Human and Various Humanoids, Final Humanoids design gave a closer approach to the structural design of human body.

II. All Electronic components were neatly studied and resulted in successful electronic interfacing of all actuators and sensors.

III. Kinematics Study showed neat approach to realize motion of humanoid. Forward and inverse kinematics analysis helped in programming of Humanoid.

IV. Structural Analysis validated mechanical modelling of Humanoid.

V. The lower body of the skeleton structure of this project has been manufactured and assembly of the all required electronics equipment to mechanical structure successfully completed.

VI. The conclusions and result achieved from the project is a light and effective weight Humanoid robot, which delivers a Stable Humanoid Locomotion on plane surface.

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