DEVELOPMENT OF BIO-MIMETIC FORCE ATTENTIVE ROBOT HEAD

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119103B

Degree of Master of Science

Department of Electrical Engineering

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Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Industrial Automation

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Declaration

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Signature: …………………….. Date: ……………….

A.G.N. Jayasekara

The above candidate has carried out research for the Masters under my supervision

Signature: …………………….. Date: ……………….

A.G.B.P. Jayasekara

Abstract

This research was focused on the development of force attentive robot head for external forces acting on the head and used same as research plat form for future researches.

An anthropomorphic robotic head has been designed and developed to comply with the biometrical data of adult human head. The developed robot head has 3 degree of freedoms in the neck section. It is capable of ascertaining natural human like neck movements into a greater extent. This design is capable of minimizing the displacements between the moving axes and facilitating for a compact modular design. Commonly available DC motors in the market can be used as actuators instead of custom-made actuators. Therefore, the design is cost effective while providing adequate performance. DC motor driven brass metal structure was integrated with force sensor and other electronic components.

A detailed design of mechanical structure, selection of DC motors and electrical design of control system was included in the thesis. In addition to design of force sensors signal conditioning and interfacing circuits were designed and assembled all the components to a single assembly so that size of the head designed is similar to size of human head.

Force attentive features of robot head were developed based on two main modes of force. First, robot head is capable to detect the direction of external force acting on head and as the result head will move away from the direction of force. Here, by analyzing force sensor reading at neck of the robot, controller will identify the direction of external force and control command will activate to axis motor so that head is away from the force. Robot head was tested with main 8 directions of forces and it was functioning successfully for each case. This is what exactly happening once human head collide with an obstacle. Instantly Head will move away from the external force.

Second force attentive feature is to respond for the magnitude variance of the external force acting on the head. Robot head was tested by varying the magnitude of external force acting on the head. For less force, head was moving away to small distance with slow speed whereas once force is increased it moved to larger distance with higher speed. This feature is also with human head. If something collides with head hardly, the respond of the head will be faster than same thing collide with head gently.

Apart from that, the robot head has been developed in such a way that it can be used as a research platform that can be used for further research purposes.

Acknowledgement

I express my sincere gratitude to all the following individuals, those who contributed towards the completion of this project successfully.

At the very beginning, I would like to thank specially, my supervisor, Dr. A.G.B.P. Jayasekarafor his valuable suggestions and guidance provided throughout the project in spite of his busy schedules.

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Finally, I am very much thankful to my family for their understanding and motivation given throughout this project to make it a success.

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1.0. INTRODUCTION

Robot is atypically designed automated machine which is used to replace human and his activities. The word robot comes from the Slavic word robota, which means labor. In the past robotic machines were mostly used in manufacturing lines, especially in the auto industry. At present, robots are used not only in such industries but also in workplaces, houses, and even on the International Space Station. More technically, it is a system that contains sensors, control systems, manipulators, power supplies and software all working together to perform a task. Designing, building, programming and testing a robot is a combination of physics, mechanical engineering, electrical engineering, structural engineering, mathematics and computing. In some cases biology, medicine, chemistry might also be involved. A study of robotics means that students are actively engaged with all of these disciplines in a deeply problem-posing problem-solving environment.

The term robotics is derived from the word robot. It was first introduced by Czech writer Karel Capek in his 1920 play “Rossum’s Universal Robots”. Robotics is a branch of technology that deals with the design, construction, operation, and applications of robots and autonomous systems, as well as the computer systems that power such devices, including control, sensory feedback and information processing .Modern robotics can be broken down into dozens of subfields. Robotics includes everything from biomechanics to micro engineering and artificial intelligence to behavioral science.

Robots have developed a lot up to now since the early days of robotic innovation. Large, complex, and expensive industrial robots were popular during the beginning of robotics but with the evolution nowadays robotics focus on inexpensive, smaller, safer, and human friendly robots which are also human like[1][2]. Some of these new robots can perform human like activities but they don’t have a very human like appearance (e.g. anthropomorphic robots) but some of them have both above features (e.g. android robots). The next generation robots will have the ability to think, act, and evolve on their own. [3]

Commercial and industrial robots are now in widespread use performing jobs more cheaply or with greater accuracy and reliability than humans. They are also employed for jobs which are too dirty, dangerous or dull to be suitable for humans. Robots are widely used in manufacturing, assembly and packing, transport, earth and space exploration, surgery, weaponry, laboratory research, and mass production of consumer and industrial goods. With recent advances in computer hardware and data management software, artificial representations of humans are also becoming widely spread [5][11].

Development of bio-mimetic robot heads isarapid developing research area of robotics with the purpose of associating robots for more social activities. Human head has large number of degree of freedom for its natural movements which are very complex to model. Other than basic movements of the head like tilting, rotating muscles have more complex movements at different expressions of humans. As an example when person is crying his eyes, eye brows, mouth & other muscles in face is having different movements when compared with smiling. Researchers have been developing human-like head robots in order to develop new head mechanisms and functions for a humanoid robots that have the ability to communicate naturally with a humans by expressing the human-like emotions [5].Robot heads with bio mimetic approach have been developed and they are more analogues to natural human head in movements, sensing and appearance as well. Hiroyasu Miwal of Humanoid Robotics Institute, Waseda University, Tokyo, Japan developed four sensations (the visual, auditory, coetaneous and olfactory sensations) of a human’s five senses by developing robot WE-3 series since 1995**.** In 2002, they have developed a new human-like head robot called WE-4 and realized emotional expression with not only the face, but also the upper-half of the robot’s body [5]. Hashimoto & Kobayashi of Tokyo University has developed the robot SAYA [6], it can scan the staring expression, and identify a certain mood the expression represented, and then reflect the corresponding expression by the motion of Facial points driven by the artificial muscle. T.Asfour and team of the Karlsruhe University have developed a robot, whose head motions are accomplished by artificial muscles developed to achieve both rotating and sliding mechanisms [7].

Takizawa and Shiraiof Osaka University Japan have developed method for Recognition of intersection scene by attentive observation for a mobile robot. Perception for the Robot is achieved by the comparing homogeneous color regions of consecutive images [8]. That was the development stage of attentive robot head which

was built based on 3D stereo camera processing algorithms in 1994. Stasse andTelledeveloped an attentive robot head which is functioning based on 3D stereo image analysis which was further development of above mentioned research.[9]
Most of attentive robot heads were focused on only vision base systems. There is a vast research gap in the area of force, temperature and touch (soft or rough) sensing & adopting attentive features to those inputs by the robot head. Out of above researches WE4 developed in Waseda University, Tokyo has developed temperature sensing & olfactory ability for the head but it is still not incorporated to take decisions by the robot based on above sensing inputs. So this research is focusing to these areas and development of hardware implementation of a bio mimetic robot head that can sense & react for the resistive forces acting on his head as well as feel the environment temperature by his skin and make decision based on temperature variances.

1.1. Robot Heads

When designing and developing robotic heads, vision system, auditory system, facial expressions, and neck movements are mainly considered. Controlling of each of these systems to implement interactive features as much as closer to natural interactions is the main focus. At present there are ongoing researches in the world to develop mainly anthropomorphic and android robotic heads which can perform perfectly as a human head.

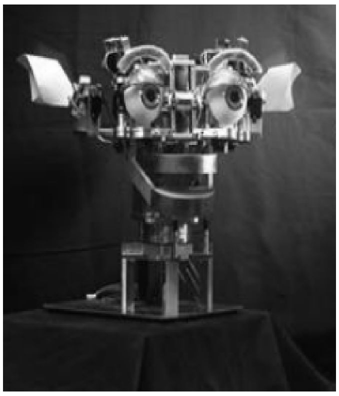
There are several bases to classify robotic heads such as appearance, controlling method, functionality, and behavioral characteristics. The main classification is given as anthropomorphic, zoomorphic, and technomorphic. Based on the method of controlling there are three robot heads such as autonomous, semiautonomous, and manual control.

1.2. Robot heads developed for vision based systems

This is the most developing area of robot head when it compares with other sensations of robot heads like force, odor, etc. So far scientists have carried out so many researches on visual tracking, image processing algorithms to develop a robot head more similar to human vision and perception. It is thus essential to study about these vision based robot heads developed by scientists and same will provide clear idea of head control principles which will be compulsory for our project scope.As a literature review, the following existing robotic heads are considered.

1.2.1. Twente

This has been realized in thepurpose of having a research platform for human-machine interaction. The design features a fast, four degree of freedomneck, with long range of motion, and a vision system withthree degrees of freedom, mimicking the eyes. The vision system is based on a saliency algorithm that uses. the camera images to determine where the humanoid headshould lookThe motion control algorithm receives, as input, the output of the vision algorithm and controls thehumanoid head to focus on and follow the target point[14]



- Degree of freedoms (neck – 4 , eyes – 3)
- Sensing equipment(stereo camera, encoders)
- Actuators (geared DC motors, gravity compensators)
- Controlling methods (parallel and series
- kinematic operation)
- Human like interactions: mimicking eyes, facial expressions, tracking objects, etc. [14]

Fig1.1: Twente

1.2.2. Kismet

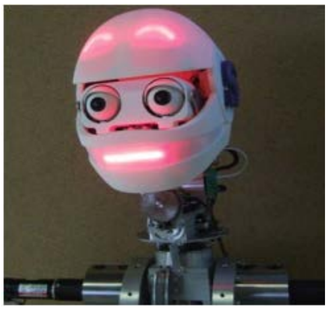
The humanoid robots Kismet and Cog, designed at the MIT Artificial Intelligence Laboratory, exemplify such objects, explicitly designed to relate to people in human-like ways, to detect stimuli that humans find relevant respond to stimuli in a human-like manner, have a roughly anthropomorphic appearance. This work was not experimental, but exploratory and qualitative, meant to increase understanding of the issues children raise at a first encounter with a novel form of social intelligence [15]

- 4 Degree of freedoms (vision system)
- 15 Degree of freedoms (facial features)
- Sensing equipment (color CCD camera)
- Actuators (servo motors)
- Human like interactions (facial expressions
- anger, fatigue, fear, disgust, excitement

Fig 1.2: Kismet

1.2.3 .WE-4RII

This emotion expression humanoid robot WE-4RII (Waseda Eye No.4 Refined II) was developed by integrating the new humanoid robot hands RCH-1 (RoboCasa Hand No.1) into the emotion expression humanoid robot WE-4R. Furthermore, Researches confirmed that RCH-1 and WE-4RII had effective emotional expression ability because the correct recognition rate of WE-4RII's emotional expressions was higher than the WE-4R's one. Mechanical features of WE-4RII are as below [16]



- Degree of freedoms (neck - 4, eyes – 3, eyelids – 6, eyebrows – 8, lips – 4, jaw – 1)
- Sensing equipment (CCD camera, microphone, gas sensors, force
- Sensing resistors, and thermistor)
- Actuators (DC motors)
- Controlling methods
- Human like interactions (emotions like happiness, anger, surprise,Sadness, disgust, and fear)

Fig1.3: WE-4RII

1.2.4. Roman

ROMAN is a humanoid head introduced which will use behavior-based control to realize facial expressions which are a basic ability needed for interaction with humans is presented. Furthermore apoll in which the generated facial expressions should be detected is visualized. Additionally, the mechatronic design of the headand the accompanying neck joint are given. From the researcher's point of view, if the robot head is human-likethe complexity of this problemwill be reduced. Using behavior-based control architecture for the robot headROMAN, facial expressions were realized. In experimentswith several persons it is shown that the generated facialexpressions are in general classified correctly [17]

Fig 1. 4:Roman

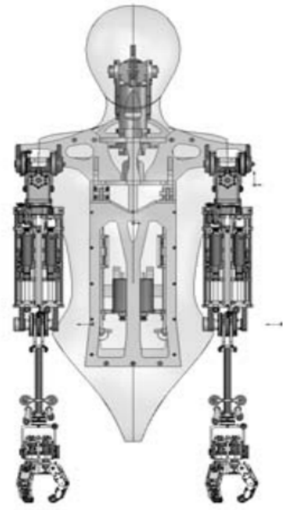
- Degree of freedoms (vision system –4, facial features – 15)
- Sensing equipment (stereo vision cameras, microphones, inertial system)
- Actuators (Servo Motors, stepper motors and DC motors)
- Human like interactions (head movements, wrinkling nose, eye movements, stretching and pressing lips, raising and lowering eyebrows)

1.3. Existing force sensing robot heads

There are several researches have been carried out in the area of force sensing of robot arms. But there is vast research gap can be identified in the field of developing of force attentive bio mimetic robot heads. If we go through the below researches carried out in the area of force sensing, it can be easily identified, all these researches has been focused on developing a different kind of force sensing algorithms only in robot arms and no any humanoid head has been developed in the area of force sensing.

1.3.1. DOMO- A force sensing humanoid robot for manipulation

Domo is to be a research platform for exploring issues in general dexterous manipulation, visual perception, and learning. This project is currently in the design and development phase. The real-time sensorimotor system is managed by an embedded network of five DSP controllers. The vision system includes two FireWire CCD cameras and utilizes thesoftware library for visual processing. The cognitive system runs on a small, networked cluster of PCs running the Linux operating system [11]

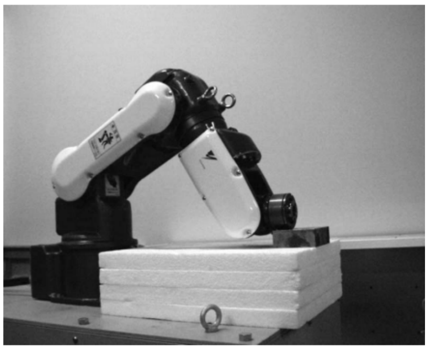


- DOMO is an ongoing research for developing a humanoid robot as a research platform for exploring issues in general dexterous manipulation.
- Out of 29 DOF only 2 DOF available for the head (neck)
- Proposed to develop force sensors for the head by using potentiometers. Integrated through signal amplifier and filters.
- Still, no development on force attentive features of the head.

Fig 1.5:DOMO- A force sensing humanoid robot for manipulation research

1.3.2. Modeling of Force Sensing Disturbance Observer for Force Control

This research reveals, in order to solve the instability of force control, the disturbance observer is implemented instead of the force sensor. The disturbance observer can observe the external force without force sensors. When the disturbance observer is implemented in a robot, a force control system does not include a soft mechanism between a robot and the environment. Since a robot can detect the environmental information directly, a wide bandwidth of force sensing is attained. In this way, this paper solves the problems of force control by considering the force sensing method without changing the control architecture, and the ability of force control is improved. Experimental results show viability of the proposed method [10]



- It was tested on convectional type robot arm with 6 DOF
- No force sensors were incorporated for force Control.
- Reaction torque observer used instead of force sensors
- More structural changes, experiments required to use the principle for humanoid robot head

Fig1.6: Robot arm used for disturbance observer based force controller

1.3.3. Intrinsic Force Sensing Capabilities of Continuum Robots

This research presents the theoretical analysis and the experimental validation of the force sensing capabilities of continuum robots. These robots employ super-elastic NiTi backbones and actuation redundancy. The paper uses screw theory to analyze the limitations and to provide geometric interpretation to the sensible wrenches. The analysis is based on the singular value decomposition of the Jacobian mapping between the configuration space and the twist space of the end effectors. The results show that the sensible wrenches belong to a two-dimensional screw system and the insensible wrenches belong to a four-dimensional screw system. The theory presented in this paper is validated through simulations and experiments [12]

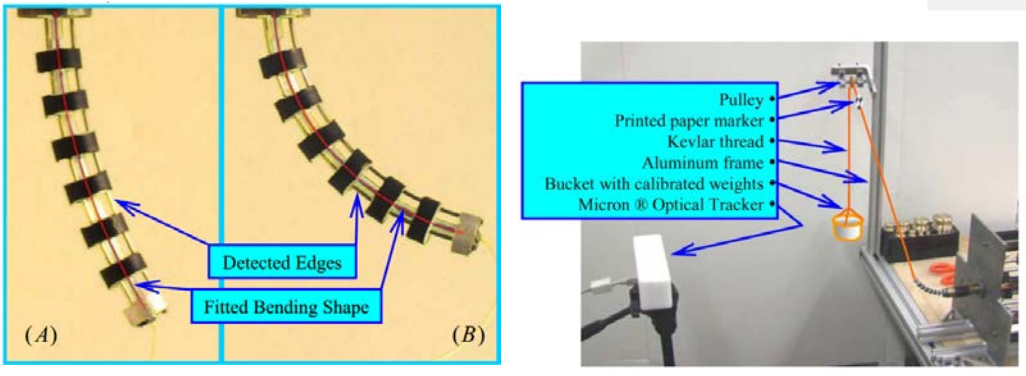


Fig 1.7: Intrinsic Force Sensing Capabilities of Continuum Robots

- The analysis is based on the singular value decomposition of the Jacobian mapping between the configuration space and the twist space of the end effecter.
- experimental setup was constructed to validate the possible use of joint-level force information to sense the wrench applied at the distal end of the robot
- Limited to slight forces and no experiments about control actions intergraded to the model
- Not possible to apply to hard external forces and suitable for applications like surgery where small external forces are involved.

1.3.4. Tactile Sensing Suite for Robot Hands and Use in Force Control

This Research presents a full tactile sensing system for the Utah/MIT Dextrous Hand, which is now commercially available through Sarcos Inc. (Salt Lake City, UT). The tactile sensing system covers all finger segments including curved fingertips and the palm (Fig 1.8). The tactile sensors slip on to the finger segments, and while developed initially for the UMDH could readily be recast for other finger segment shapes [13]

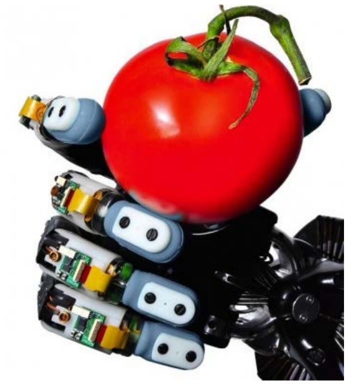


Fig 1.8: Tactile force sensing suite for robot hand

- This research was focused to develop a full tactile sensing system for the dexterous Hand, which is now commercially available
- Capacitive type force sensors were used for finger tips
- The combination of tactile plus force sensor yielded the best response, as the dynamic range could be divided between them
- No research has been developed so far to use this kind of force sensing method for robot head or neck.

The report starts with an introduction as a 1st chapter where describe the present development of attentive robot heads. 2nd chapter describes design aspects of interactive robot head. The 3rd chapter consists of different reactions for external forces of the designed robot head. The 4th chapter consists of few case studies for different mode of external forces. Fifth and sixth chapters will describe the conclusion and future directions of my research

2.0. DESIGN OF ROBOT HEAD

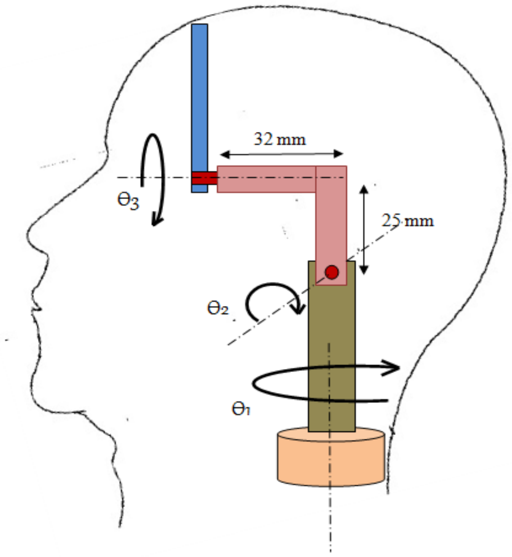
2.1. Overview

Designing of interactive robot headsfor different kinds of sensations is a rapidly developing area of the robotics.Manyrobot heads with anthropomorphic features are developed by the researchers to improve the social interaction between robots and humans. However, the existing robotic heads are basically focused on visual based interactions and need to have force attentive features to facilitate friendlier interactions with humans.Also among researches in the area of force sensation, hardly no any research have been carried out to develop a humanoid robot head for force sensing by mapping human head movements. Therefore, this research was focused on design and development of an anthropomorphic robotic head that can make reflex actions based on external forces applied on it. The design parameters of the robotic head have been decided by examining the biomechanics of human head. Basic design targets were to develop its force attentive features for both directional based response and magnitude based responses.

The functionality of the overall system is briefly described in this chapter. Particulars on mechanical design of the robot head are also presented.Details about the electrical and control system are also presented in this chapter. Proposed robot head was designed based on the actual movements of human head. Rotational centers, limits of each rotational movement were set according to the biomechanical geometry of human head. This exact mapping of human head geometry to the proposed robot head make humanoid head in the aspects of aesthetic and functioning as well. Head movements are achieved by electric motors which more controllable compared to other means of actuations like pneumatics, hydraulics, etc. Brass and mild steel are used as base material for the structural components. Other than those, regiform and plastics were used for making other outer accessories of the head.

2.2. Mechanical design

For the movement of head rack and pinion mechanism has been used for each rolling, pitching and yawing motions of the robot head. Basically this method was chosen because this method requires comparably less space and all mechanism can be inserted into head structure itself. Mechanical analysis has been carried out for kinematic and dynamics based on speed of motions of actual human head.



For an adult, position of pitching center,

X=-9.7 mm, Y= -32 mm, Z= -25 mm

Fig 2.2: Geometrical centers of well build human head

According to biomechanical geometry of human head, its pitching center is located at (-9.7mm,-32mm,-25mm) with respect to the rolling center of the head [25]. Please refer Fig 2.1. As per above rotational center diagram, centers of proposed robot head need to be located at exact locations to perform human like head movements. Auto CAD software has been used as the software for the designing of structure.

Auto CAD model Real model

Fig 2.2: Head mechanism design and implementation

Above rolling and pitching rack and pinion assembly has been arranged to rotate a single vertical axis with the arrangement of a base structure to the head as in Fig 2.2. Neck motor was placed over there and yawing movements for the above assembly is generated through the yawing motor. Rotary encoders were on pinion wheels of each rolling and pitching assemblies. Final assembly of robot head was consisting of other supporting brackets for axis motor and encoders as well. Hardware model during developing stage was as in Fig 2.3.

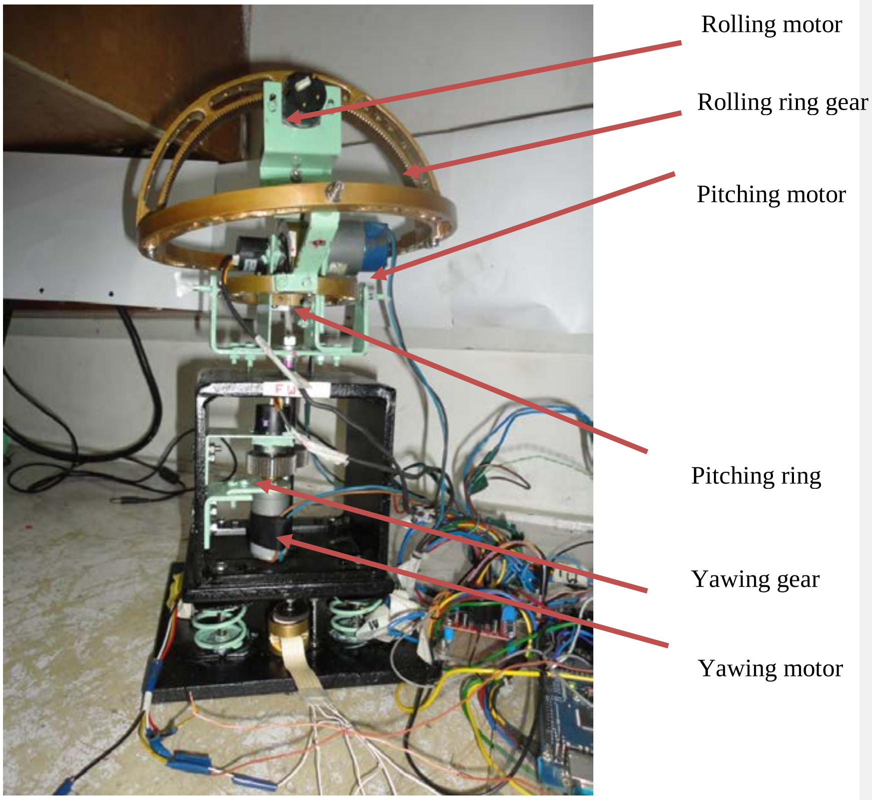


Fig 2.3: Complete mechanical assembly of robot head

2.3. Kinematics and dynamics

In this case, end position of robot head is known and controller needs to determine individual rotational angles of each axis motor. So kinematic algorithms are written on MATLAB and solutions of these algorithms are fed to the Arduino controller. According to the force signals controller will determine head destination. According to the destination, rotation angles of each motor will be determined as below.

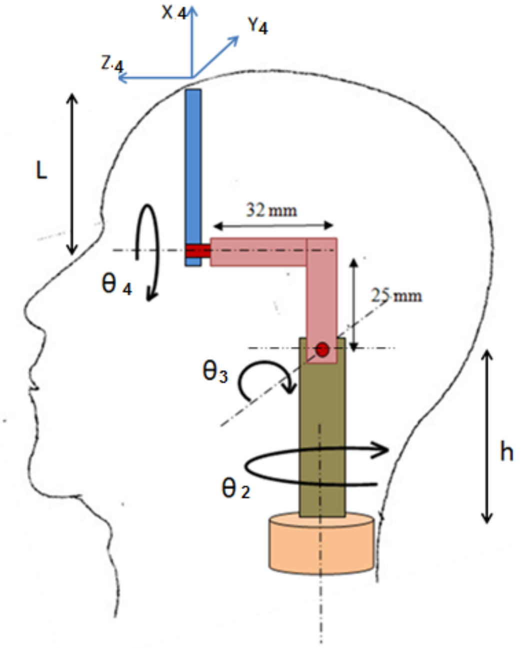


Fig 2.4: Locations of movement centers and rotational axis of the robot head

By using the kinematic model we can determine a position of the robotic head with respect to a defined base frame when we know the rotate angles of the three motors. A kinematic analysis has been carried out for the robotic head using the Euler angle method to determine the trajectory of a pre-specified point on the head with the variation of rotational angles of actuating motors in the neck section. Based on the prior studies done, kinematics is the geometry of pure motion which considered without reference to force or mass. Here the kinematic model has been used to determine motion and geometry of the head with respect to the base frame. In kinematic model each motor has been considered as a frame and face of the head has been also taken as frame. Coordinating system which we define and consider for the kinematic analysis is shown in Fig 2.4.

For an adult, position of pitching center,

X= -9.7 mm,Y= -32 mm, Z= -25 mm

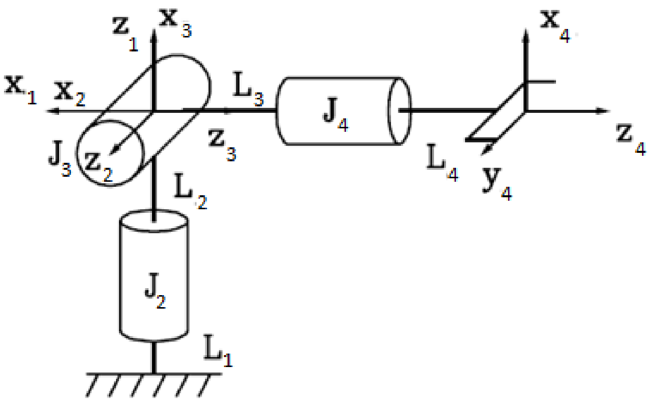


Fig 2.5: Kinematic model of the robot head

DH parameters of the robot head were calculated as below

Table 2.1: DH parameter of the robot head

Frame	**d**	**ϴ**	**A**	**α (deg)**
L_1	0	Θ_2	0	-90
L_2	0	Θ_3	0	90
L_3	d_4	Θ_4	0	0

Where

$d_4 = h + (0.25/\sin\Theta_2) + L\cos\Theta_3/\sin\Theta_2$

For the simplicity it is indicated Sin as S and Cos as C for future notations.

Transformation matrices of each joint are,

$$ {}^{1}_{2}H = \begin{bmatrix} C2 & 0 & -S2 & 0 \\ S2 & 0 & C2 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \qquad {}^{2}_{3}H = \begin{bmatrix} C3 & 0 & S3 & 0 \\ S3 & 0 & -C3 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

$$ {}^{3}_{4}H = \begin{bmatrix} C4 & -S4 & 0 & 0 \\ S4 & C4 & 0 & 0 \\ 0 & 0 & 1 & d4 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

So, total Transformation Matrix,

$$ {}^{1}_{4}T = \begin{bmatrix} C2.C3.C4 - S2.S4 & -C2.C3.C4 - S2.C4 & C2.C3 & C2.S3.d4 \\ S2.C3.C4 + C2.S4 & -S2.C3.S4 + C2.C4 & S2.S3 & S2.S3.d4 \\ -S3.C4 & S3.C4 & C3 & C3.d4 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

So, The rotation matrix of the robot model is,

$$ {}^{1}_{4}R = \begin{bmatrix} C2.C3.C4 - S2.S4 & -C2.C3.C4 - S2.C4 & C2.C3 \\ S2.C3.C4 + C2.S4 & -S2.C3.S4 + C2.C4 & S2.S3 \\ -S3.C4 & S3.C4 & C3 \end{bmatrix} $$

2.4. Inverse Kinematic model

Now the optimal rotational angles of each joint needs to be calculated for predefined 8 destinations of the robot head and same needs to be feed to the microcontrollers to generate PWM for each axis motors.

First robot head was moved to our desired destination and each axis rotational angles were measured by using encoder signal coming to the controller. Rotational matrices were calculated for all 8 nos of head destinations.

As example for the right-back movement of robot (please see Fig 3.4) below rotation matrix were calculated through axis encoder angles.

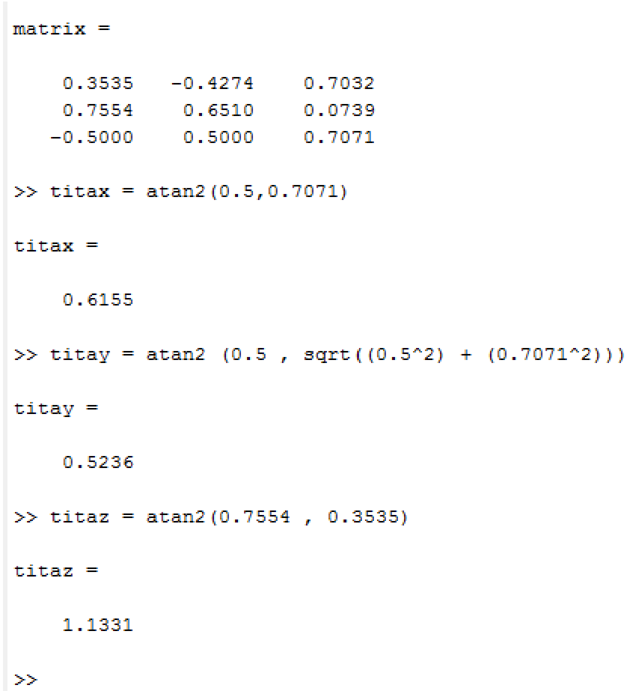
Case: Destination of the robot head-Most right-back end

Joint angle measured (Θ_2,Θ_3,Θ_4): 06^0, 45^0, 45^0

So, Rotation Matrix, R = $\begin{bmatrix} 0.3535 & -0.4274 & 0.7032 \\ 0.7554 & 0.6510 & 0.0739 \\ -0.5 & 0.5 & 0.7071 \end{bmatrix}$

Now this rotational matrix was solved by using MATLB to find Euler angles. Out of the resultant angles optimal solution was selected and that value insert to the Arduino program.

MATLAB code for generating Eular angles of above rotation matrix:



```
matrix =

    0.3535   -0.4274    0.7032
    0.7554    0.6510    0.0739
   -0.5000    0.5000    0.7071

>> titax = atan2(0.5,0.7071)

titax =

    0.6155

>> titay = atan2 (0.5 , sqrt((0.5^2) + (0.7071^2)))

titay =

    0.5236

>> titaz = atan2(0.7554 , 0.3535)

titaz =

    1.1331

>>
```

In addition to above base solution, some other solutions also can be derived by substituting Θ_x = (2π-Θ_x). Out of all these solutions, optimal solution will be selected.

For remaining 7 destinations of the robot also Euler angles were derived and optimal solutions were feed to the Arduino program so that robot head is moved to its destination.

2.5. Electrical design:

Selection of axis motors has been done by considering speed of each head movements of human. Gear ratio of rack and pinion mechanisms has been predetermined and motor speed limits calculated based on selected gear ratios. DC geared motors have been used as axis motors and feedback encoders used to get feedback for the controllers. Theoretical calculations for the selection of motors are given below.

Selection of rolling motor:

According to the biological data of well build human head its maximum rolling speed during walking is 90deg/s and maximum rolling range is +/- 50 degree from its vertical position [27]. Also according to the biological data volume of well build human head was taken as 3947 cm3 [28] whereas diameter of head can be approximated as 196 mm.

So, according to biological data,

Minimum time takingby head to roll its destination = 50/90

= 0.55 s

So, Gear ratio of rack and pinion = 70*360/(90*60)

Gear ratio of rack and pinion = 4.67

Real value taken for fabrication (due to machine facility) = 7

Minimum number of teeth that can be machined in milling = 18

So, No of gear teeth of Ring gear = 18* 7

= 126

Width of a gear teeth = 2.4 mm

So, diameter of the human robot head = $(252*2.4)/2\pi$

= 192.62 mm

Outer diameter of the head (with 8mm metal thickness) =193mm + 16mm

= 209 mm

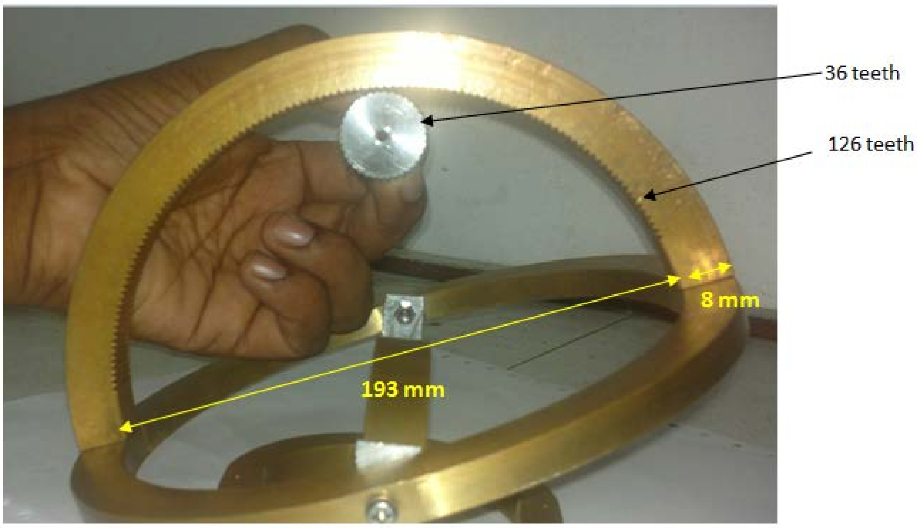


Fig 2.6: Designed parameters of rolling gear assembly

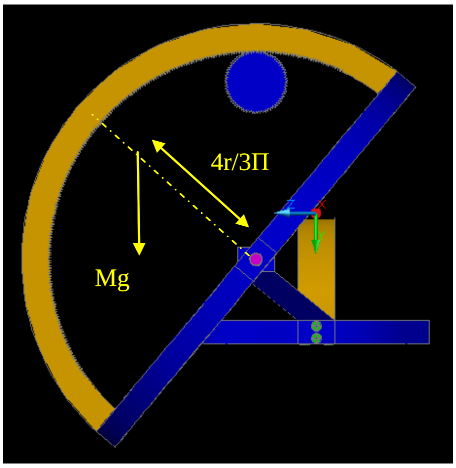


Fig 2.7: Loads on rolling motor of the robot head

Mass of rolling semi ring, M = 0.450 kg

Max ideal torque on rolling motor $= M * (4r/3\Pi)$

$= 0.45*4*0.1/3\Pi$

= 2.00Kgcm

Estimated frictional torque = 0.14*2.00kgcm

= 0.28 kgcm

Inertia torque, $\Pi = I\ \alpha$

$\Pi = (Mr^2)\ \alpha$

$= 0.45(4*0.1/3\Pi)^2 * 1000$

= 0.81 kgcm

Torque on rolling motor (estimated) = 2.00+0.28+0.81

= 3.09 kgcm

So selected rolling motor specifications,

DC geared Motor: 70 rpm, 5kgcm, 12VDC

Selection of pitching motor:

According to the biological data of well build human head its maximum rolling speed during walking is 90deg/s and maximum rolling range is +/- 50 degree from its vertical position [27]

So, pitching motor gear ratio = (40*360)/(90*60)

= 2.667

According to machining availability selected gear ratio = 1:4

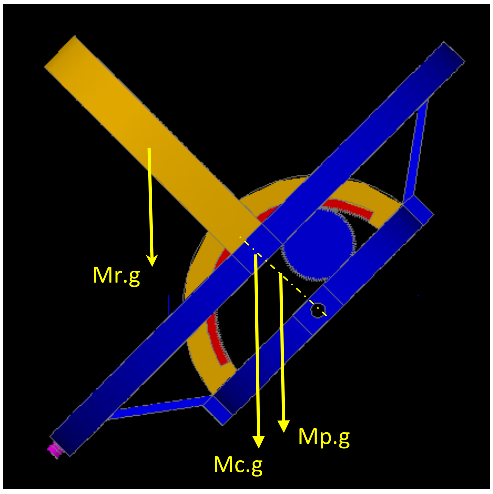


Fig 2.8: Loads on pitching motor of the robot head

Mass of pitching semi ring,M_p = 0.340 kg

Mass of rolling semi ring,M_r = 0.450 kg

Mass of rolling connecting ring, M_c = 0.400kg

Ideal torque on pitching motor $=M_r(4R_r/3\Pi + 0.025)+ M_p(4R_p/3\Pi)+ 0.025M_c$

$=6.68$kgcm

Estimated frictional torque $= 0.14*6.68$kgcm

$= 0.93$ kgcm

Inertia torque Π $= \Sigma\, (Mr^2)\, \alpha$

$=[(0.4*0.025^2)+0.45*(0.025+4Rr/3\Pi)^2]*1000$

$= 0.48$ kgcm

Torque on pitching motor (estimated) $= 6.68+0.93+0.48$

$= 7.62$ kgcm

So selected pitching motor specifications

DC geared motor:40rpm, 8kgcm, 12VDC

After completion of our design, biological data and design targets of the robot head has been compared with achieved results as in Table 2.1. It is verified that designed robot head is well has met the limits and bio mimetic features of human head.

Table 2.2: Validation of designed targets with biological parameters of human head

Parameter	**Biological value**	**Designed value (Design targets)**	**Achieved results**
Diameter of the head	196 mm	196 mm	209 mm
Rolling range	0 to +/- 50 deg	0 to +/- 50 deg	0 to +/-48 deg
Pitching range	0 to +/- 40 deg	0 to +/- 40 deg	0 to 42 deg& 0 to -35 deg
Maximum speed	90 deg/s	90 deg/s	82 deg/s

2.6. Control system

Control system of the robot head basically consist of several components as indicated in below Fig 2.9. Force sensor signals coming through signal amplifier circuits are analyzed by the central controller and will generate control signals to the each axis motor drivers. Each axis motors are consists of digital magnetic encoders which will provide feedback to the controllers. Entire system is working as on-off controller. Home reset switch will be used as interrupt switch and ones it pressed robot head will come to its zero position. Force sensors will feed Force signal [F] and based on the program written in central controller command signals,[C_m] will be given to motor drivers. Angular positions,[θ_m] will be feed to central controller through magnetic encoders. Home switch is used to take robot head to its rest position

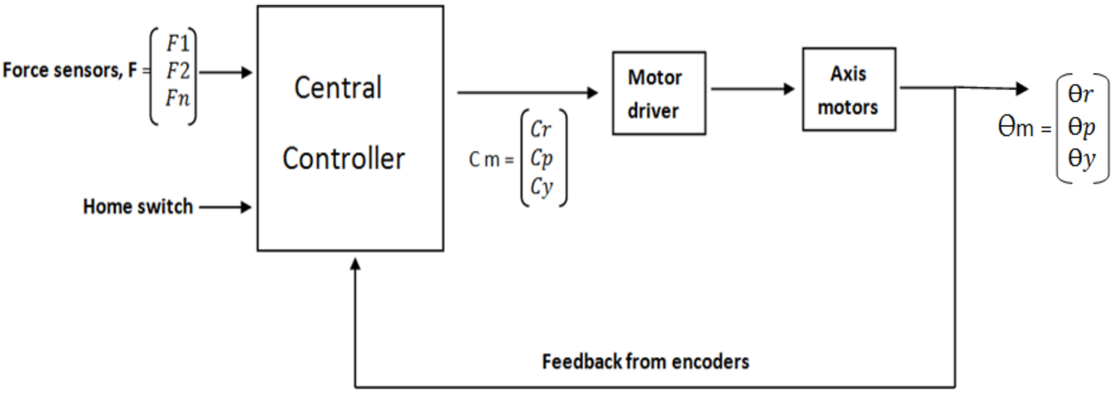


Fig 2.9: block diagram of control system of the robot

2.6.1. Central controller

Microprocessor based programmable controller in Arduino series was used as the central controller. Used controller is “ArduinoAtmega-2560”.It consist of considerable numbers of various types of inputs and outputs as indicated below in Fig 2.10. High level language programming interface in Arduino make programming the controller very easy. Online simulation while programming the controller is key advantage of the selected controller. Due to these factors, Arduino Atmega-2560 are used as central controller.

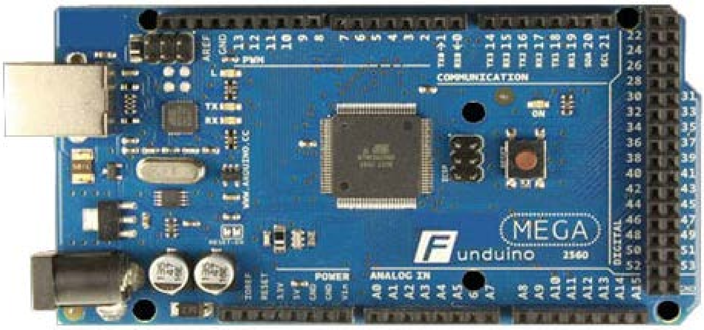


Fig 2.10: Arduino Atmega 2560 controller board

Arduino Mega 2560 key features

☐ Microcontroller ATmega2560

☐ Analog Input Pins 16

☐ Operating Voltage 5V

☐ Clock Speed 16 MHz

☐ Digital I/O Pins 54 (of which 15 provide PWM output)

☐ Flash Memory 256 KB of which 8 KB used by boot loader

☐ SRAM 8 KB

☐ EEPROM 4 KB

☐ USB communication facility

☐ Open source

☐ Libraries are freely available

☐ User friendly

2.6.2. Motor drivers

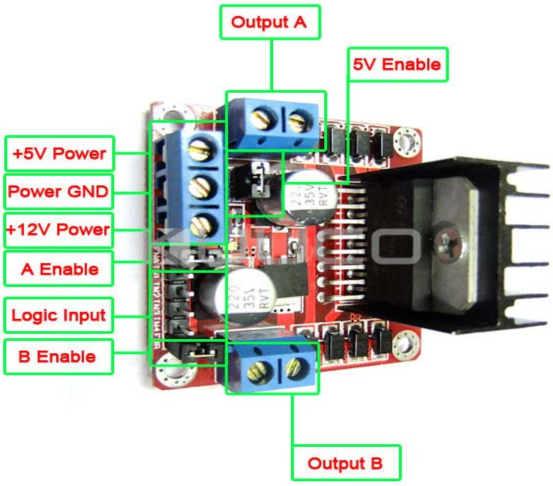


Fig 2.11: H- bridge motor driver

H bridge motor drivers were used to drive axis motors of the robot. With one motor drive two motors can be controlled independently by manipulating the control signals (logic signals) to the drive board. Two H bridge boards are used for the robot controller.

2.6.3. DC gear motors and magnetic encoders

DC gear motors are used as axis actuators since their high torque and compatibility. Motor dimensions were selected so that both rolling and pitching motors can be installed inside the head.

Fig 2.12: DC geared motor and magnetic encoder used for the robot

Motor specifications:

Rolling motor: Supply = 12VDC, Max speed = 70 rpm, Max torque = 5 kgcm

Rolling motor: Supply = 12VDC, Max speed = 40 rpm, Max torque = 8 kgcm

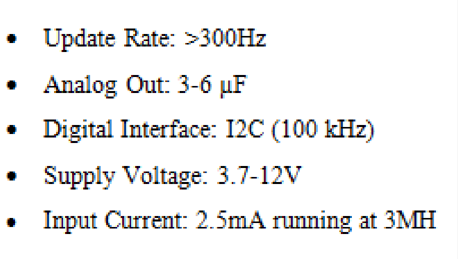
Encoder specifications:

Type: Magnetic, Resolution: 10 bit, Supply: 5VDC, Max mechanical speed: 12000 rpm

Magnetic type rotary digital encoders were used on each axis motor to take position feedback for the central controller. This encoder is having 10 bit resolution (1024 pulses per revolution).

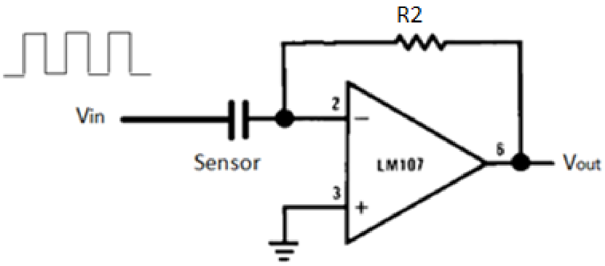
2.6.4. Force sensors

Capacitive type force sensor force sensors designed and developed by the project were used and signal were filtered through signal conditioning circuits developed. External force is applying on the head same will cause to change capacitance of the force sensors mounted on base as shown in Fig 2.13.



- Update Rate: >300Hz
- Analog Out: 3-6 µF
- Digital Interface: I2C (100 kHz)
- Supply Voltage: 3.7-12V
- Input Current: 2.5mA running at 3MH

Fig 2.13: Arrangement of force sensors on the base of the robot head



$$V_O = -R.C.\frac{dVi}{dt}$$

At any single constant frequency, V_O = R2/ (2 C.Π.f) Vi Where R2 = 100KΩ and F= 1 GHz

2.6.5. Integrated electrical control system

All components of electrical control system were assembled to a single module through newly made interfacing circuit board.

01). Arduino central controller

02). Force sensor circuits boards

03). DC motor drives

04). Power supply & regulating board

In order to minimize individual interfacing wiring of above each circuit boards, new interfacing PCB was designed with PCB designed software. Please refer Fig 2.14. All above electrical circuits were interfaced through this interfacing board and final model was assembled to a single module as shown in Fig2.15. Final module was assembled so that only Encoder, motor& power supply connections are externally coming to the final assembly. This makes system more compact and more reliable in operations since loose connections mess-up wirings were eliminated. When we compare the wired version of individual circuit boards in Fig 2.15 with interfaced version in Fig 2.15,It clearly shows the significant improvement of control system of the robot in its compactness & appearance.

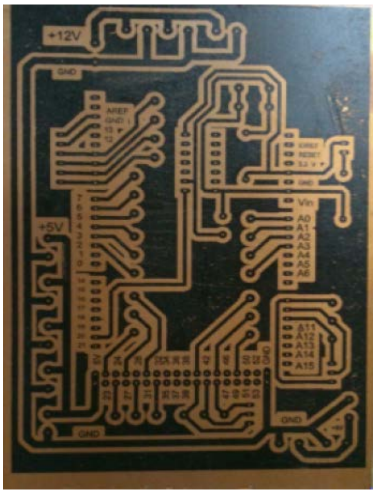


Fig 2.14: PCB developed to interface various PCBs of the electrical circuit

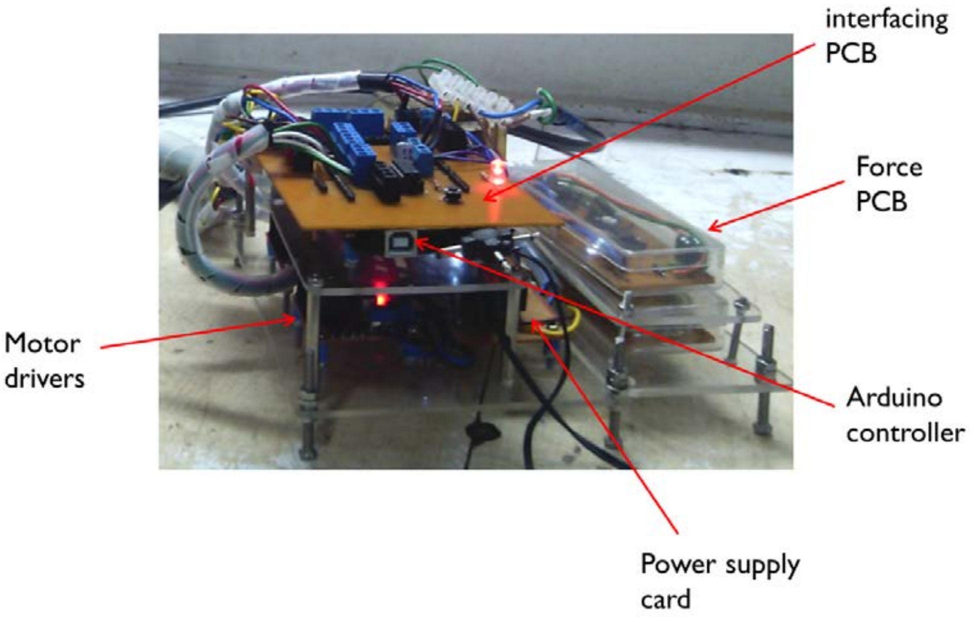


Fig 2.15: Integrated electrical control system of the robot

2.7. Basic movements of the robot head

Designed robot head is having 3 DOF.Those are the pitching, rolling and yawing movements. It can move head to a any position like human head.

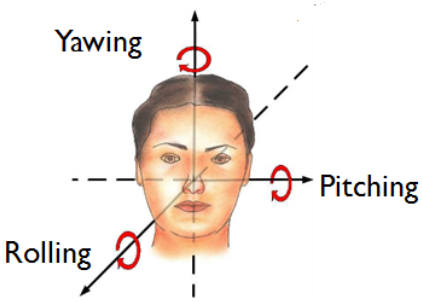


Fig 2.16: Basic movements of the robot head

Rolling:

Rolling motor located inside head structure will rotate the head around rolling axis as per the control signal supplied to the motor drivers by the controller. Fig 2.17.(a) andFig 2.17.(b) will shows how ring gears are moving during rolling movement of the head.

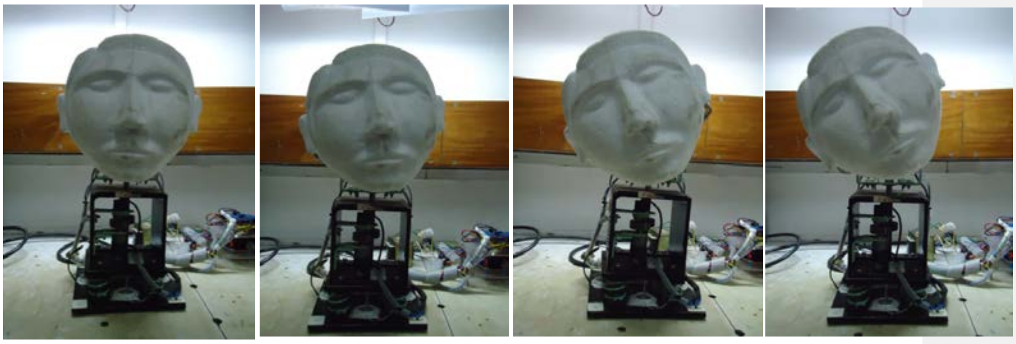


Fig 2.17.(a): Rolling movement of the robot head with face

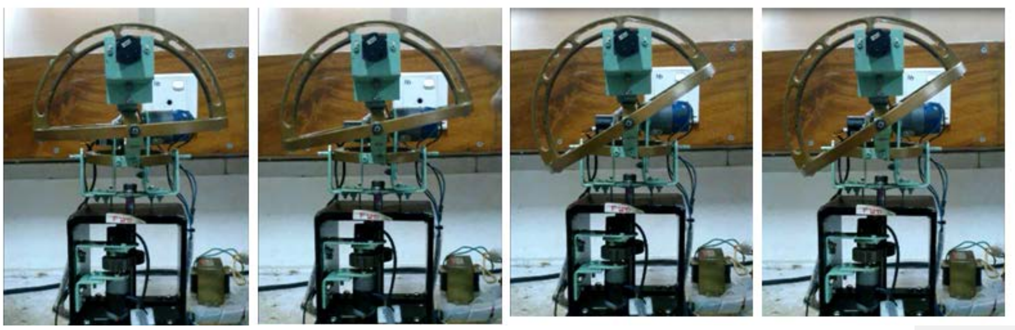


Fig 2.17.(b): Corresponding frame movement

Pitching:

Pitching motor located inside head structure will rotate the head around pitching axis as per the control signal giving to the motor drivers by the controller. Fig 2.18.(a) and Fig 2.18.(b)will shows how ring gears are moving on pitching movement of the head.

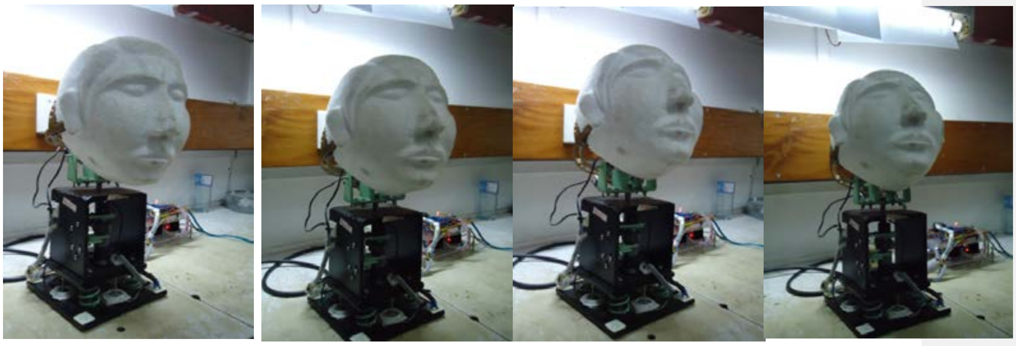


Fig 2.18.(a):Pitching movement of the robot head with face

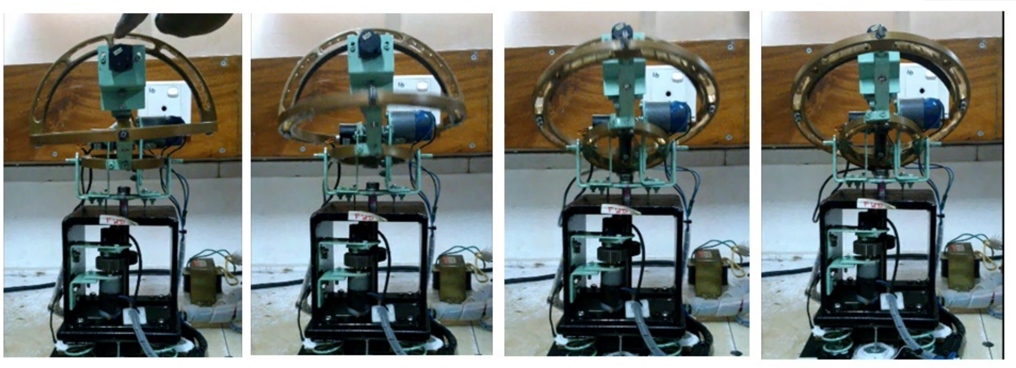


Fig 2.18.(b):Corresponding frame movement

Yawing:

Yawing motor located inside the base structure which function as the neck of human head. Neck motor will rotate around vertical axis according to the control signal giving to the motor drivers by the controller.Fig 2.19.(a) and Fig 2.19.(b)will shows how ring gears are moving on yawing movement of the head.

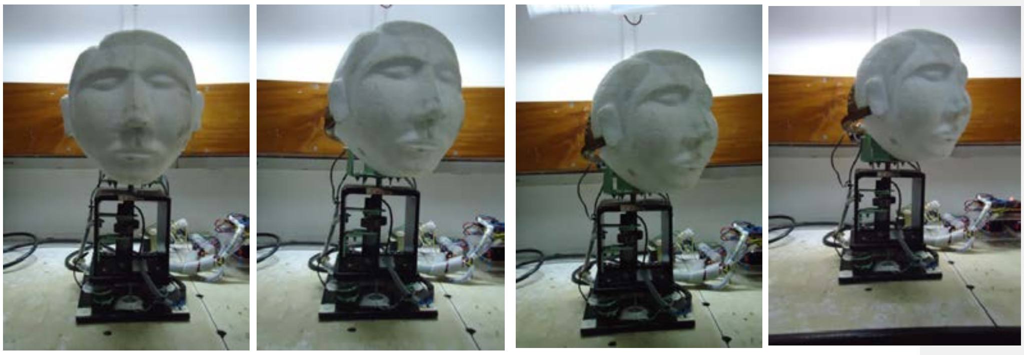


Fig 2.19.(a):Yawing movement of the robot head with face

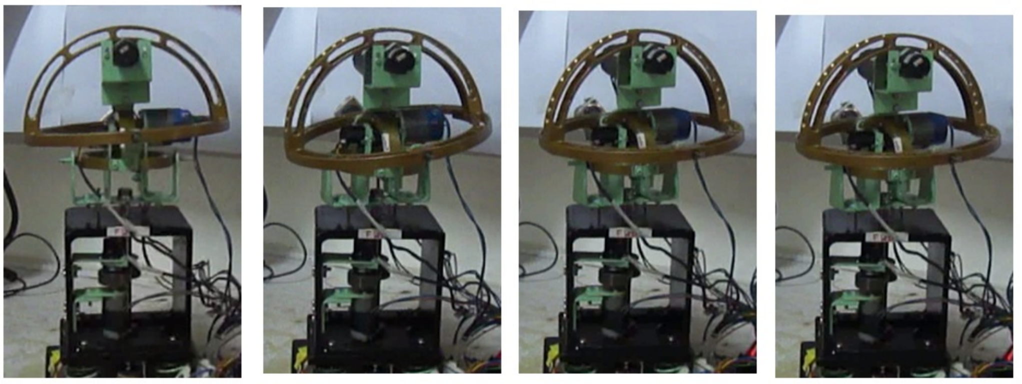


Fig 2.19.(b):Corresponding frame movement

3.0. FORCE SENSING AND REACTIONS

3.1. Force sensing principle

Designed robot head will determine magnitude and direction of the external force acting on the head by analyzing the readings of the force sensors mounted on base structure. Head will detect and analyze the forces acting towards the downside which make compression force on the base springs. So out of 3 dimensional spaces designed head will analyze the forces only on the upper portion of the head. Refer Fig 3.1 below. If an external force with magnitude P is acting on the head with the angle α with XY plane and angle θ with Y axis, the basic force equilibrium equations can be written as below.

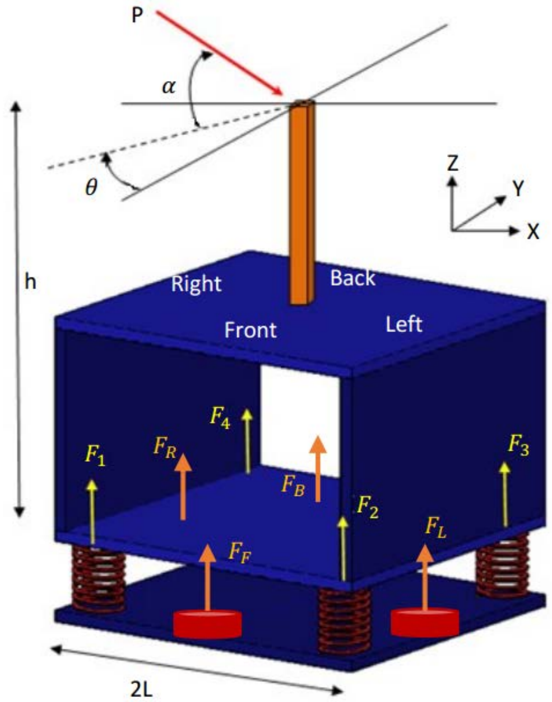


Fig 3.1: Force distribution on the robot head under an external force

P sin α= $F_1 + F_2 + F_3 + F_4$…..……………………………………………………….(01)

P cos α cos θ = $(F_3 + F_4)\,L$-$(F_1 + F_2)\,L$ (Movements around X axis)…………..(02)

P cos α sin θ = $(F_2 + F_3)L - (F_1 + F_4)L$ (Movements around Y axis)……..…..(03)

tan θ = $\frac{(F_2 + F_3) - (F_1 + F_4)}{(F_3 + F_4) - (F_1 + F_2)}$ ……………………………………………………(04)

For the sake of simplicity, it is assumed that,
$F_L \approx (F_2 + F_3)/2$,$F_R \approx (F_1 + F_4)/2$,$F_B \approx (F_2 + F_3)/2$and $F_F \approx (F_1 + F_2)/2$

Where, F_L, F_R, $F_F$and F_B are the reading of the left, right, front and back force sensors respectively. So,

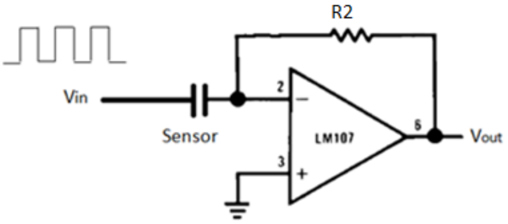
tan θ =$\frac{(F_L - F_R)}{(F_B - F_F)}$……………………………………………………………..(05)

When it maps to human head angle of the external force with horizontal plane, α is not a decision factor for the direction of head movement. So angle of the external force in the horizontal plane, θ and magnitude of the external force are the decision factors of brain for control action.

Algorithms were written to central controller to workout above angle of Equation 05for each case of the external force. Further system was tuned, calibrated by applying known forces at known directions.

3.2. Design of force sensor

New force sensor was designed to the robot since used piezoelectric type sensors were damaged during system testing of developing stage of the robot. The slight movement of the base structure under an external force was used as the force sensing factor at each side of the base. Capacitive type force sensing circuit was designed with op amps as shown in Fig 3.2.



Vout = -RC d(Vin)/dt

At any single constant frequency, Vout = -2πf R2C.Vin

Where R2 = 100KΩ & F= 1 GHz

Fig 3.2: PCB designed for force sensing circuit

Table 3.1: Force sensor output for force acting on the sensor

No	Applied force(with dead weights)	Output at 5v offset(V)
1	100g	5.010
2	150g	5.030
3	200g	5.030
4	250g	5.050
5	300g	5.071
6	350g	5.090
7	400g	5.112
8	450g	5.132

Force sensitivity of the circuit (including main controller)

Analogue pin registry size of Arduino board = 10 bit

So minimum voltage can be sensed from analog port = 5V/1024

Sensitivity of the force sensing loop = 0.020v/50g

So minimum force that can be sensed through the

Sensing loop = 50/0.02*(5/1024)

= 12.21g

= 0.12 N

3.3. Reactions for external forces

Reactions for the external forces acting on the human head are determined by the human brain based on direction, magnitudes of the force. Also, reaction is determined by the brain based on training or experience of human. As an example if suddenly something hit on human head the reaction given by child will be differ from reaction given by an adult. Also according to the magnitude the reaction of human head will vary its response. So response function to an external force is a very complex phenomenon and very difficult to map it’s all aspects to an artificial brain. Developing a robot head which act, reacts exactly as human head is a great challenge of robotics.

Generally, if some external force acting on a human head, once it exceeds critical limit brain will decided to take away the head out of the external force. Simply brain will decided to take out head away and muscles of neck will actuate and head will move away. Also based on magnitude of external force will determine the reaction of the head.

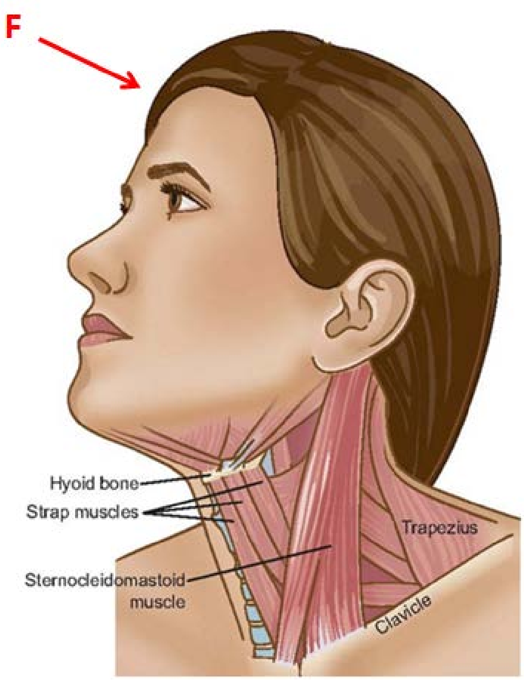


Fig 3.3: External force acting on the human head

3.4. Detection of direction of external force

When external force acting on the human head, the stresses induced in the muscles of neck area will provide signals to the brain for decision making. Please refer Fig 3.3. Based on the decision made by the brain, command will be given to move head away. Direction detection algorithm has been implemented on Arduinocontrollerso that in each program execution cycle force sensor readings will be scanned by the controller. Whenthe sensor readings exceed their set points, Controller will be calculating the direction of angle θ as in above Equation 05 of page no 34. Once direction of external force is known, any kind of force attentive feature can be developed.

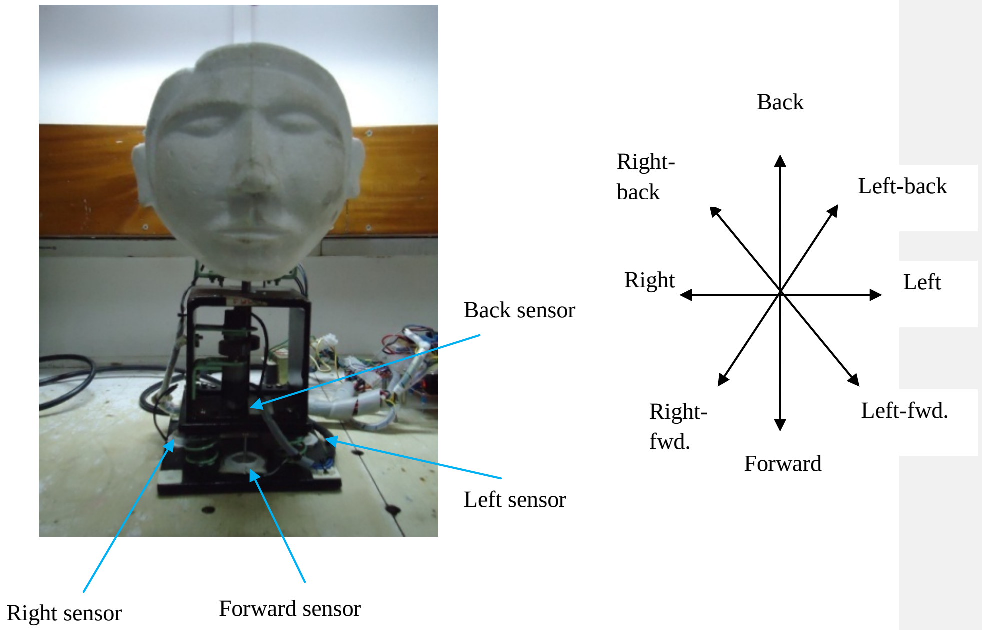


Fig 3.4: Main 8 direction of external forces acting on the head

After final set-up implemented, force sensors was indicating readings since self-weight of the entire model is acting on sensors partially. First springs were adjusted and make the force sensor readings zero before calibration starts. Constant force was given to the robot head on the head and direction matrix was programmed on the controller as mentioned in Table 4.1 in chapter 4. For any force acting on the head axis motors are rotating so that head is moved to the direction of the external force. Force. An external force was applied to main 8 directions as in Fig 3.4 and model was fine-tuned so that robot can sense the direction of force if is acting on these 8 main directions.

For the analytical purposes and to set the threshold values to start output actions sensor readings for different directions of external forces were taken through MATLAB and plotted. Based on these graphs threshold values were set on arduino program to move head away under external forces.

Case 01: Force acting on a main four directions

Magnitude of 10 N force was applied on the robot head right hand direction and all four force sensor actual responses were plotted with MATLAB software.(please refer Fig 3.5).

Maximum percentage increase of force on a force sensor is with right sensor.

Percentage increase of force on right sensor = (275-70)/70 * 100%

= 292 %

So controller will calculate the direction of external force, θ from the algorithms written on controller for $\tan\theta = \frac{(F_L - F_R)}{(F_B - F_F)}$. So, head will move away from the force to the calculated direction.

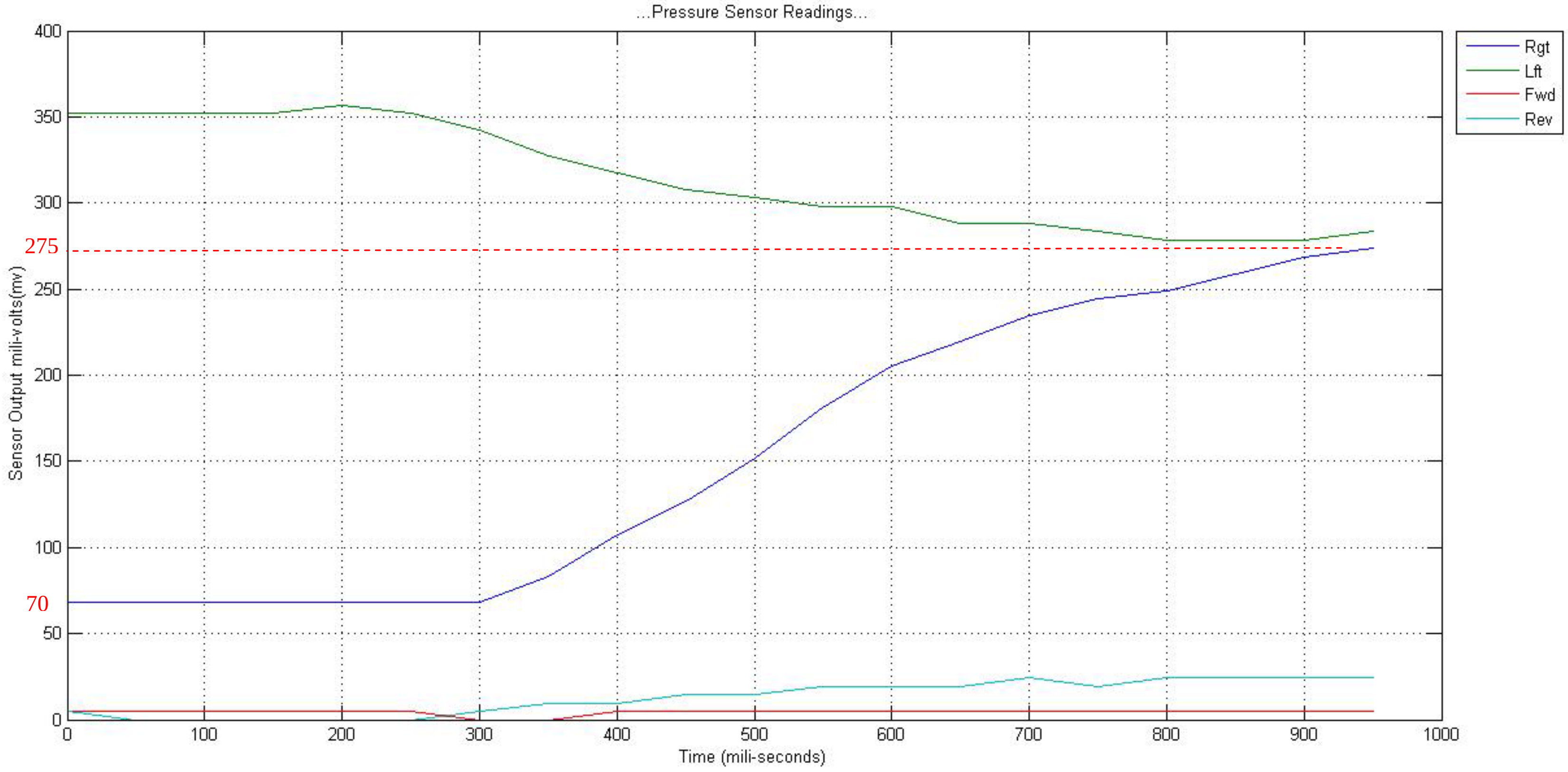


Fig 3.5: Force sensor readings under a constant force (10N) on right direction

Case 02: Force acting on a diagonal direction

Magnitude of 10 N force was applied on the robot head right-fwddirection and all four force sensor reading were plotted with MATLAB software.(please refer Fig 3.6).

In this case significant percentage increase can be seen on two sensors out of four. Force on both Right and forward sensors have been increase significantly.

Percentage increase of force on right sensor = (320-220)/220 * 100 %

= 45.45%

Percentage increase of force on forward sensor = (180-120)/120 * 100 %

= 50%

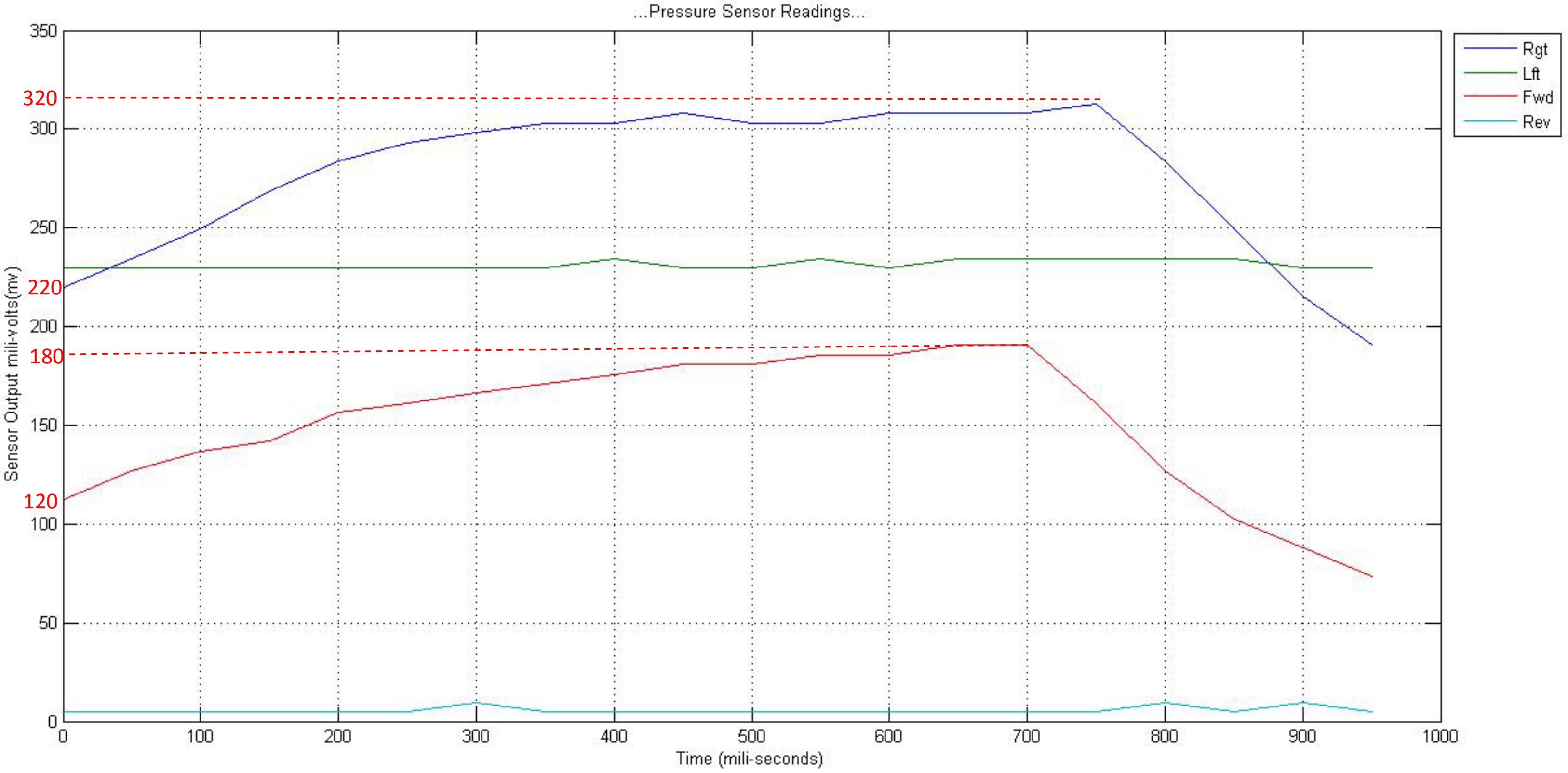


Fig 3.6: Force sensor readings under a constant force (10N) on right-fwd direction

As above, external force was applied to all 8 Nos of directions and force sensor readings were plotted for each direction of force. After that system was fine-tuned by analyzing the each force sensor characteristics of each directional force.

3.5. Detection of magnitude of the external force

As explained in above 3.4, controller is detecting the direction of external force based on the readings of the force sensors mounted on the base structure. Magnitude of the external force also can be directly read through force sensors.

Magnitude of the external force applied to the robot head, P = $f(\theta, F_1, F_2, F_3, F_4)$

Algorithms written to the controller will calculate the direction of external force θ as soon any external force comes to the head. As second step controller will calculate the magnitude of the external force acting on the head toward above calculated direction as per below equations.

P sin α= $F_1 + F_2 + F_3 + F_4$……………………………………………………………..(01)

P cos α cos θ = $(F_3 + F_4)\ L$-$(F_1 + F_2)\ L$ (Movements around X axis)………………..(02)

P cos α sin θ = $(F_2 + F_3)L - (F_1 + F_4)L$ (Movements around Y axis)…………..…..(03)

In practical implementation, sometimes soon after force is applied, structure is affecting with small vibration due to spring damping. So it will cause to take small time to make the force sensor readings steady. So algorithms written to the Arduino controller was associated with introduced delay time before analyzing the each sensor by the written algorithm. So approximately, steady force has to be applied and hold on the head around 1 second until it runs entire algorithms on the controller to detect the direction & magnitude of the external force successfully.

3.6. Reaction functions of robot head for the external force

Based on magnitude and direction of the external force acting on the head, reaction of the human head will vary based on the decision taking by human brain based on the training and experience. If some external force acting on a head of infant or child he will react to it different way than a well build human. When something falling down or touching on a head of small kid the speed of reaction, mode of reaction will be very differ than well build human and this reaction function basically decide by the human brain. In research area of the robotics developing reaction function exactly like a human is a great challenge for scientists since it need to incorporate entire decision making function of human brain to a artificial brain. In this project this reaction function to the robot head basically will be implemented based on,

01). Reaction based on direction of external force

02). Reaction based on magnitude of the external force

First experiments have been carried out to validate the basic neck movements of the robotic head. The robot head hasbeen commanded to perform the basic neck movementsandthose movements have been captured. The captured images are shown in Fig.2.16,Fig 2.17 and Fig 2.18. According to the observations during the experiments, the robotic head is capable of performing basichead movements in anthropomorphic manner like human.

3.6.1. Reactions based on direction of external force

Direction of the external force is a main key factor that decides the mode of reaction for that force by the human head. When any external force acted on human head or something hit on the head stresses or impacts induces on muscles of head or neck will send signal to brain to identify the direction of force acted to the head. Then brain will decide to take the head away from the force and will send signals to the muscles of the head, neck to act accordingly. In human anatomy each and every cell works as individual sensor to send stress signal to the brain. In our robot head also same principle was used to detect the direction of external force. Instead of stresses generated in muscles of human head, four force sensor mounted on robot head base will sense the force. According to the algorithm written on controller direction of external force will be determined by the controller as explained in Chapter 4.. Each element of the robot head can be mapped to human head as below.

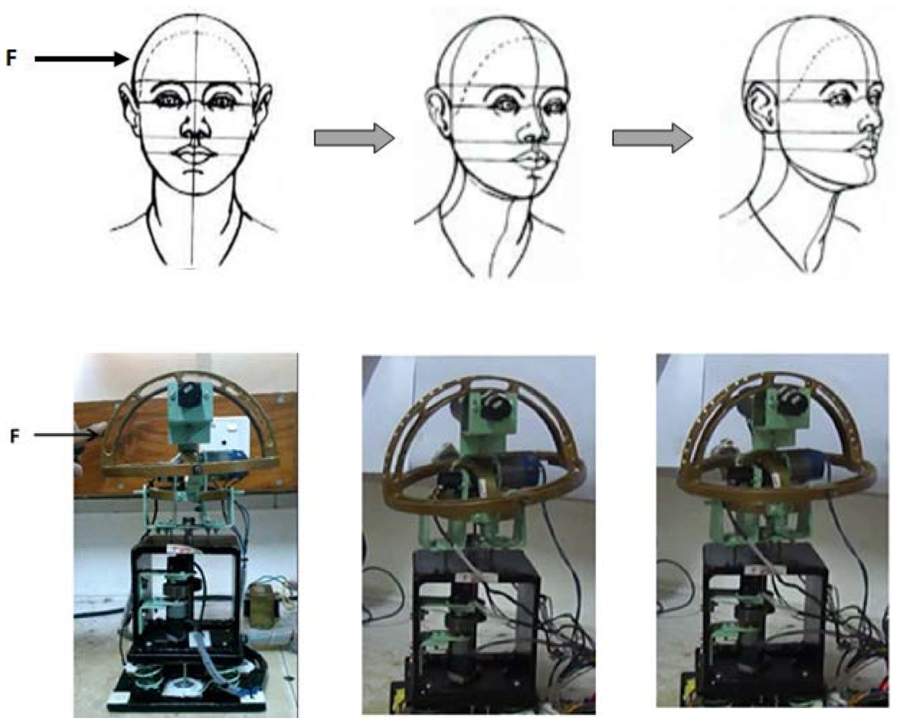
Stresses on muscles due to an external forces → Forces acting on force sensor of the base

Human brain → Arduino controller and algorithms running

Muscles of head used for head movements → Axis motor used to move the head

Movement of head is having multiple degrees of freedom when it acts to an external force. In this robot head, basically head movements are accomplished with 3 DOF called rolling, pitching and yawing as explained in early chapters. For each action against external forces, controller is activating its axis motors as indicated below. Each rotation of motor is measured with 10 bit digital encoder (accuracy =360/1024 = 0.35 deg). Initial rest position is configured as zero and limits for each rotation has been given by considering the human head motion limits.

When an external force acting on a human head, the first action human head is implementing is to take away head from the external force towards the direction of force. As a example if something hit on human head automatically human will take head away at a instant. For this case stresses formed in muscles of head will send the signal to the brain and brain will give output to the set of muscles of human head, neck area to take the head away. In this case this movement will have several DOF and combined movement of set of muscles will cause to move head away. Also this movement is consisting of rotational and longitudinal movement of muscles. But in our robot, after direction of external force is decided by the algorithms of controller, it will give output commands to the motor drivers(motors) so that combined motion of each motor will results to take head away towards the direction of external force. Fig 3.7and Fig 3.8 will show the how axis motor generate combined movements of the head.

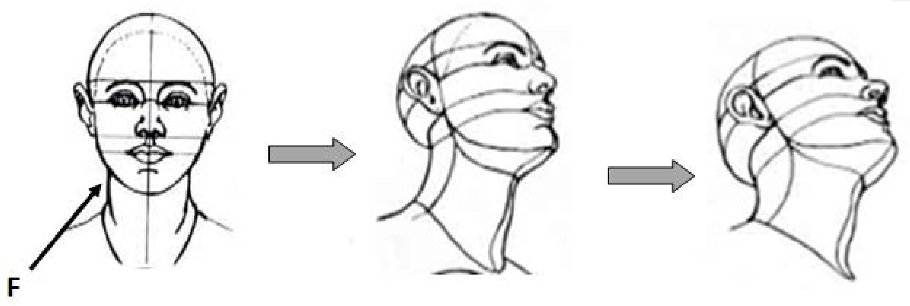


Yawing motor ON, Pitching & Rolling motors are OFF

Fig 3.7: Rotational reaction for the external force acting on left direction

As explained above, if an external force applied on forehead area toward left hand side of the head (refer Fig 3.7) head will move away by rolling the head toward direction of force. So, controller will activate only the yawing motor to rotate the head anticlockwise as indicated above. Once it comes to predefined destination digital encoder will give feedback to stop the motor. In this robot head rolling movement was limited to 48 degrees from rest position.

If external force on the head is acting along a diagonal direction of main four directions left, right, forward, back then more than one motor need to be activated to move the head to the force acting direction. Combined rotation of axis motors will move the head to any direction of space.



All Yawing, Pitching & Rolling motors are ON

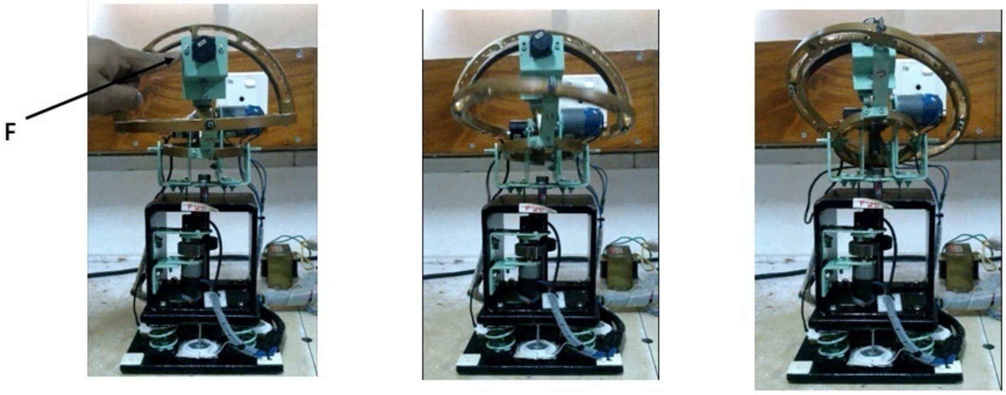


Fig 3.8: Rotational reaction for the external force acting on left back direction

Based on direction of external force, controller can identify the direction of external forces by means of algorithms written to the controller as summarized in Table 4.1. External force was applied on the head for all 8 nos of directions and robot head was successfully identified the direction of force and react accordingly. Further, Itwill shows the force sensor graphs taken through serial port for all these 8 directions at the end of this chapter. After final set-up implemented, force sensors were indicating readings since self-weight of the structure is acting partially on the sensors. Therefore the percentage variations of the sensors were used for calculations.

Further, when there is more than one solution for calculated angle by the controller, , appropriate solution of equation $\tan\theta = \frac{(F_L - F_R)}{(F_B - F_F)}$ will be selected by considering the rotational direction of magnetic encoders as well.

Case01: Applying an external force towards left direction

Please refer the graph in Fig 3.9.

Percentage increments of left, right, forward and back sensors were 131%,-50%,0% and 0%.

So, the calculated angle by the controller, $\tan\theta = \frac{(F_L - F_R)}{(F_B - F_F)}$

$$= \frac{(131-(-50))}{(0-0)}$$

$$\theta = 90^0$$

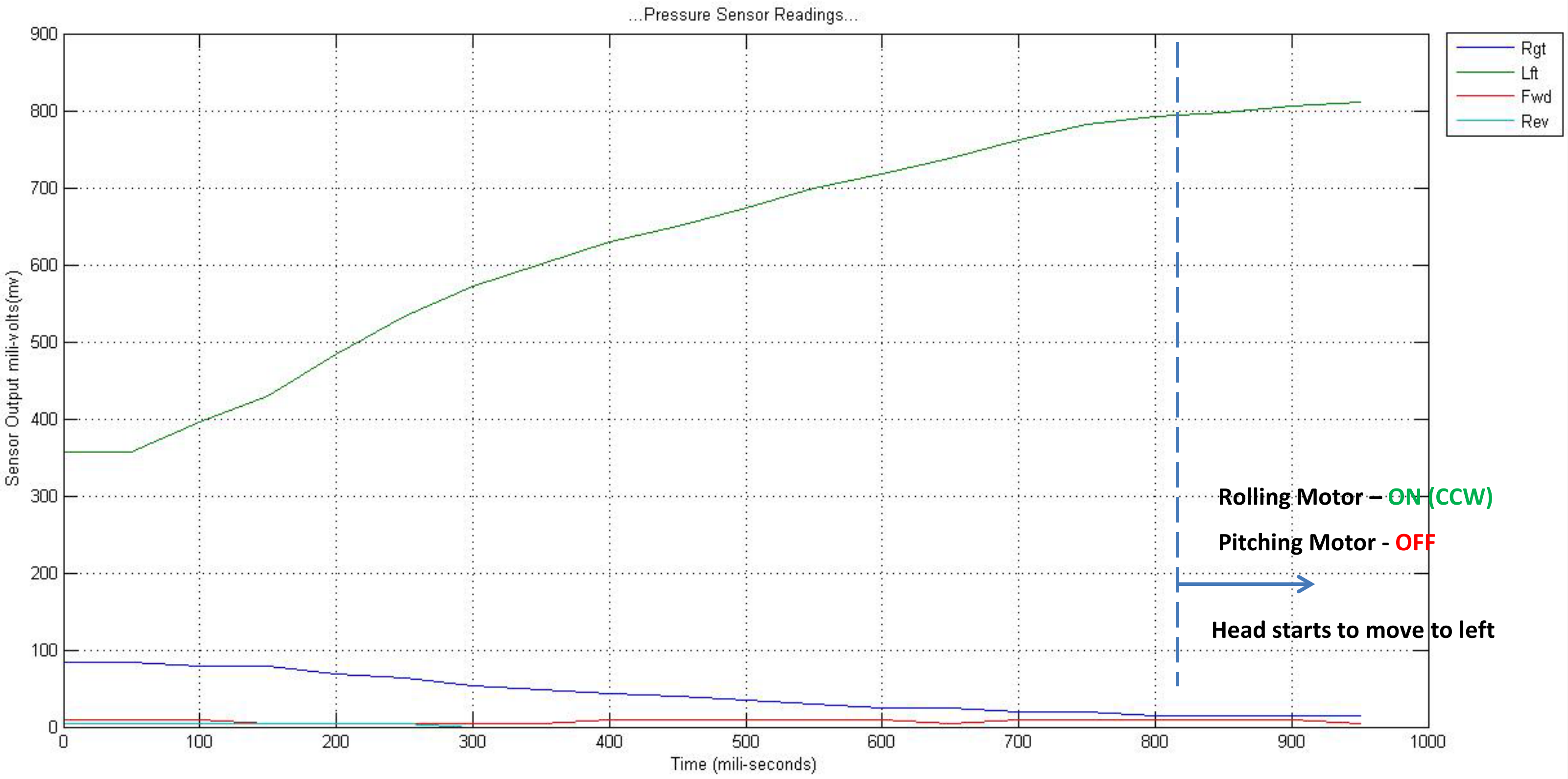


Fig 3.9: Force sensor readings for external force acting towards the left direction

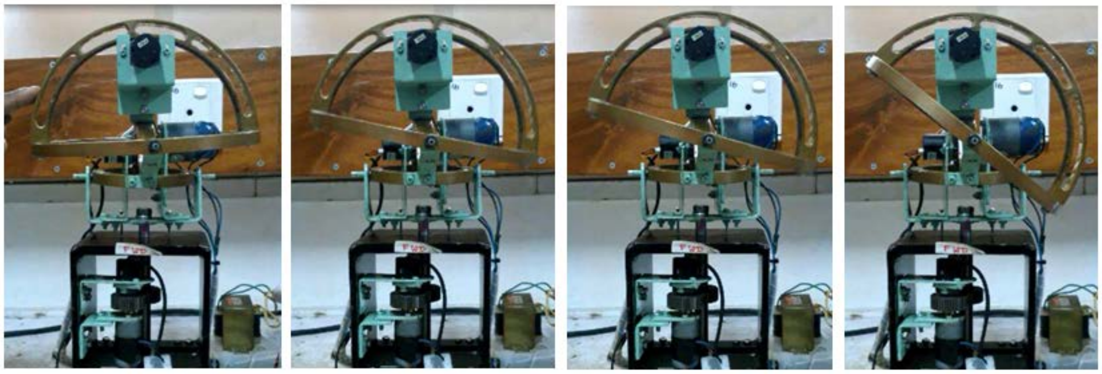
When an external force is applied towards the left direction of the head,force sensor signal variation is shown in Fig 3.9. When time is reached to around 800 ms, controller is providing command signals to motor drivers to move rolling motor counter clockwise up to 48 deg (please refer Table 2.2 for designed movable ranges).

Designed time taken to rotate head to its destination = 48/82 s

= 585ms

Time taken in real movement = 600ms

Movements snap shots of robot head for 3 equal intervals of above time span (600ms) are shown in Fig 3.10.



T = 800 mS
$\Theta_R = 0^0, \Theta_P = 0^0$

T = 1000 mS
$\Theta_R = -14^0, \Theta_P = 2^0$

T = 1200 mS
$\Theta_R = -32^0, \Theta_P = 0^0$

T = 1400 mS
$\Theta_R = -48^0, \Theta_P = 0^0$

Fig 3.10: Robot head movement snap shots for force on left direction

Case02: Applying an external force towards right direction

Please refer the graph in Fig 3.11.

Percentage increments of left, right, forward and back sensors were 292%,-22%,50% and 0%.

So, the calculated angle by the controller, $\tan\theta = \frac{(F_L - F_R)}{(F_B - F_F)}$

$$= \frac{(292-(-22))}{(0-50)}$$

$$\theta = -81^0$$

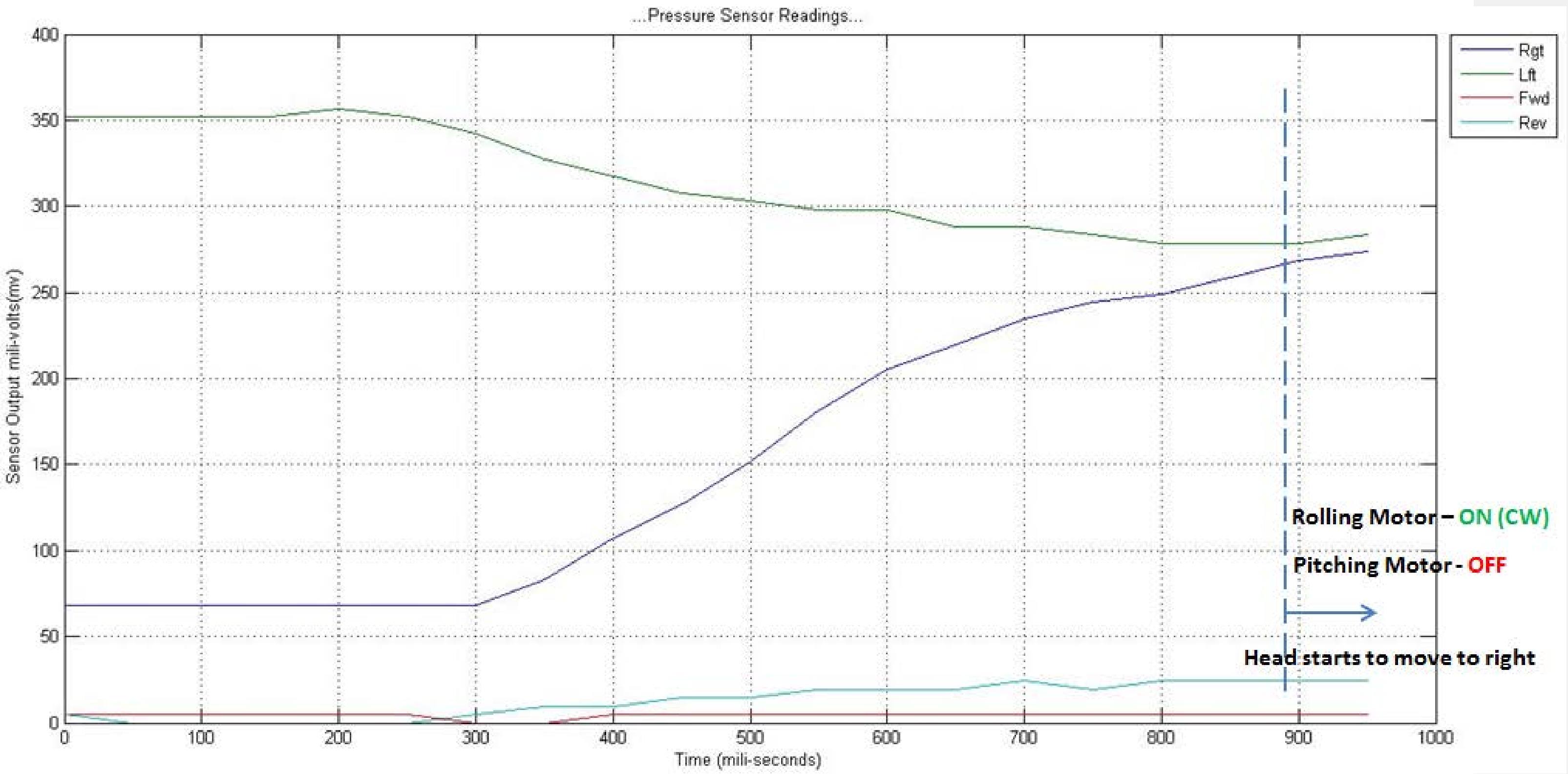


Fig 3.11: Force sensor readings of external force acting to the right direction

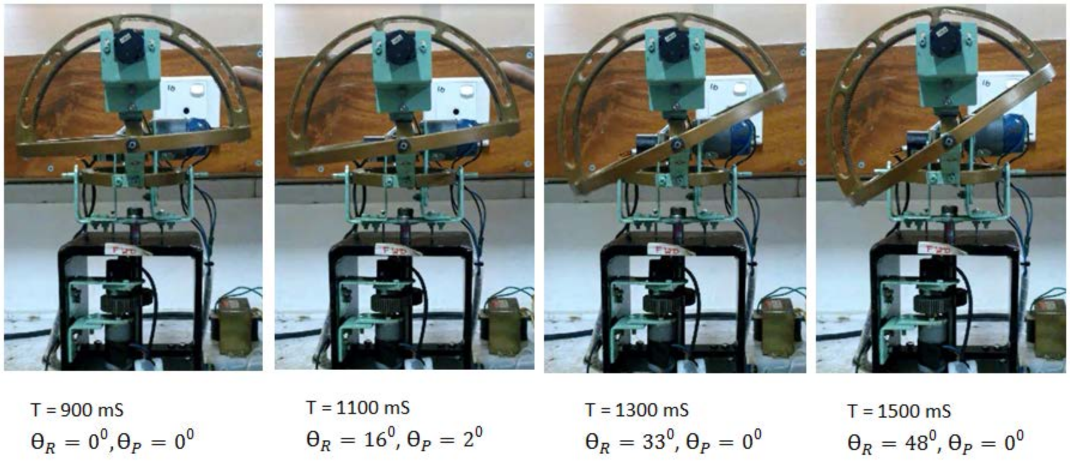
When an external force is applying towards the right direction of the head force sensor signal variation is shown in Fig 3.11. When time is reached to around 900 ms controller is providing command signals to motor drivers to move rolling motor to counter clockwise up to 48 deg (please refer Table 2.2 for designed movable ranges).

Time taken to rotate head to its destination = 48/82 s

= 585ms

Time taken in real movement = 600 ms

Movements snap shots of robot head for 3 equal intervals of above time span (600ms) are shown in Fig 3.12



T = 900 mS
$\theta_R = 0^0, \theta_P = 0^0$

T = 1100 mS
$\theta_R = 16^0, \theta_P = 2^0$

T = 1300 mS
$\theta_R = 33^0, \theta_P = 0^0$

T = 1500 mS
$\theta_R = 48^0, \theta_P = 0^0$

Fig 3.12: Robot head movement snap shots for force on right direction

Case03: Applying an external force towards forward direction

Please refer the graph in Fig 3.13.

Percentage increments of left, right, forward and back sensors were 20%,6%,0% and 100%.

So, the calculated angle by the controller, $\tan\theta = \frac{(F_L - F_R)}{(F_B - F_F)}$

$$= \frac{(20-6)}{(0-100)}$$

$$\theta \quad = 172^0$$

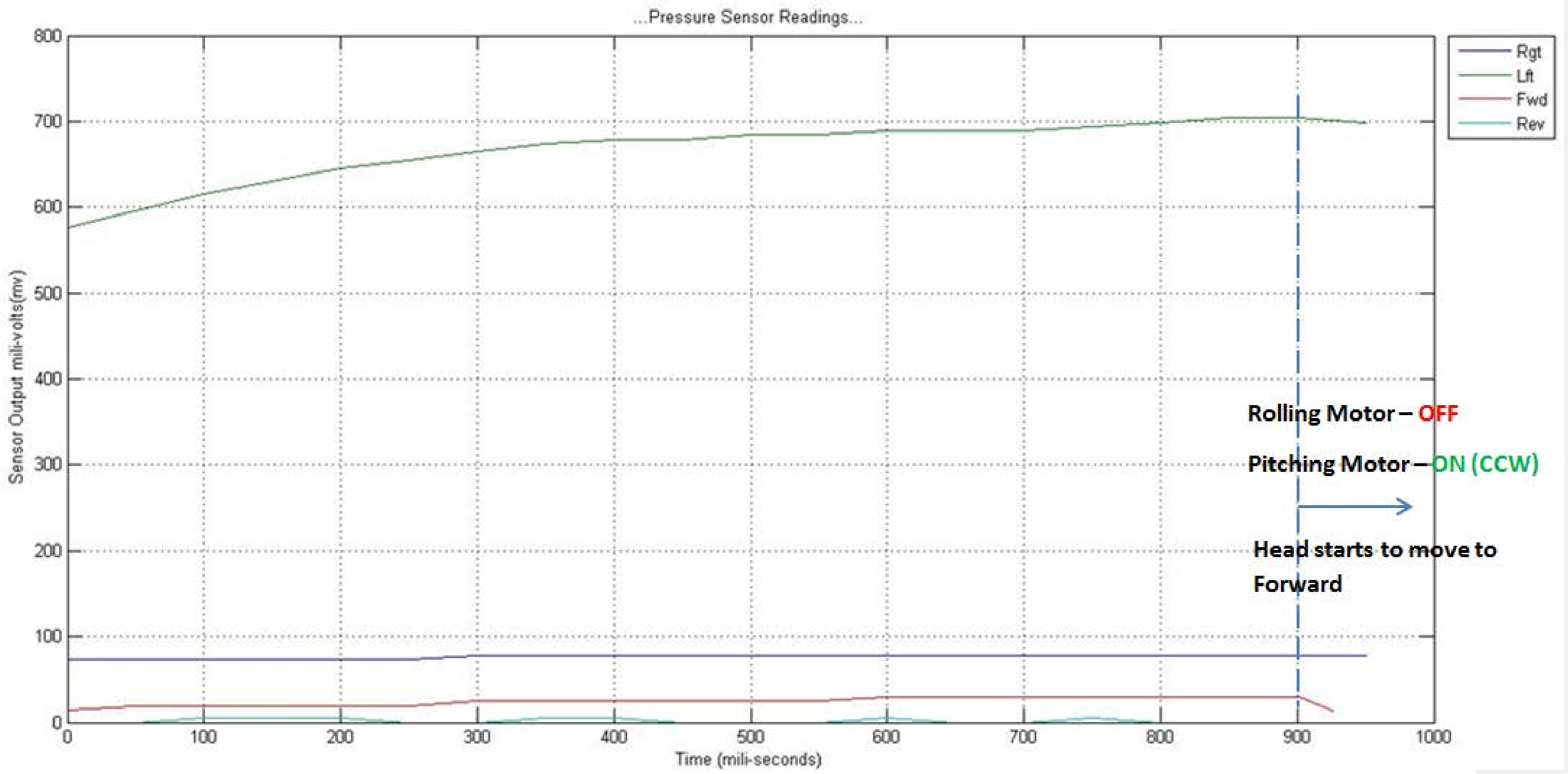


Fig 3.13: Force sensor readings of external force acting to the forward direction

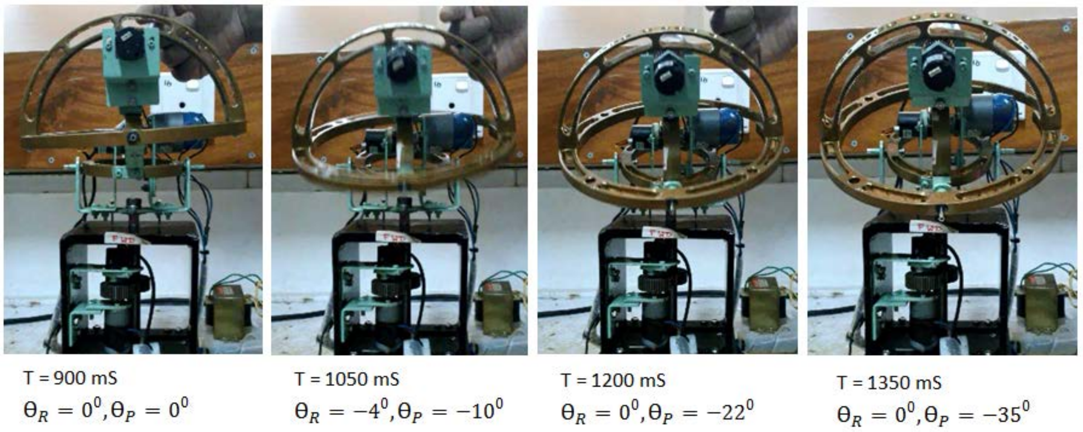
When an external force is applying towards the forward direction of the head force sensor signal variation is shown in Fig 3.13. When time is reached to around 900 ms controller is providing command signals to motor drivers to move pitching motor to counter clockwise up to 35deg (please refer Table 2.2 for designed movable ranges).

Time taken to rotate head to its destination = 35/82 s

= 426ms

Time taken in real movement = 450 ms

Movements snap shots of robot head for 3 equal intervals of above time span (450ms) are shown in Fig 3.14.



T = 900 mS
$\Theta_R = 0^0, \Theta_P = 0^0$

T = 1050 mS
$\Theta_R = -4^0, \Theta_P = -10^0$

T = 1200 mS
$\Theta_R = 0^0, \Theta_P = -22^0$

T = 1350 mS
$\Theta_R = 0^0, \Theta_P = -35^0$

Fig 3.14: Robot head movement snap shots for force on forward direction

Case04: Applying an external force towards back direction

Please refer the graph in Fig 3.15.

Percentage increments of left, right, forward and back sensors were 32%, 10%, 88% and -50%.

So, the calculated angle by the controller, $\tan\theta = \frac{(F_L - F_R)}{(F_B - F_F)}$

$$= \frac{(32-10)}{(-50-88)}$$

$$\theta = -9^{0}$$

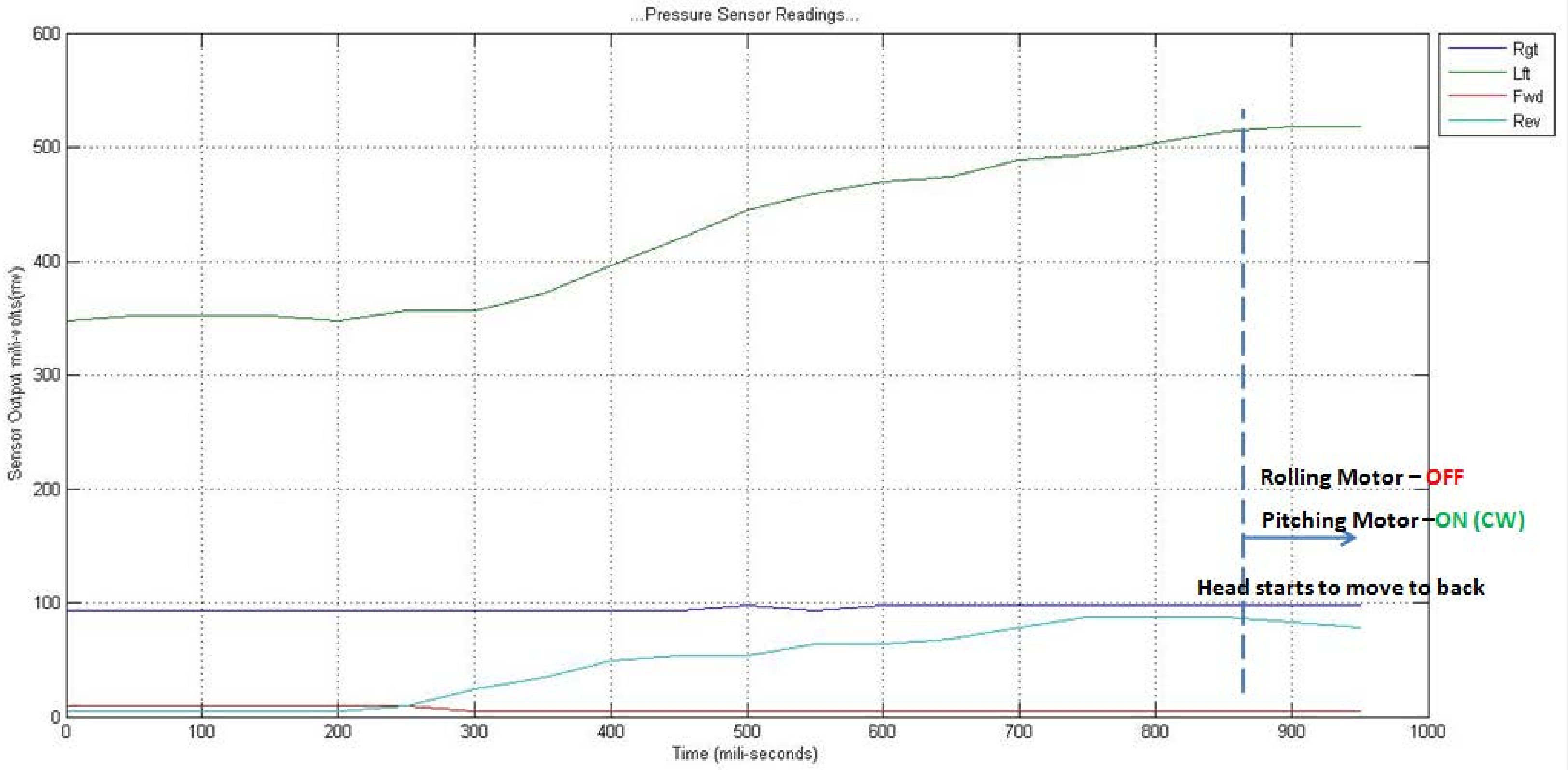


Fig 3.15: Force sensor readings of external force acting to the back direction

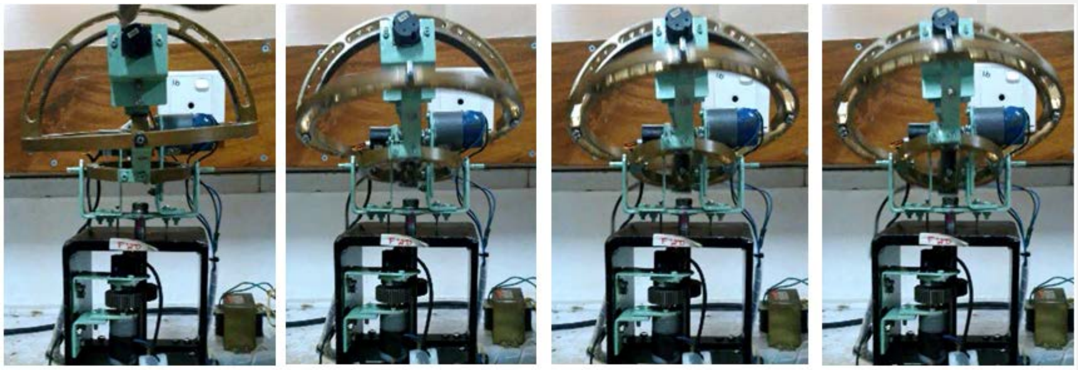
When an external force is applying towards the back direction of the head force sensor signal variation is shown in Fig 3.15. When time is reached to around 875ms controller is providing command signals to motor drivers to move pitching motor to clockwise up to 42deg (please refer Table 2.2 for designed movable ranges).

Time taken to rotate head to its destination = 42/82 s

= 512ms

Time taken in real movement = 525 ms

Movements snap shots of robot head for 3 equal intervals of above time span (525mS) are shown in Fig 3.16.



T = 875 mS $\Theta_R = 0^0, \Theta_P = 0^0$

T = 1050 mS $\Theta_R = 3^0, \Theta_P = 12^0$

T = 1225 mS $\Theta_R = 2^0, \Theta_P = 30^0$

T = 1400 mS $\Theta_R = 0^0, \Theta_P = 42^0$

Fig 3.16: Robot head movement snap shots for force on back direction

Case05: Applying an external force towards Left-back direction

Please refer the graph in Fig 3.17.

Percentage increments of left, right, forward and back sensors were 109%, 30%, 0% and 400%.

So, the calculated angle by the controller, $\tan\theta = \frac{(F_L - F_R)}{(F_B - F_F)}$

$$= \frac{(109-30)}{(400-0)}$$

$$\theta = 11^0$$

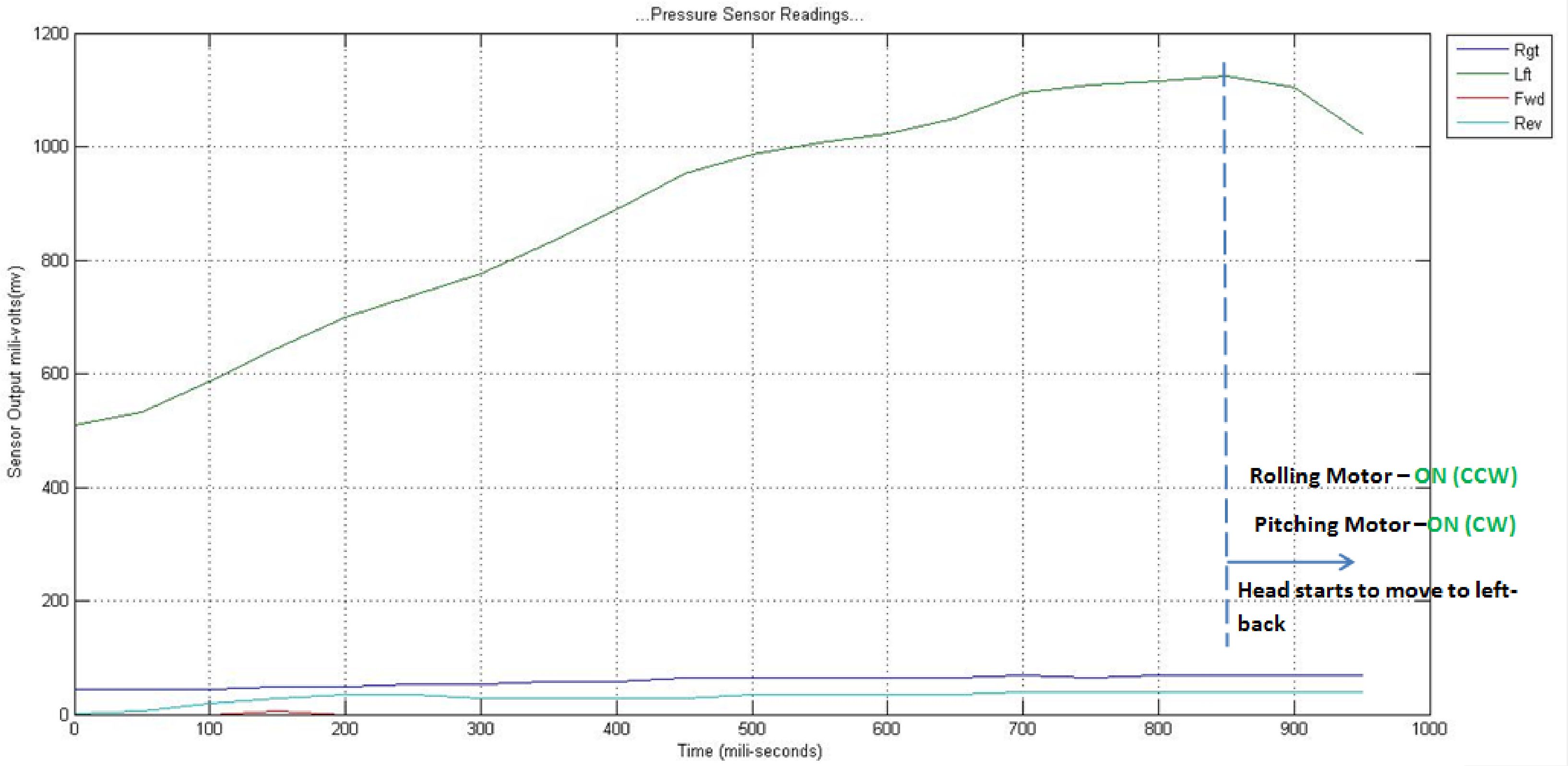


Fig 3.17: Force sensor readings of external force acting to the left-back direction

When an external force is applying towards the left-back direction of the head force sensor signal variation is shown in Fig 3.17. When time is reached to around 850 ms controller is providing command signals to motor drivers to move pitching motor to clockwise and rolling motor to counter clockwise up to 42 deg and 48 deg respectively. (Please refer Table 2.2 for designed movable ranges).

Time taken to rolling motor for its destination = 48/82 s

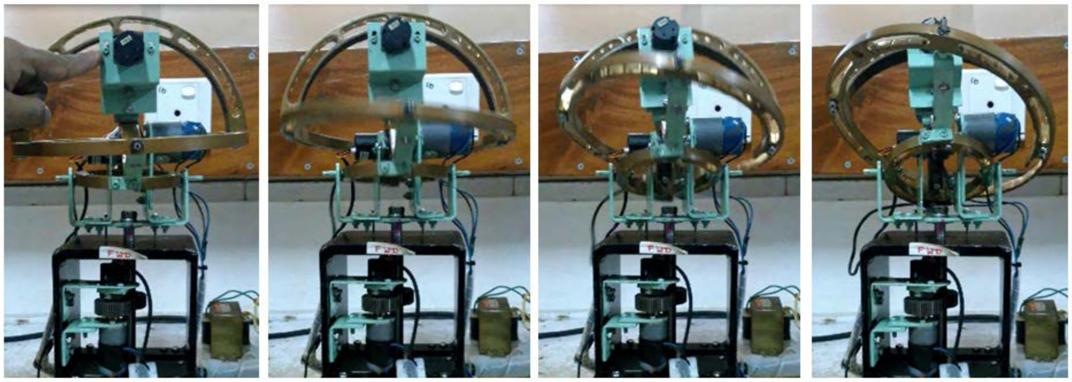
= 585 ms

Time taken to pitching motor for its destination = 42/82 s

= 512ms

Time taken in real movement of left back motion = 525 ms

Movements snap shots of robot head for 3 equal intervals of above time span (525mS) are shown in Fig 3.18.



T = 850 mS
$\theta_R = 0^0, \theta_P = 0^0$

T = 1025 mS
$\theta_R = -15^0, \theta_P = 13^0$

T = 1200 mS
$\theta_R = -33^0, \theta_P = 25^0$

T = 1375 mS
$\theta_R = -47^0, \theta_P = 40^0$

Fig 3.18: Robot head movement snap shots for force on left-back direction

Case06: Applying an external force towards Left-forward direction

Please refer the graph in Fig 3.19.

Percentage increments of left, right, forward and back sensors were 160%, -50%, 400% and 0%.

So, the calculated angle by the controller, $\tan\theta = \frac{(F_L - F_R)}{(F_B - F_F)}$

$$= \frac{(160-(-50))}{(0-400)}$$

$$\theta \quad = 152^{0}$$

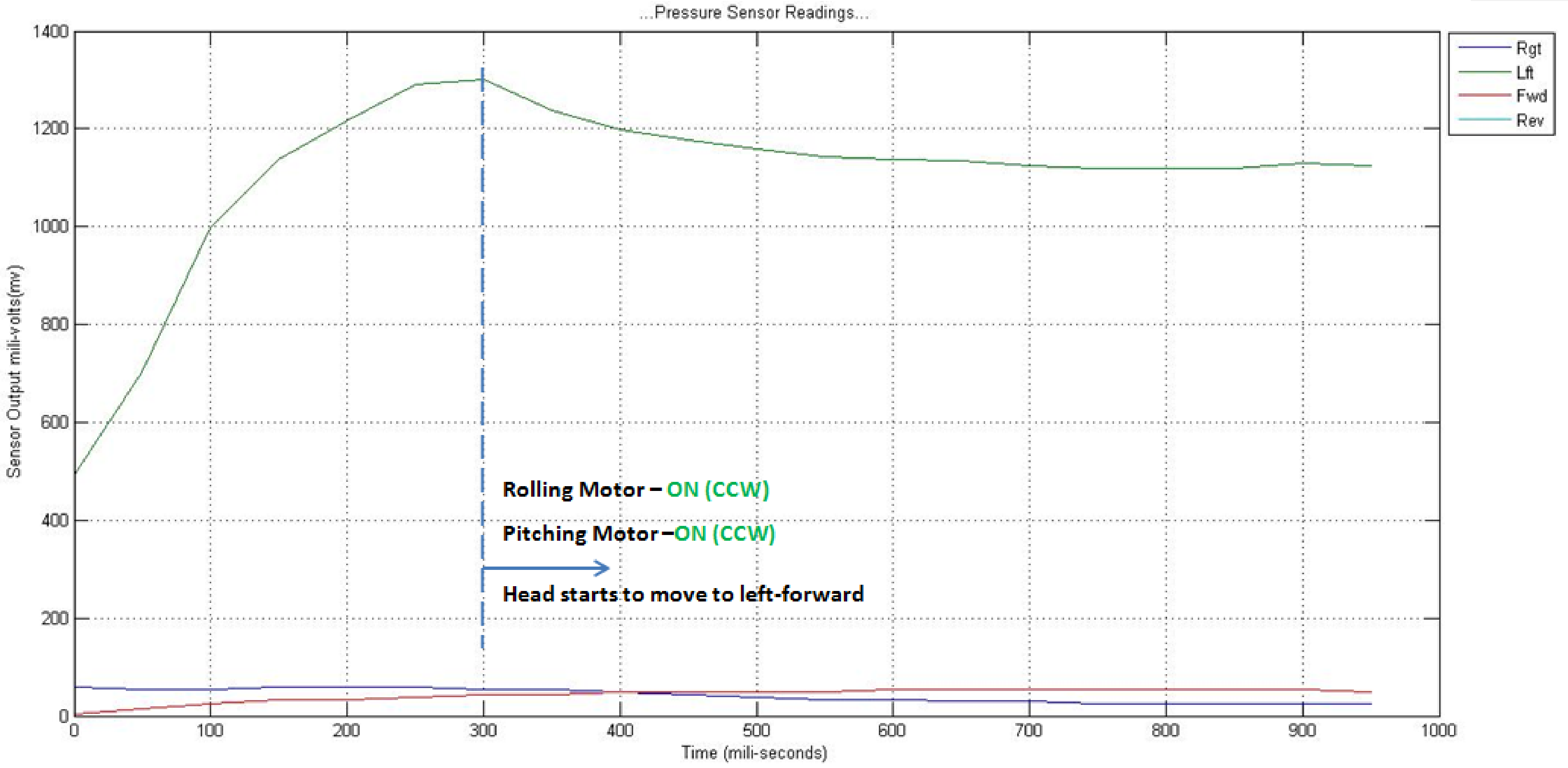


Fig 3.19: Force sensor readings of external force acting to the left-forward direction

When an external force is applying towards the left-forward direction of the head force sensor signal variation is shown in Fig 3.19. When time is reached to around 300 mS controller is providing command signals to both pitching and rolling motor to counter clockwise up to 35 deg and 48 deg respectively. (Please refer Table 2.2 for designed movable ranges).

Time taken to rolling motor for its destination = 48/82 s

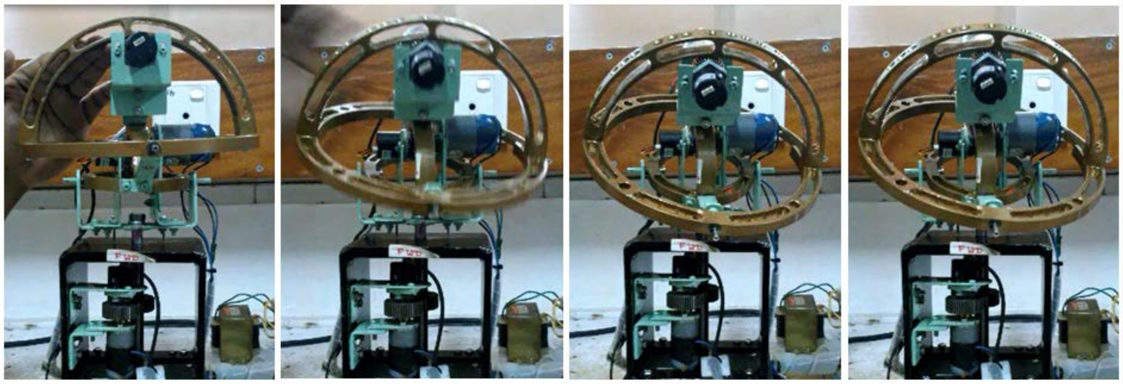
= 585 ms

Time taken to pitching motor for its destination = 35/82 s

= 427 ms

Time taken in real movement of left-forward motion = 525 ms

Movements snap shots of robot head for 3 equal intervals of above time span (525ms) are shown in Fig 3.20.



T = 300 mS $\theta_R = 0^0, \theta_P = 0^0$

T = 475 mS $\theta_R = -16^0, \theta_P = -12^0$

T = 650 mS $\theta_R = -30^0, \theta_P = -25^0$

T = 825 mS $\theta_R = -46^0, \theta_P = -33^0$

Fig 3.20: Robot head movements snap shots for force on left-forward direction

Case07: Applying an external force towards right-forward direction

Please refer the graph in Fig 3.21.

Percentage increments of left, right, forward and back sensors were 0%, 60%, 72% and 0%.

So, the calculated angle by the controller, $\tan\theta = \frac{(F_L - F_R)}{(F_B - F_F)}$

$$= \frac{(0-60))}{(0-72)}$$

$$\theta = -140^{0}$$

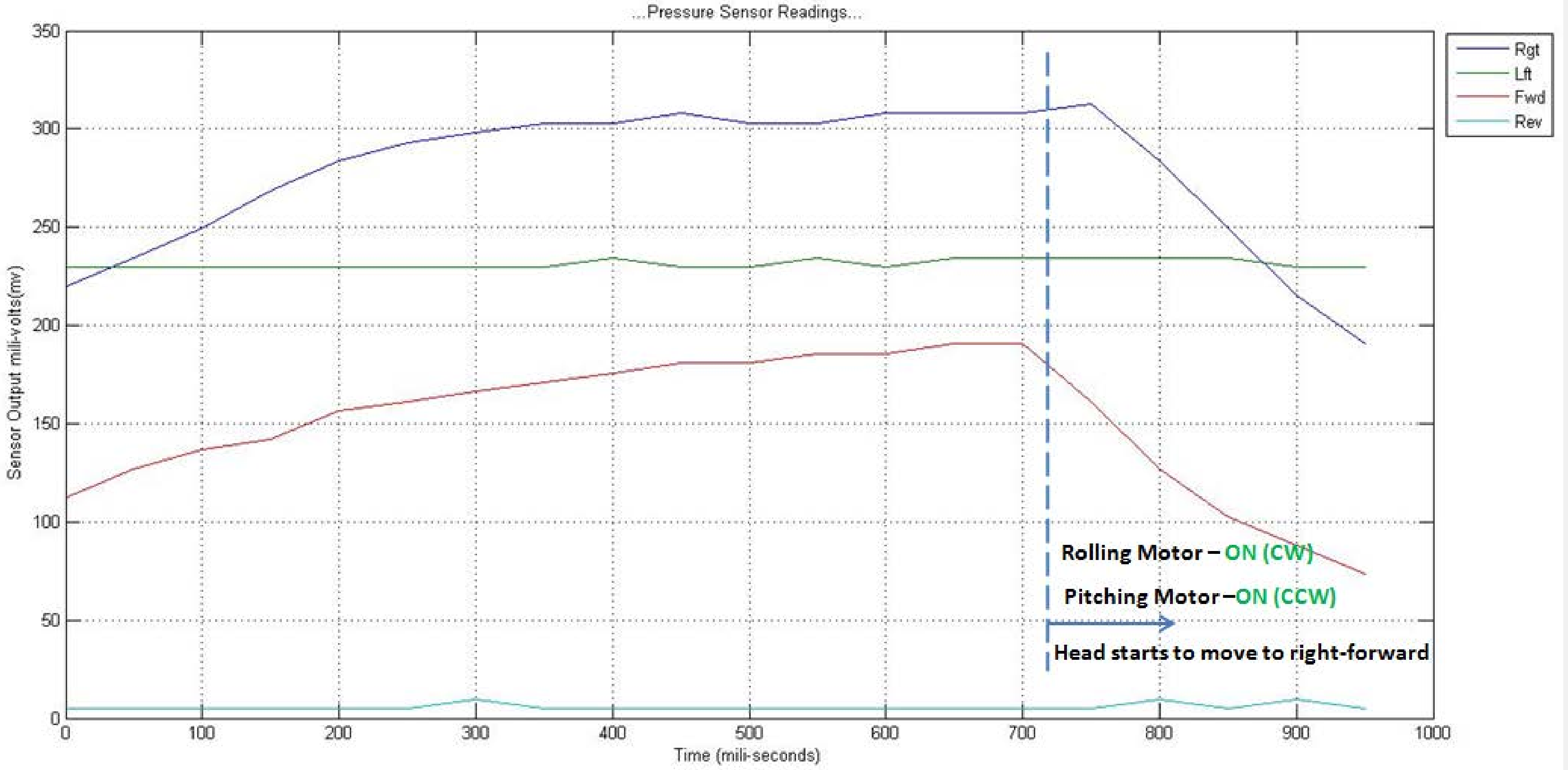


Fig 3.21: Force sensor readings of external force acting to the right-forward direction

When an external force is applying towards the right-forward direction of the head force sensor signal variation is shown in Fig 3.21. When time is reached to around 700 ms controller is providing command signals to pitching motor to counter clockwise and rolling motor to clockwise up to 35 deg and 48 deg respectively. (Please refer Table 2.2 for designed movable ranges).

Time taken to rolling motor for its destination = 48/82 s

= 585 ms

Time taken to pitching motor for its destination = 35/82 s

= 427 ms

Case08: Applying an external force towards right-back direction

Please refer the graph in Fig 3.22

Percentage increments of left, right, forward and back sensors were -3%, 66%, 0% and 66%.

So, the calculated angle by the controller, $\tan\theta = \frac{(F_L - F_R)}{(F_B - F_F)}$

$= \frac{(-3-66))}{(66-0)}$

$\theta = -46^0$

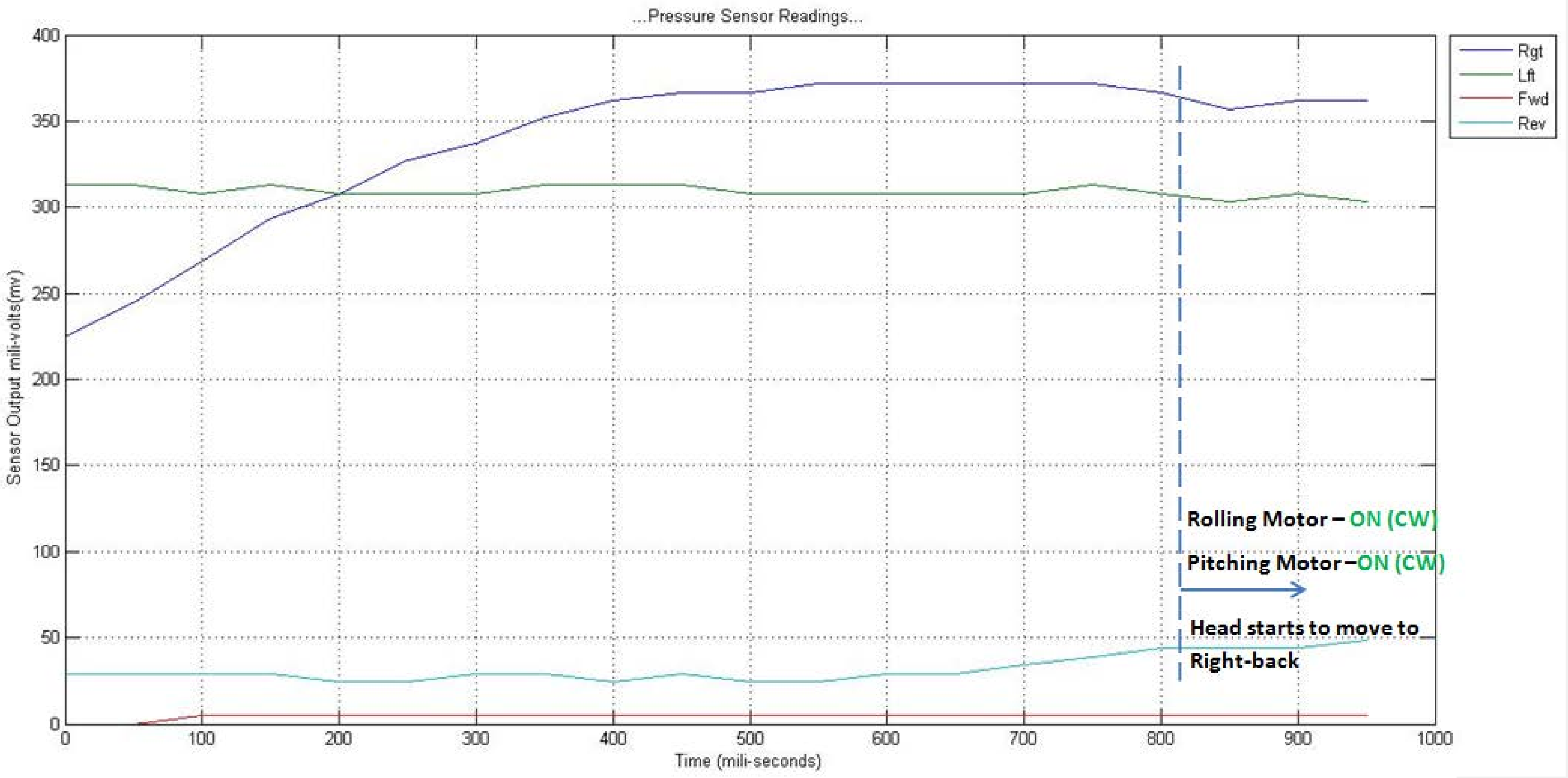


Fig 3.22: Force sensor readings of external force acting to the right-back direction

When an external force is applying towards the right-back direction of the head force sensor signal variation is shown in Fig 3.22. When time is reached to around 815ms controller is providing command signals to both pitching motor and rolling motor to clockwise up to 42deg and 48 deg respectively. (Please refer Table 2.2 for designed movable ranges).

Time taken to rolling motor for its destination = 48/82 s

= 585 ms

Time taken to pitching motor for its destination = 42/82 s

= 512ms

Time taken in real movement of left-forward motion = 535 ms

Movements snap shots of robot head for 3 equal intervals of above time span (535ms) are shown in Fig 3.23.

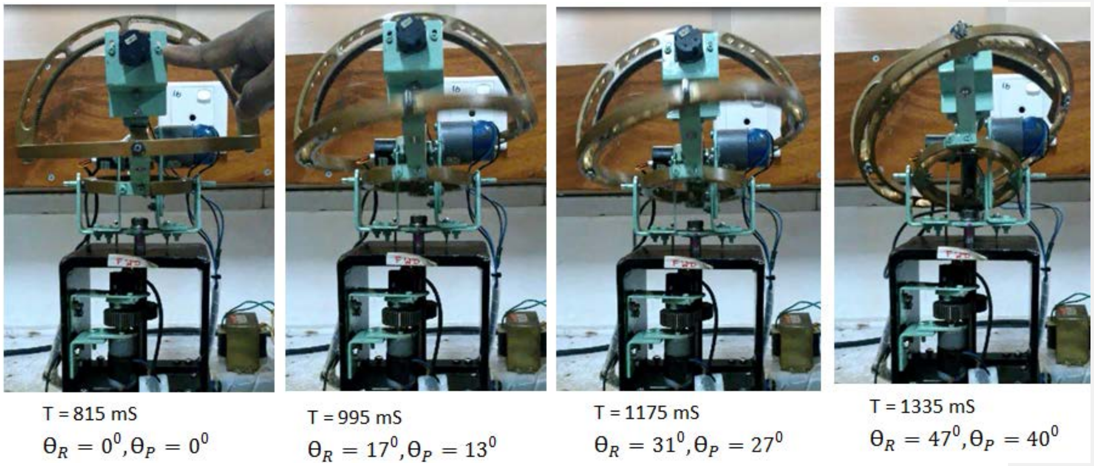


Fig 3.23: Robot head movements snap shots for force on right-back direction

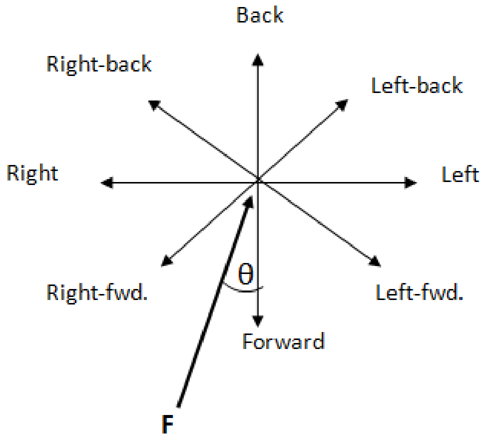
As explained above for an external force coming to any direction robot head will move the head away by activating its axis motors accordingly. For all directions limits has been assigned comparing anatomy of human head. Controller has been programmed so that head will stay its destination for 0.5 S and head will rotate back to zero position. Table 4.1 of Chapter 4 will show above all test results.

3.6.2. Tests carried out for other ranges of directions of external forces.

Comment [t2]: Cations of table on top of the table

Case 01: When direction of external force is $0 < \theta < 45$ deg

So far we have discussed about the testing of the robot head for main 8 directions as shown in Fig 3.4.In other way, we have tested robot head for the directions of XY plane 45 deg multiples. Now we want to consider the behavior of the robot head for the angles between 0- 45 deg.



Where $0 < \theta < 45$ deg

Fig 3.24: Direction of external force where $0 < \theta < 45$ deg

Fig 3.25: Movement of robot head for 0 < θ < 45 deg

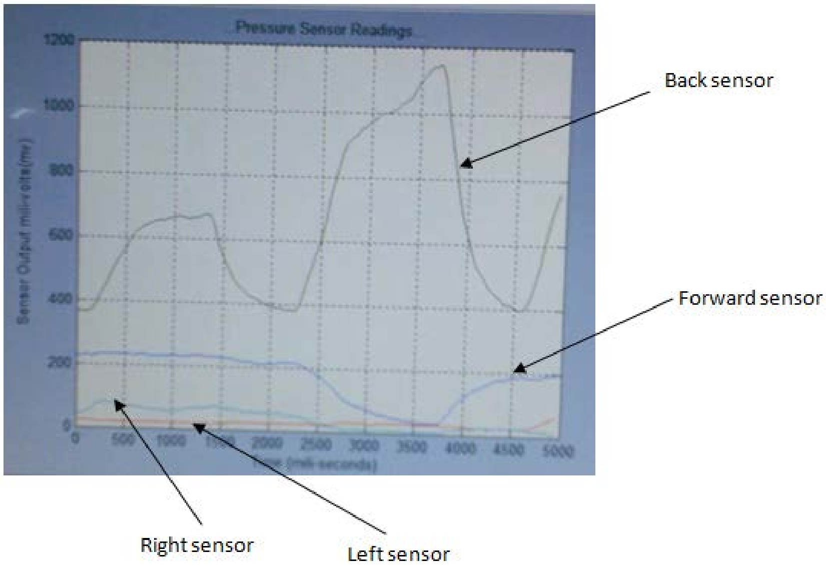


Fig 3.26: Movement of robot head for 0 < θ < 45 deg

Please refer above Fig 3.25 and Fig 3.26. During testing of the robot, A external force was applied with 20 deg with forward direction and observed the robot movement. It was moved to direction of external force. But we were not going to develop these algorithms further since our main objective was to develop directional based responses for main 8 directions. So, for further development of this robot model can be proceed by developing more algorithms to detect angles between 0 and 45 deg.

Case 02: When direction of external force converge toward Z axis

Robot head was tested by converging direction of external force toward the Z axis. When it converge to Z axis force sensors were providing analog signal with much ripples due to spring vibration of base. Let's consider the direction detecting algorithm of the robot, $\tan\theta = \frac{(F_L - F_R)}{(F_B - F_F)}$

When direction of external force is converge to Z axis all force sensor readings tends to be equal. So, It is very clear that when force sensor signals, $F_L, F_{R,}\, F_B$ and $F_F$are very closed to each other, detecting angle by the robot, θ will be very small value. So robot head will not be able to identify this small angle. Force sensor behavior of this kind of case as shown in Fig 3.27.

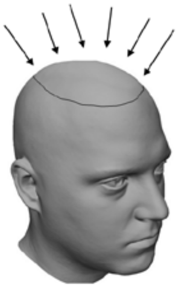


Fig 3.27: Direction of external force converging toward Z axis

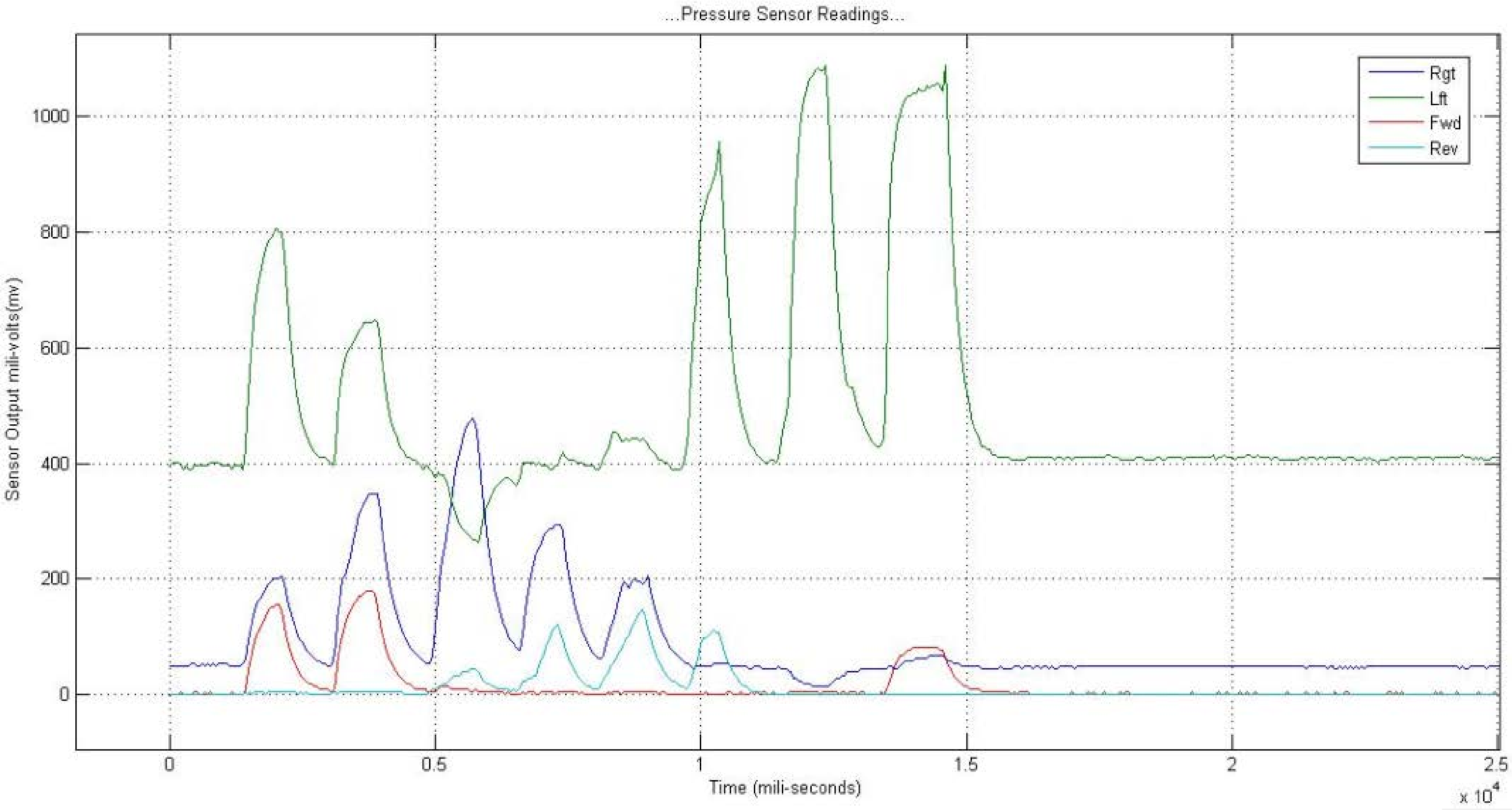


Fig 3.28: Force sensor readings for an external force converging toward Z axis

3.6.3. Reactions based on magnitude of external force

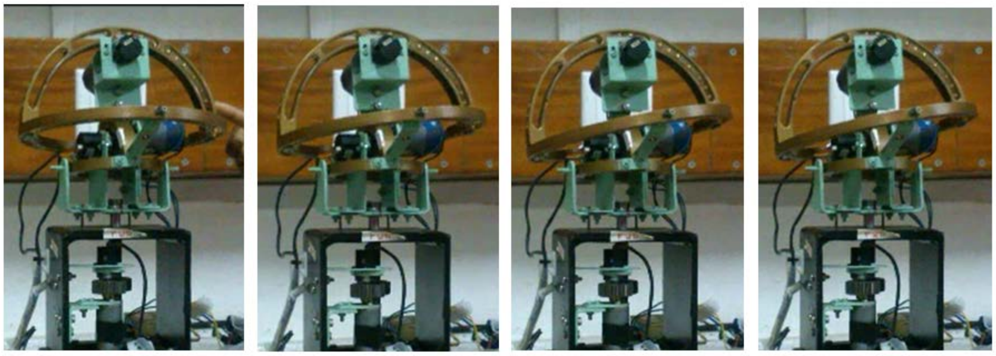
When we analyze reactions of human head under different magnitude of external forces it is a complex function of human brain. As e example if something hit gently on our head the reaction will be vary differ compared to if same thing hit hardly. it is obvious that when human head react to a external force magnitude of the same force is a decisive factor in all aspect. Normally if something hit on the head the speed of head taking away will proportional to the magnitude of the external force. In less significantly, angle of rotation also will approximately proportional to the magnitude of the external force. So, same reaction function was applied to the robot head

Table 3.2: Movement reactions for various magnitudes of external forces

Action	**Applied force(N)**	**Rotating Angle(degree)**	**Speed**	**Remarks**
Rolling	10	20	0.5* full speed	
	25	45	full speed	
Pitching	10	20	0.5* full speed	
	25	38	full speed	Beyond this, pitch is limited due movement limitations.
Yawing	10	20	0.5* full speed	
	25	45	full speed	

The speed variations were achieved changing the PWM value assigned to the each motor. After setting these speed limits system was tuned by applying above forces several times. When motor is driving with full speed, sometimes robot head will moves beyond the set points of axis encoder, due to movement of inertia of rotating elements. In this case

Controller will try to stop motor atpre-determined point. Same was caused to make little vibration. This problem was eliminated by reducing the speed of the motor when it closed to its destination. This issue was happened only for pitching due to imbalance weight distribution around pitching axis.



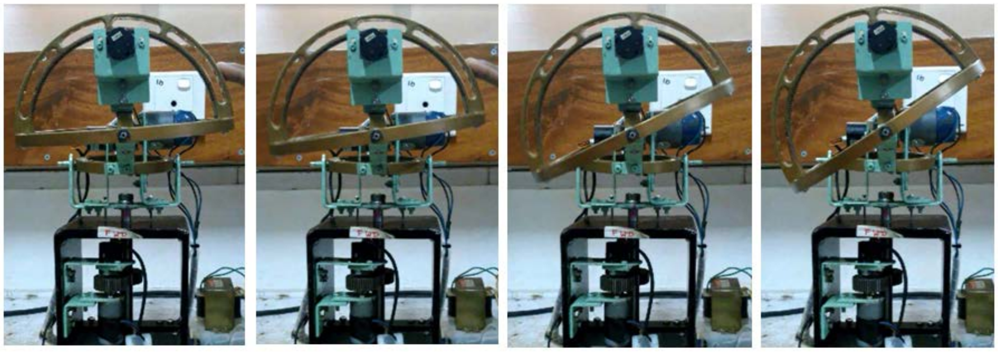
T = 900 ms $\Theta_R = 0^0, \Theta_P = 0^0$

T = 1100 ms $\Theta_R = 8^0, \Theta_P = 0^0$

T = 1300 ms $\Theta_R = 15^0, \Theta_P = 0^0$

T = 1500 ms $\Theta_R = 22^0, \Theta_P = 0^0$

Fig 3.29: Movements snap shots for half magnitude force (5N) on right direction



T = 900 ms $\Theta_R = 0^0, \Theta_P = 0^0$

T = 1100 ms$\Theta_R =$ $16^0, \Theta_P = 2^0$

T = 1300 ms $\Theta_R = 33^0, \Theta_P = 0^0$

T = 1500 ms $\Theta_R = 48^0, \Theta_P = 0^0$

Fig 3.30: Movements snap shots for full magnitude force (10N) on right direction

4.0. RESULTS AND DISCUSSION

First a set of experiments has been carried out in order to validate the basic neck movements of the robotic head. The robot head has been commanded to perform the basic neck movements and those movements have been captured. The captured images are shown in Fig.2.16 to Fig.2.18 According to the observations during the experiments; the robotic head is capable of performing basic head movements in anthropomorphic manner. During the experiment, external forces were applied on the robotic head in all 8 principle directions for verification of the force direction detecting algorithm and the reaction functionality. Variations of the readings of the force sensors and reaction movements of the robotic head in each test case have been recorded for further analysis. Variation of the readings of the sensors and the estimated force direction; θ for selected test cases are given in Table 4.1. The obtained force directions are plotted with the numbered lines in the Fig.4.2 for better understanding. The variation of the readings of the force sensors during the case 7 is shown in Fig.4.1. The variation of the force sensor readings shows a sudden reduction of the readings of the force sensors after 700 ms.This sudden reduction caused due to the movement of therobotic head away from the force. This phenomenon is analogues to the natural behavior of humans, since humans try to reduce the stress exerted on the muscles by moving the head away from the force.

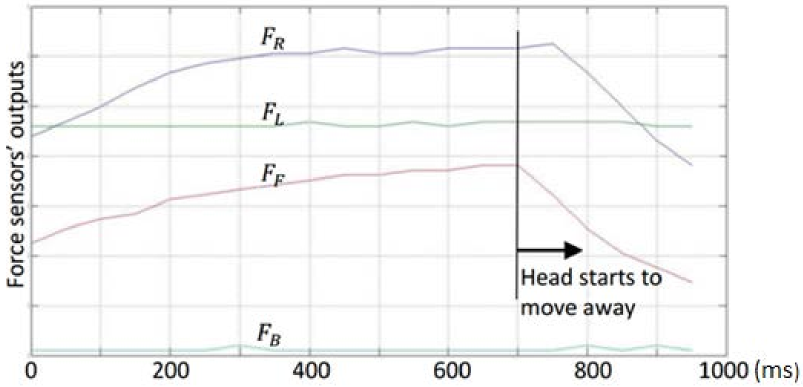


Fig 4.1: Variation of the force sensor readings during case 7

According to the obtained results, there are minor deviations in the estimated direction of the force. As an example in the case 1, the direction of the applied force is back and the calculated value of the θ is 9◦ which should be 0◦. However, during the experiment, the external forces were applied using the hand of the user. Therefore, the exact direction of the applied force could not be guaranteed as towards 'back' since the external force is not a pointed one. In addition to that, during the force direction identification phase it is assumed that the external force is applied on to a point of the head. However, in realistic situations the force is applied on to a small area instead of a point. This could also affect the results somewhat. However, the robotic head can adequately identify the direction, since the approximate direction is enough for the decision making. Therefore, it can be considered that the robotic head is capable of effectively detecting the direction of the external forces applied on the robotic head. However, the performance of the system can be further improved by incorporating more accurate force sensors and signal conditioning circuits. Further, it is capable of responding to the external forces applied on to the robot head. Currently the system is not capable of identifying the torque exerted around the rotational axis of the robotic head due to an external force applied on the head. Therefore, the rotational movement of the neck system is not used when reacting to an external force

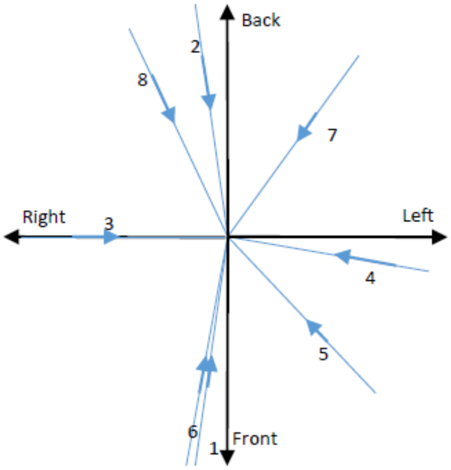


Fig.4.2. Calculated force directions by the robot for the test cases given in Table 4.1

Table 4.1: Experimental results for the external force act in main 8 directions

No	**Direction of external force**	**Forward sensor reading**		**Back sensor reading**		**Left sensor reading**		**Right sensor readings**		**Theoretical angle**	**Calculated angle by the controller**
		Difference (mV)	Percentage increase	Difference (mV)	Percentage increase	Difference (mV)	Percentage increase	Difference (mV)	Percentage increase		
1	back	20-10	-50%	90-10	88.88%	520-350	32.70%	100-90	10%	0°	9°
2	Forward	40-20	100%	0	0	700-580	20.69%	85-80	6.25%	180°	172°
3	left	20-20	0%	0	0	810-350	131.4%	20-80	-50%	90°	90°
4	Right	0	0%	50-0	50%	275-355	-22.55%	275-70	292%	-90°	-81°
5	Right-back	0	0%	50-30	66.66%	310-320	-3.22%	375-225	66.66%	-45°	-46°
6	Left back	5	0%	50-10	400%	1150-650	109%	60-40	50%	45°	11°
7	Right-front	190-110	72.72%	0	0	0	0%	320-200	60%	-135°	-140°
8	Left-front	50-10	400%	0	0	1300-500	160%	30-60	-50%	135°	152°

5.0. CONCLUSION

An anthropomorphic robotic head has been designed and developed to comply with the biometrical data of adult humanhead. The developed robot head has 3 degree of freedoms inthe neck section. The developed robotic head is capable ofascertaining natural human like neck movements into a greaterextent. A novel cost effective mechanical design for the necksection of the robot has been introduced. This design is capableof minimizing the displacements between the moving axes andfacilitating for a compact modular design. Commonly availableDC motors in the market can be used as actuators instead of custom-made actuators. Therefore, the design is cost effectivewhile providing adequate performance. The developed robotic head is capable of identifying the direction of an external force applied on it and appropriate acting to the force. Therefore, the robotic head has a novel attentive feature. Force attentive mechanism could be further developed by introducing more parameters for the reactionfunction. Apart from that, the robot head has been developed in sucha way that it can be used as a research platform that can be used for further research purposes.

5.1. Contribution

Contribution of my research can be discussed under main two areas as below. In the bio mimetic force attentive robot head developed, below force based reactions were incorporated to the robot head as my contribution.

5.1.1. Reactions based on direction of external force acting on the head

Direction of the external force is a main key factor that decides the mode of reaction for that force by the human head. When any external force acted on human head or something hit on the head, stresses or impacts induces on muscles of head or neck will send signal to brain to identify the direction of force acted to the head. Then brain will decide to take the head away from the force and will send signals to the muscles of the head, neck to act accordingly. In human anatomy each and every cell works as individual sensor to send stress signal to the brain. The robot head developed in this also same principle was used to detect the direction of external force. Instead of stresses generated in muscles of human head, four force sensor mounted on robot head base will sense the external force. According to the algorithm written on controller direction of external force will be determined by the controller and robot head will instantly move his head away from the force like human. This function was verified with 8 case studies that applied forces on the head in different 8 directions.

5.1.2. Reactions based on magnitude of external force acting on the head

When we analyze reactions of human head for different magnitude of external forces, it is a complex function of human brain. As an example if something hit gently on our head the reaction will be vary differ compared to if same thing hit hardly on the head. It is obvious that when human head react to an external force, magnitude of that force is a decisive factor in all aspect. Normally if something hit on the head, taking away speed of head will proportional to the magnitude of the external force. In less significantly, angle of rotation also will approximately proportional to the magnitude of the external force. So, same reaction function was applied to this robot head.

Reaction functions on magnitude of the external force were developed for this robot head for 2 magnitude limits for main for directions as shown in table 4.1

5.2. Problems Encountered and corrective measures taken

5.2.1. Problems of unexpected vibration at end of movement

Robot head was mounted on the base by means of 4 springs placed at each corner. When external force is applied on the head, robot head will move away from the applied force. But in the instant motors are stopping sudden jerk is acting due to momentum of the robot head. This sudden jerk is causing to induce forces on force sensors which may mislead the controller. So in some instants when robot head moved and stopped at a point again it will start to move even without having any external force acting. So, robot head had to be tuned very precisely to eliminate subjected vibration effects. Springs of the bases were mounted so that they can be adjusted easily to vary its length.

5.2.2. Slight play in gear motors due to weight of structure

There was a slight play in gear motors even after DC power cut-off due to weight of the brass ring gears those were used in head structure. After stopping the head movements by the controller, if this stop position is making a movement of any axis motor, that motor tend to rotate in very little amount. Especially when we consider the rolling motor this issue was significant since maximum moment is coming around rolling axis of then robot head. As corrective action some tolerance limit had to be introduced in the Arduino program for the encoder signals.

5.2.3. Difficulty of finding zero position of the head

Sometimes when resetting the robot head by pressing the reset button, it was not coming to rest position at once. It will pass its rest position and again will come back to the rest position. This is happening because of due to momentum of the head, it will go beyond the encoder limits defined in the controller program. This was fine-tuned so that frequency of this fault happening is minimum.

5.2.4. Issues related to material, machinery selection

Since we have used brass material to machine ring gears for rolling and pitching mechanisms the weight of the structure was increased up to considerable amount. Further, used ring gears were custom made especially for this project and those had to be machined in milling machines which has minimum size of gear teeth. As the result, gear ring gears made for rolling and pitching mechanisms were somewhat heavy and robust. This was caused to form a large momentum of rotational parts which cause to make some unexpected issues as explained above.

5.3. Recommendations and Further developments

We have implemented reaction function only for external force acting on the head and it also implemented only for main eight directions as discussed above chapters. But control algorithms can be developed to sense impulsive forces and many more reaction functions can be implemented for various modes of external forces.

Also force sensing methodology can be improved further by introducing more force sensors to the model. When the model is consist of more force sensors means accuracy of detecting the external force is going high.

If we consider the mechanical features of the model it can be implemented some corrective methods to eliminate issue arise during testing and tuning of the robot head. In order to eliminate vibration effect of the robot structure some set of dampers can be introduced to the base. This will ensure smooth functioning of force sensing mechanism and will caused to eliminate false sensor readings caused due to vibration of the robot head.

Also more sensitive types of force sensors can be used for better results for future implementations. Also impulse sensors, torque sensors can be used to sense different modes of external forces. Further, more advance attentive features like human can be incorporated to this robot model by introducing more DOF to the shoulder area of the robot head assembly.

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Rolling Motor – ON (CW

Pitching Motor - OFF

Head starts to move to right