Mechanical Design of Humanoid Robot, AUTOMI

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Abstract— **This paper describes all the sub-systems viz. Design, Controller, Walking Algorithm and Operating System, that are responsible for the mechanical design of AUTOMI, the humanoid robot developed by Team Humanoid, IIT Kanpur. AUTOMI has a total of 21 degrees of freedom (DOF): 6 for each leg, 4 for each hand and 1 for the head. The joints are actuated with the help of dynamixel servos namely MX-64, MX-28 and AX-18, depending on the torque requirement and range of motion. This paper, here onward, tries to present every relevant details, pertaining to any sub-system, that has contributed towards the designing of AUTOMI.**

I. INTRODUCTION

It is beyond question that a man's best assistant is another man himself. If ever in near future, there arises a possibility of a machine replacing a man's role, the chosen machine has to be made to look as close as to a human in appearance and has to be capable of adapting to human environment without much modification. With this vision, many companies, research institutes and universities have been developing various humanoids.

The most famous and impressive humanoid robot is ASIMO [1] made by HONDA. After the prototype robot P2 [2] was revealed in 1996, HONDA has steadily released the progress of ASIMO. Other than ASIMO, we followed the research work of famous kid size robot, NAO [3]. Their research work guided us and provided us the basic framework for our study.

All this research about different humanoids signifies the importance of mechanical design in developing a humanoid robot. Mechanical design of any humanoid depends on various parameters. So before designing the final model on CAD [4], a lot of research was done on the shape and orientation of different body parts, torque and load on each joint, dimension and specification of electrical components, processing unit, operating system, orientation of sensors and the optimized trajectory for walking.

Many research papers were studied to build the actuating system of the humanoid. Initially, the design of actuator assembly was built and tested on VRep (Simulation software) to find the appropriate orientation of each actuator (Smart Servos) and to minimize the internal vibrations occurs due to misalignment of actuators and links. After finalizing the orientation, torques on each joints were calculated using MSC ADAMS (Simulation software). After this, Stick model MATLAB simulation was done to find out the optimized walking algorithm, corrected torque (taking dynamic torque into account) and the dimensions of different links. With all this research data, CAD model was constructed with simple links to avoid any manufacturing errors. After this, a biped was fabricated according to finalized design. This design was as close to human legs as possible. To fabricate error free biped, some parts were manufactured several times. Similarly, the torso (upper half of the humanoid) was manufactured and integrated with the biped to get the final

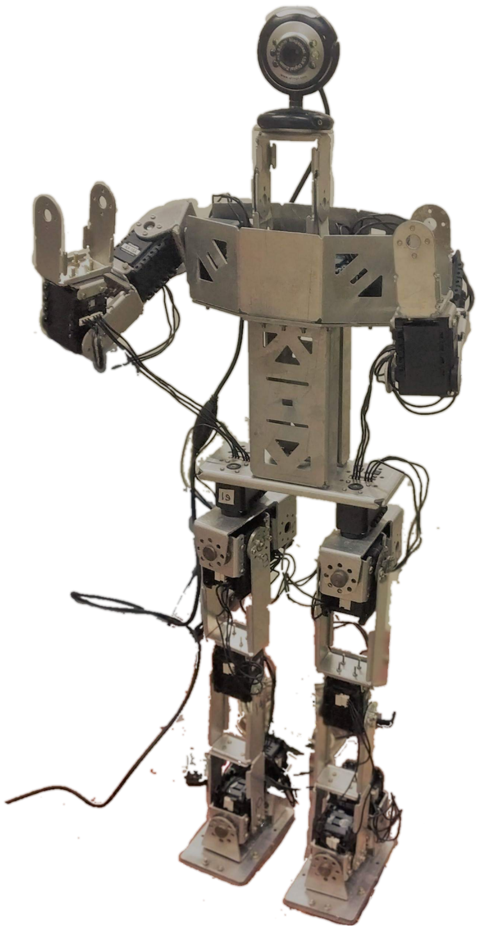

Fig. 1. AUTOMI (Humanoid Robot)

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TABLE I

SPECIFICATION OF AUTOMI

Height		72 cm
Weight		4.8 kg
Walking Speed		1.7 cm/s
Step Period		6 s
Actuator		MX-64, MX-28, AX-18
Control Unit		Odoroid
Sensory Devices		FSR, IMU, Camera
Power Supply	Battery	12V 10000 mAH
	External Power	SMPS 12V 30A
Operation Devices		Dynamixel Servos

TABLE II

DEGREE OF FREEDOM

Part		DOF	Actuator
Head	Neck	1	MX-28
Arm	Shoulder	2x2 = 4	AX-18
	Elbow	1x2 = 2	AX-18
Hand	Wrist	1x2 = 2	MX-28
Leg	Hip	3x2 = 6	AX-18, MX-28, MX-64
	Knee	1x2 = 2	MX-28
	Ankle	2x2 = 4	MX-28, MX-64
Total		21	

robot, AUTOMI.

II. DESIGN CONCEPT

A. Design Philosophy

AUTOMI was designed keeping in mind the specifications required to participate in FIRA HUROCUP. Its design was majorly dependent on the following four factors:

- Specifications (Needed for FIRA HUROCUP)
- Dimensions of components
- Low weight and less power consumption
- Minimum constraints possible

Keeping the above four factors as base for design, mathematical calculations were done on MSC ADAMS to find the required static torque on each joint. Dynamixel smart servos of different specifications were used as the actuators as they can provide high torque along with high angular precision and that too in very small size. After orienting these smart servos at different joints, further design process was carried out.

B. Overview of AUTOMI

AUTOMI is a humanoid robot of 21 DOF explained in the TABLE I. Its height and weight are 72cm and 4.8 kg respectively. The main frame is manufactured using Aluminium while connectors and fasteners are made using mild steel. The buckling effect was minimized by giving a sideways bend[5]. Simplicity in designing the different links was preferred to minimize the errors due to manufacturing. The technical specification of AUTOMI can be inferred from Table-I, Table-II, Table-III, Figure-I and Figure-II.

C. System Integration

1) Control Architecture: While developing AUTOMI, a centralized computing system has been implemented using

TABLE III

LIST OF PARTS

Part	Material	Features
1	Aluminium	Function - Orients 2 servos in such a way that their axis is perpendicular to each other. Location of Use - Foot & Hip Quantity - 2 x 2 = 4
2	Aluminium	Function - Connects to joints in biped Location of Use - Link for knee to ankle and knee to hip Quantity - 3 x 2 = 6
3	Aluminium	Function - Basic servo frames Location of Use - Foot and Hip Quantity - 2 x 2 = 4
4	Mild Steel	Function - Servo Backside Horns Location of Use - Each servo Quantity - 4 x 2 = 8
5	Aluminium	Function - Connects links with servos Location of Use - Knee, shoulder, arms, and neck Quantity - 3 x 2 + 1 = 7
6	Aluminium	Function - Foot base Location of Use - Foot Quantity - 2
7	Aluminium	Function - Connect servos in arm Location of Use - arm Quantity - 2 x 2 = 4
8	Aluminium	Function - shoulder joint Location of Use - shoulder Quantity - 1 x 2
9	Aluminium	Function - Chest Base Location of Use - Chest Quantity - 1
10	Acrylic	Function - Gripper claws Location of Use - Hand Quantity - 1 x 2 = 2
11	Acrylic	Function - Hand Location of Use - Hand Quantity - 1 x 2 = 2
12	Aluminium	Function - Torso plate Location of Use - Torso Quantity - 2
13	Aluminium	Function - Waist Plate Location of Use - Waist Quantity - 1
14	Aluminium	Function - Chest Plate Location of Use - Chest Quantity - 2

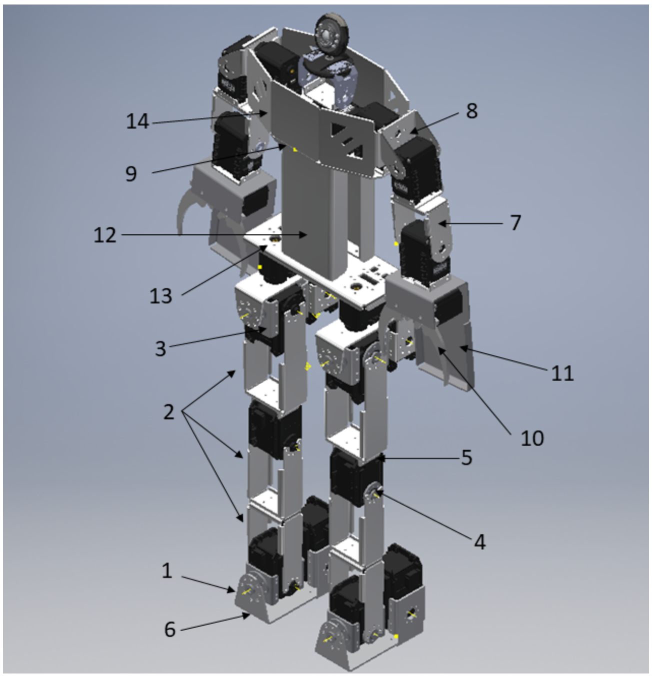

Fig. 2. AUTOMI'S CAD Model

TABLE IV
MAIN PROCESSING UNIT

On-Board PC Model	Odroid XU4
Processor	Exynos5422 Cortex-A15 @ 2.0 GHz octa-core CPUs
GPU	Mali-T686 (Open GL ES 2.0)
RAM	2GB LPDDR3 RAM at 933 MHz PoP stacked
Storage	microSD card slot, eMMC 5.0 HS 400 Flash Storage
Price	∼Rs. 11,900
Power Source	5V 4A DC input
Dimensions	82 x 58 mm
OS	Ubuntu 16.04

Odroid XU4, which has a Linux-based operating system (Ubuntu 16.04) as the main computer. It supervises the control of actuators at the joints by providing appropriate angles and velocities, obtained after accurate computations (refer walking algorithm, Section V).

Using distributed version control systems [6], with the help of Git, the modules (designing, simulation, IP) were distributed to multiple computers, handled by different team members. Once the modules were completed, they were loaded onto the main computer and integration was achieved using Robot Operating System, abbreviated as ROS [7].

2) Sensors and Actuators: Essentially AUTOMI has been equipped with 3 different sensors to obtain data from the surrounding environment. One Inertial measurement unit (IMU UM7) is mounted at the Center of Mass, i.e. pelvis joint of AUTOMI, to obtain the body's current orientation, eight pressure sensors (FSR-402) are fixed on each foot and one camera (Logitech C270) is placed at the head, to get visual data input from the surroundings.

For actuators, DYNAMIXELS have been used. DYNAMIXELS are designed to be modular and daisy chained on any robot or mechanical design for powerful and flexible robotic movements. The DYNAMIXEL is a high-performance actuator with a fully integrated DC (Direct Current) Motor + Reduction Gearhead + Controller + Driver + Network, all in one servo module actuator.

The method of serial communication between actuators and Odroid is TTL serial (transistor-transistor logic), which transmit one bit at a time at a specified data rate (i.e. 9600bps, **115200bps**, etc).

3) Software and Packages: ROS Kinetic Kame, an open-source meta-operating system, primarily targeted at Ubuntu 16.04, was used to integrate the different modules. Integration included receiving information from the sensors, doing the computations on them and finally feeding the data to the

TABLE V
SPECIFICATIONS OF UM7 ORIENTATION SENSOR

Weight	11 grams
Data Output Rate	1 Hz to 255 Hz, binary packets 1 Hz to 100 Hz, NMEA packets
Output Data	Attitude, Heading (Euler Angles) Attitude quaternion GPS altitude, position, velocity (w/external GPS) GPS position in meters from home configurable home position. Raw mag, accel, gyro data Calibrated mag, accel, gyro, temperature data
Communication	3.3V TTL UART, 3.3V SPI bus
Operating Temperature	-40C to +85C
Power Consumption	50 mA at 5.0V
Dimensions	27x26x6.5 mm

TABLE VI
SPECIFICATIONS OF FSR 402

Force Sensitivity Range	0.1-100 N
Stand-Off Resistance	>10 M ohms
Operating Temperature	-30C to +70C
Dimensions	18.28 mm diameter x 0.7 mm thickness

TABLE VII
SPECIFICATIONS OF CAMERA MODEL: C270

Resolution	720p/30fps
Field of View	69 degree
Rotation	360 degree
Dimensions	13x5.2x18.1 cm

TABLE VIII
SPECIFICATIONS OF ACTUATORS

	AX-18	MX-28	MX-64
Operating Voltage	12V	12V	12V
Stall Torque	18.3 kg-cm	25.5 kg-cm	61 kg-cm
No-load Speed	97 RPM	55 RPM	63 RPM
Operating Temperature	-5C to 85C	-5C to 80C	-5C to 80C
Protocol	TTL	TTL	TTL
Weight	54.5 g	72 g	126 g
Dimensions	32 x 50 x 40mm	35.6 x 50.6 x 35.5 mm	40.2 x 61.1 x 41.0 mm

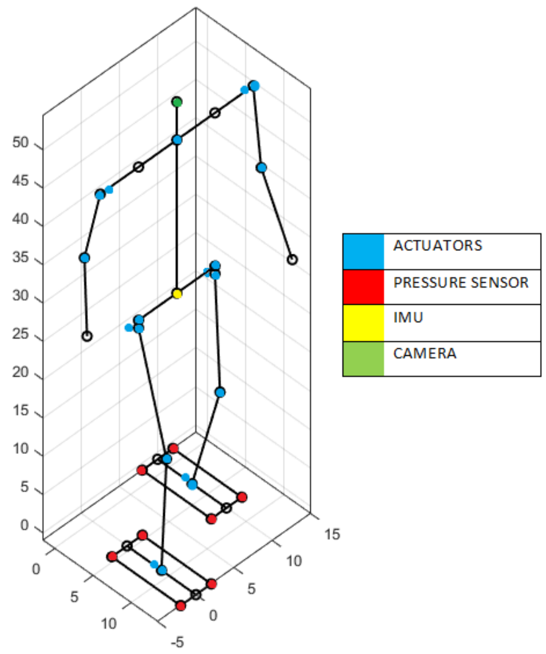

Fig. 3. Ball and Stick Model showing position of actuators and sensors

actuators.

III. Design Research

A. Research Structure

The aim of this research was to develop a humanoid that would be capable of doing: Walking, Running, Archery, Ball throwing, Weight lifting and Obstacle avoidance as per as per the rules of FIRA HUROCUP. So, the design research was divided into two major parts:

1) Biped (Lower body)
2) Torso (Upper body)

B. ESSCEL (Acrylic based biped)

On the basis of the MATLAB based ball-stick simulation [9], dimensions for the different parts of biped have been deduced. Smart servos were used to provide the controlled rotary motion at the joints. Body links were manufactured with acrylic and were joined to the actuators using aluminium based L-clamps and frames. After designing a simple looking biped on Autodesk Inventor, design of the links were modified to impart them a shape similar to that of a human leg.

Drawbacks:

1) Due to manufacturing errors, tolerance level of angular motion at some joints became very low, thus adding unnecessary constraints at those joints and hence leading to a improper rotary motion.
2) Since acrylic is not stiff as compared to aluminium, acrylic based Pelvis plate started bending over a period of time leading to a unstable walking motion.

Fig. 4. ESSCEL - Biped

3) Some of the clamps were manufactured by bending 3mm thick aluminium sheet. Improper bending of these clamps leads to imperfect shape that creates unnecessary blocking of servo motion.
4) Since the whole body was covered by acrylic based links, some of the errors remained undiscovered during real-time testing.
5) Bearings were not used on the rear side of servo, which led to occurrence of improper rotary motion and jerk at each joint.

C. AUTOMI (Biped + Torso)

To get better visuals and understanding on the motion of rotatory joint during real-time testing, unnecessary links were removed and the remaining links were reduced to simple rectangular shapes. Hence, the biped structure of AUTOMI was a simple link to link structure manufactured using 1.5mm and 2mm thick aluminium. Servo frames were manufactured using 1.5mm thick aluminium while servo horns were manufactured using mild steel. All the design related details of the AUTOMI is provided in the TABLE III.

Corrections:

1) Bearings were used on the rear side to reduce friction.
2) Sideways bends were provided to prevent the buckling of links.
3) Effort was made to fabricate the whole structure with minimum number of links.

Drawbacks:

1) Large error crept during machining and cutting of small part due to the presence of machining tolerances.
2) Bending of complex parts usually resulted in unwanted distortion in other regions of the respective part.
3) Precision became a significant issue in drilling of holes in servo horns.

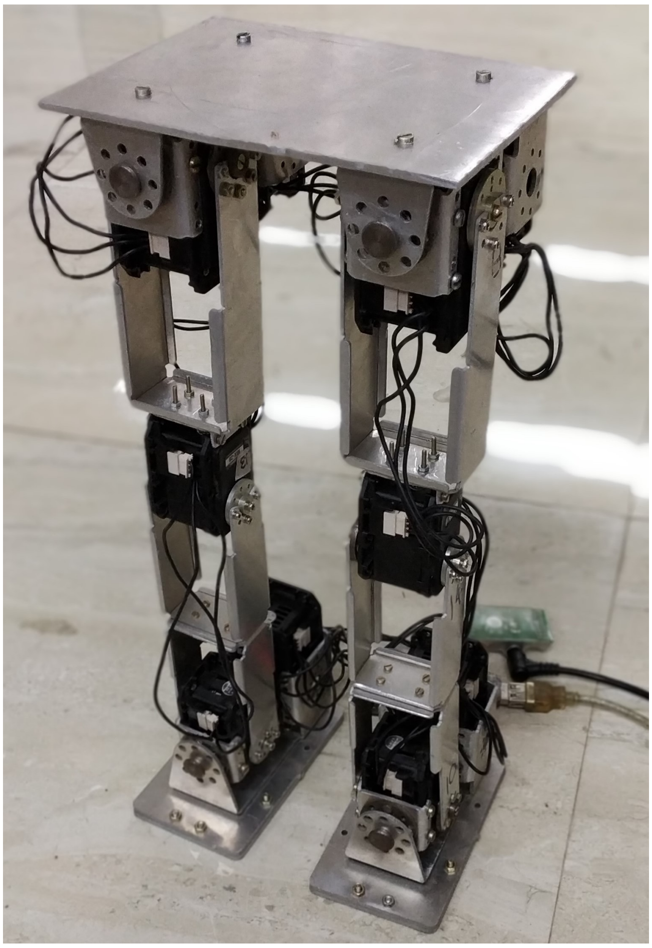

Fig. 5. AUTOMI'S Biped

D. Foot Base (TABLE III: Part 1,6)

Flat foot is a physical disorder that affects the normal walking behaviour of human beings. Human legs with flat feet experienced contact force on the center of the foot. Due to this, toppling force increased and hence stability during the walking decreased.

1) To remove flat foot problem in our biped, cuboidal rectangular frames were attached at the corners of the base of the foot. This transformation shifts the contact force from the center of the foot to the corners and hence provides a stable base for the biped.
2) Also, the screws used to fix the servos at the foot touched the ground. So to remove this mechanical error, countersunk screws were used to fix the base servos.

E. Torso Base (TABLE III: Part 3,13)

Servo Orientation:

1) Mostly at the intersection of biped and torso, three servos with mutually perpendicular axis of rotation were attached to every leg forming a hip joint.
2) Instead of keeping the axis of third servo (Axis of rotation parallel to front face of AUTOMI) parallel to the base of torso, we can also orient it by rotating the axis by $45°$ in the front plane.
3) This orientation provides easy turning of the bot, reduces the lifting torque and decrease the bending torque on the servo's shaft.

Extra DOF at base of Torso:

1) If we provide extra DOF at the base of the torso (Align at the center; TABLE III: Part 13) we can shift the COM of the body according to our needs and hence increase the overall stability.
2) To reduce the additional torso on this extra DOF due to the weight of torso, bearings should be mounted at the top and bottom point of this additional servo (between the biped and the torso). This assembly also increase the efficiency of rotation at this particular joint.

IV. Motion Control

Motion control is the part of automation that handles moving parts of machines in a deliberate and controlled manner. It can be primarily divided into two control algorithms: first, that assists in AUTOMI's stable walking; and second, that enables it to perform tasks.

A. Real Time Balance Control

An offline gait was obtained through energy optimization [Section IV], while a real time feedback system was used to stabilize the walking. Pressure sensors at the ankle and Inertial Measurement Units at the COM of AUTOMI were installed. The sensor data is processed and the results are used to modify the input joint angles to the actuators. This reduces instability produced by unpredicted external forces and torques like vibrations due to excess torque at the joints, landing shock because of untimely landing of foot and disbalance caused by overshoot in actuators.

B. Real Time Routines

The main aim here is to enable AUTOMI perform tasks like avoiding obstacles while walking, approaching a ball and throwing it in a basket and shooting arrow at a rotating target. The primary sensor was a camera attached to the head of AUTOMI. For avoiding obstacles, first the obstacle was detected using colour detection, maximum area and polygon detection and a path was planned to stay clear of the

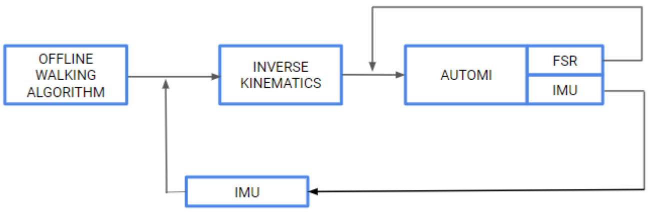

Fig. 6. Control block diagram for stable walking

obstacle. For the second task, first the ball and basket were detected and the most favourable trajectory was found for energy optimization of our 2 DOF robotic arm using Genetic Algorithm [8]. For archery, however there was almost a unique solution the challenge was to perceive the rotation target by the camera and feed in correct data to the arm actuators to hit the bullseye.

V. Walking algorithm

A. Introduction

Walking algorithm is a mathematical algorithm written on MATLAB to know how actuators of each joint should rotate to make a humanoid walk properly. This includes finding joints location from optimized trajectories through inverse kinematics and computing that optimized trajectory through inverse and forward dynamics equations (recursive Newton-Euler equations). For both tasks first, the biped needs to be perceived as a ball-stick model where all the masses are located at the location of joints because masses of links are very less as compared to actuators mass.

B. AUTOMI Dynamics

At first stage walking biped is achieved. Newton Euler forward equation gives us kinematic properties of each mass in terms of previous mass properties i.e angular velocity, angular acceleration of link, the velocity of point masses and their accelerations. These equations are:

$$[w]_i = Q[w]_{i-1} + \dot{\theta}[e_i]_i \tag{1}$$

$$[\dot{w}]_i = Q'[\dot{w}]_{i-1} + \ddot{\theta}[e_i]_i + [w]_i \times [e_i]_i \tag{2}$$

$$[\ddot{a}_i]_i = Q'[\ddot{a}_{i-1}]_{i-1} + [w]_i \times [r_i]_i + [w]_i \times [w]_i \times [r_i]_i \tag{3}$$

$$[f_i]_i = m \times [\ddot{a}_i]_i \tag{4}$$

$$[n_i]_i = [I_i]_i[w_i]_i + [w]_i \times [I_i]_i[w_i]_i \tag{5}$$

Where w is angular velocity of joint, a is acceleration of joint, f is force and n is moment over joint, I is moment of inertia, Q is rotation matrix and e is normal unit vector of i^{th} rotation frame.[9]
Through reverse dynamics, i.e. linear and angular momentum balance (6, 7, 8) , torque for each link can be calculated from the torque of next link.

$$[f_{i-1,i}]_i = [f_i]_i + [f_{i,i+1}]_i - m_i g \tag{6}$$

$$[n_{i-1,i}]_i = [n_i]_i + [n_{i,i+1}]_i + [r_i]_i \times [f_{i,i+1}]_i \tag{7}$$

$$[\tau_i]_i = [n_i]_i[e_i]_i \tag{8}$$

AUTOMI's step length is 15 cm (equal to link length), step height is 4 cm which is found through the regression data of real life after proportioning it with height ratio. One step is divided into three phases - Double Stance Phase (DSP)1, Single Stance Phase (SSP), and DSP2. DSP refers to the state of biped where both feet are on ground and torque of each frame is written in terms of Normal force of swing feet and angles of all link before it. SSP has the swing feet in the air, so torque of each frame is written only in terms of angles of links before it. Starting and ending point of COM is identified through static Zero Moment Point (ZMP) theory which states that ZMP should lie within the foot maps of landed foot. ZMP is the point on ground around which net moment comes out to be zero. According to Cart Table Model (see Fig 7) coordinates of ZMP will be as per the equation (9, 10), considering ground at $z = 0$. [10]

$$x_{ZMP} = x_{COM} - \frac{\ddot{x}_{COM}}{g} \times z_{COM} \tag{9}$$

$$y_{ZMP} = y_{COM} - \frac{\ddot{y}_{COM}}{g} \times z_{COM} \tag{10}$$

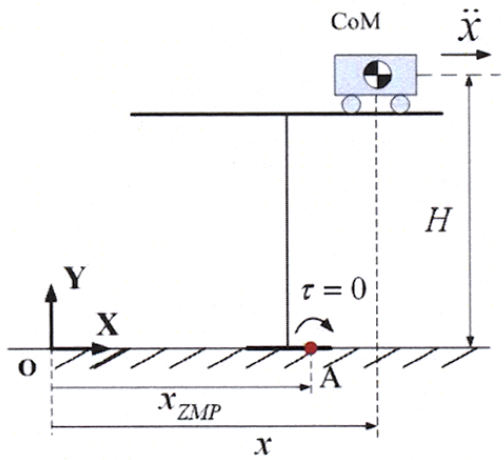

Fig. 7. Cart table model

So, to generate a suitable algorithm we need to optimize work done through variables including F (tip), COM coordinates(COM is center of the pelvis for our case) and ankle coordinates so that work required is minimal. The optimal trajectory of COM looks like sinusoidal curve and trajectory of the ankle is a straight line when viewed from the top plane. The trajectory of COM and ankle is cubical as viewed from the frontal plane, and the view from the sagittal plane is a combination of these two views. So trajectory of COM in the frontal plane during SSP is $0.015625 \times (x - 4)^2 \times (x - 2)$ (Fig 8) where $x = 2, x = 4$ are starting and ending position of COM respectively and x is in the forward direction. [11]

In the top plane, equation of COM is $3 \times (sin(wt))$ where w is $\pi/3$ (Fig 9). And the trajectory of the ankle in the frontal plane is $0.8434 \times (x9)^2 \times (x + 3)$ (Fig 10)

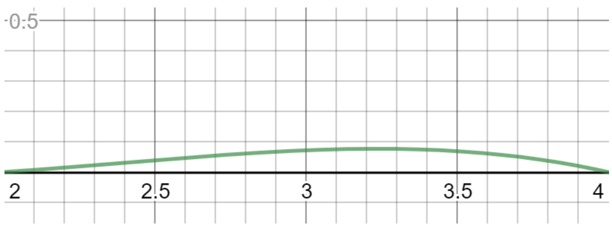

Fig. 8. Trajectory of COM in frontal plane during SSP where the vertical axis is height and horizontal is x of COM

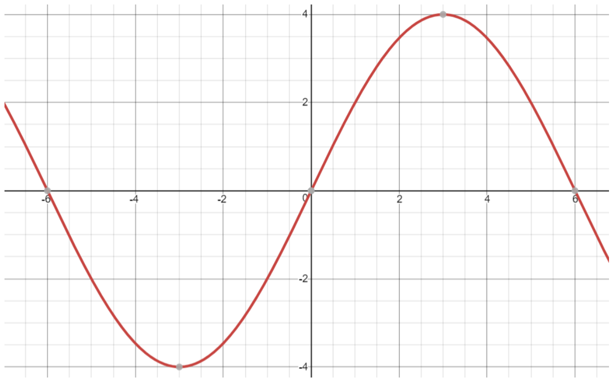

Fig. 9. COM, as viewed from top plane where the vertical axis is side displacement and the horizontal axis is x

After getting these trajectories, the angle of joints is found through inverse kinematics equations. For full humanoid torso needs to be included, as pelvis in biped simulation remains straight so torso will also be straight in whole walking. Sinusoidal swing of arm provides stability to humanoid in walking as arms act like mass damper. So -3 to 16 degrees sinusoidal swing is given to arms which is an average estimate of how human arms swing[12]. In MATLAB all joints are shown with dot and links as line. Using link length and transformations of joint angle, position of each joint is found. Joints angles are stored in a YAML file and then these are published to joint trajectory node which is responsible to move actuators.

C. Impact on mechanical design

Based on the torque calculation from simulation, proper actuators were selected. Factor of safety was taken 2. For actuators at arms torque depends on tasks performed by hand but the torque required by bipedal actuators in full humanoid walking are shown in Table IX. For implementing simulation model link should have very less mass as compared to actuators mass but strength should be high. Dimension of foot is fabricated from this algorithm as the algorithm shows that point of normal reaction has a displacement of approximately 6-7 in SSP, so including factor of safety i.e. 2, the diameter of foot is taken 12.

VI. Conclusion and Future Work

The paper describes the mechanical design and deliberation of a Humanoid robot: AUTOMI. The design involves joint positions to stabilize the system, torque calculation, and actuator selection, weight of links and clamps and actuators. Selection of material and frames for electronics subsystem, failure mode analysis and consideration of simulation approximations so that design does not deviate are some points presented in the paper. Future work will involve developing an independent closed loop feedback based actuator with a highly efficient transmission system consisting of gears, pulleys and belt that can transmit the desired torque throughout the body.

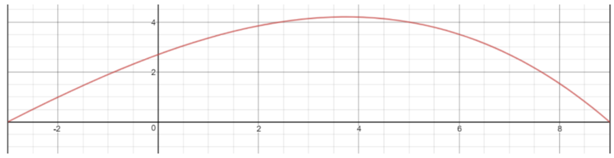

Fig. 10. Trajectory of the ankle in the frontal plane where the horizontal axis is x of ankle point and vertical one is height

TABLE IX

Actuator Selection Based on Walking Algorithm

Joint location	Rated torque including factor of safety	Actuator used
Ankle	2*3.8	MX28
Foot	2*9.6	MX64
Knee	2*2.6	MX28
Hip	2*9.3	MX64
Waist	2*4.2	MX28
Other Joints	2*x (x<2)	AX18

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