CHAPTER 2
PHYSICAL STRUCTURE

2.1 Overall Design Considerations

The overall goal of building *Pneuman* is to develop a platform that has several useful attributes conducive to humanoid robot research. In addition to research, the robot will give guided tours of the MIL. Other possible uses include entertainment and operation as a personal assistant. Due to these requirements, a humanoid platform was ideal.

A humanoid robot contains many areas for research. The two main areas can be classified as artificial intelligence and control. Artificial intelligence may be divided further into human-robot communication, path planning, machine learning, machine vision, and cognition. The overall control area may be divided into kinematics and dynamic systems control. The areas that will be discussed in this paper include kinematics and dynamic systems control.

Natural human-robot communication will be possible with verbal interaction. A speech recognition system combined with a natural language processing system will allow *Pneuman* to understand simple phrases and respond verbally with a voice synthesizer. *Pneuman* will navigate throughout its environment using a verity of sensors, including sonar, infrared emitter/detector pairs, bump switches, and optical encoders. The sonar and infrared sensors will provide robot-obstacle distance information. The bump switches will signal the robot that an obstacle was contacted. Finally, the robot can use dead-reckoning to estimate the amount of distance traveled with the optical encoders. This information is processed by *Pneuman's* computers and used to compute the possible paths it may take to move from one point to another.

Machine learning techniques will be used to improve the kinematics for the position if the end effectors, as well as positioning the drive wheels. The techniques will compensate for any unmodeled effects such as machining tolerances, backlash, flexing, friction, etc. An advantage of using these techniques is that the kinematic and dynamic models are simpler. A disadvantage is that the systems must be trained. However, the benefits outweigh the disadvantages.

Pneuman's vision system will also use machine learning techniques to identify objects in an image. Color models of objects will be generated and stored in *Pneuman's* computer. When an object is identified in the stereo images, *Pneuman's* active stereo head will focus onto the objects, and each eye will converge to center the object in the field of view. The disparity between the eyes will provide *Pneuman* with information about the location of the object in space. *Pneuman* can then use this information to position its end effectors in the proper location, possibly to pick up the object.

Cognition is defined as, "The act or process of knowing" by *Lobster's Dictionary* [25]. Many researchers throughout the world are currently trying to make robots that "know" things or "think". Some claim that it is an impossible task, while others feel that it can be done in the future. But the most advanced artificial intelligence today still falls short of anything portrayed in science fiction. Consequently, *Pneuman* will not be able to "know" everything, but it will have the ability to carry out specific tasks. *Pneuman* will be programmed to talk and demonstrate its abilities, and it may be programmed to grab a soda from a cooler. Whatever the programs are, ever so trivial by human standards, *Pneuman* will be an excellent platform for many types of artificial intelligence research.

Additionally, when *Pneuman* gives tours of the MIL, its humanlike appearance, humanlike motions, gestures, and communication should enhance the overall impact of the robot. People should feel comfortable interacting with *Pneuman* due to the humanlike structure. The eyes will wander around similar to a human's eyes. While speaking, natural gestures and motions should enhance *Pneuman's* verbal communication ability. The arms will point at objects of interest just as humans do. The articulated waist allows *Pneuman* to bend over, as if it were picking an object up from the floor. Finally, the maneuverable base will allow *Pneuman* to translate in any direction and rotate about any point. All of these features contribute to *Pneuman's* overall ability to give tours and entertain an audience.

Due to *Pneuman's* humanoid form, it will also make an ideal personal assistant. *Pneuman* can use the five joint articulated robotic arms and end-effectors to reach for and grasp objects. The natural communication interface will allow a user to issue verbal commands to *Pneuman*, instructing the robot to perform any needed tasks. The highly maneuverable base is ideal for a cluttered area, such as a home, where a personal assistant may be needed.

2.2 Specifications

2.2.1 Overall Size

Pneuman stands approximately 59 inches tall, measured from the bottom of the drive wheels to the top of the stereo head. The widest points are from shoulder to shoulder and across the base, both measuring 26 inches across. Each of the five DOF arms allows *Pneuman* to grasp objects approximately 20 inches away. The base consists of the lower 29 inches of the robot, while the rest is the upper torso. See Figure 2-1.

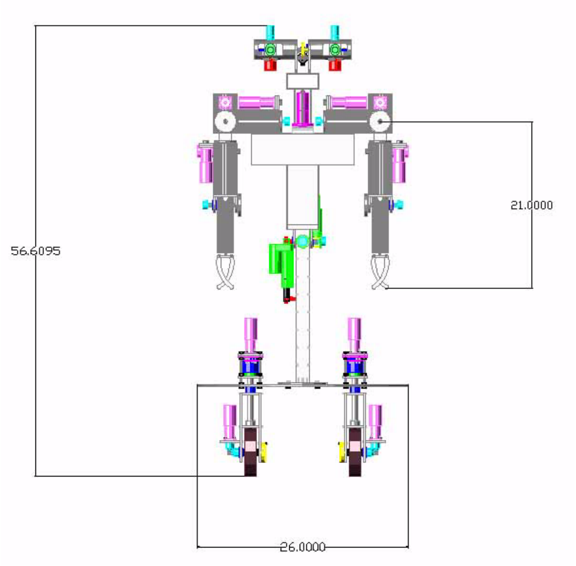

Figure 2-1: *Pneuman's* overall dimensions.

2.2.2 Weight

The overall weight of the structure is a primary concern because *Pneuman* is an autonomous robot. Therefore, the power source for all electronics and actuators are carried on-board and no external power may be used. While efficient control and motor operation techniques are utilized, the best way to ensure a long battery life is to minimize the weight of the robot. The weight-minimized configuration was not conceived initially; previous revisions called for a much bulkier structure as shown in Figure 2-2. The final design removed much of the material covering the wheels, and removed the unnecessary circular platform of the base.

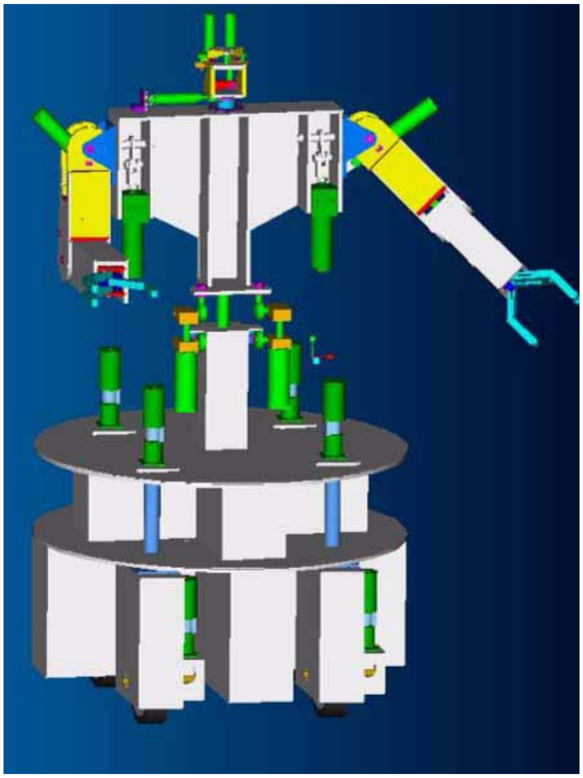

Figure 2-2: Original Design

The entire robot weighs approximately 102 pounds. A major portion of the weight may be attributed to the four sealed lead acid batteries, each weighing approximately 10 pounds. *Pneuman's* base weighs approximately 25 pounds (excluding the batteries), the upper torso weighs approximately 30 pounds (including the five DOF arms), and the head weighs approximately seven pounds.

2.2.3 Mobility

The goal was to give *Pneuman* access to the same areas humans live and work in. Two main locomotion options included a wheeled base or a legged walking mechanism. The wheeled base is more efficient for accomplishing a given task, and it simplifies the overall design considerably. While a legged mechanism offers some advantages over rough terrain, *Pneuman* will primarily travel over smooth surfaces. Due to these constraints, a wheeled drive base is used. The wheeled drive base is explained in detail in a later section.

2.2.4 Degrees of Freedom (DOF)

The human body has over 40 DOF. While *Pneuman* attempts to mimic the human form, simplifications were made to ensure autonomous real-time control. Therefore, *Pneuman* has 25 DOF. To accomplish the humanlike motions, two five DOF arms will be used. Each arm will have a gripper as an end-effector. In addition to the arms, *Pneuman* will have an active stereo head, containing two cameras, with three DOF. Each camera may be considered and “eye.” Both eyes will tilt together, while each eye can converge independently. The head will sit on a two DOF neck, allowing the entire head to pan and tilt. The entire upper torso connects to the wheeled base via a two DOF waist. The waist will allow the upper torso to tilt front to back and side to side. Finally, *Pneuman's* base moves via four drive wheels, each wheel steering independently, giving *Pneuman* maximum maneuverability.

2.3 Drive System

2.3.1 Overview

Pneuman's base contains four drive wheels arranged in a square. Each wheel is capable of steering independently, known as a modified synchronous drive system. This gives *Pneuman* maximum maneuverability. The drive system can operate in three different steering modes; “skid-steer”, Ackerman, and “four-wheel” or crab steer. While crab steering is primarily used, each has advantages and disadvantages that will be explained in later sections.

The wheels are approximately six inches in diameter, 13 inches apart. The wheels pivot about their center line and have an operating range of 180 degrees. Each wheel and steering mechanism is geared to a 485 oz.-in. planetary gearhead motor, providing adequate torque. The maximum velocity of the motors is approximately 45 r.p.m., permitting each wheel to change steering direction at a maximum rate of 180°/1.3s. The given motor/wheel combination also allows *Pneuman* to translate at a maximum rate of 14 in/s.

A quantitative description of motion involves a way to describe the path of the agent and the kinematics of the mechanism required for that motion. A straight path is described by the distance traveled, *d*. An arc of radius r_s and a sweep angle θ_s may describe a curved path. The kinematics may be determined from simple geometry. The *instantaneous center of curvature (ICC)*, a point where the base's motion appears to move around, lies where the perpendicular bisectors of each wheel intersect with each other. Any configuration of the wheels that do not allow all of the bisectors to intersect at a common point will cause wheel slippage, resulting in inaccuracies while path planning. See Figure 2-3.

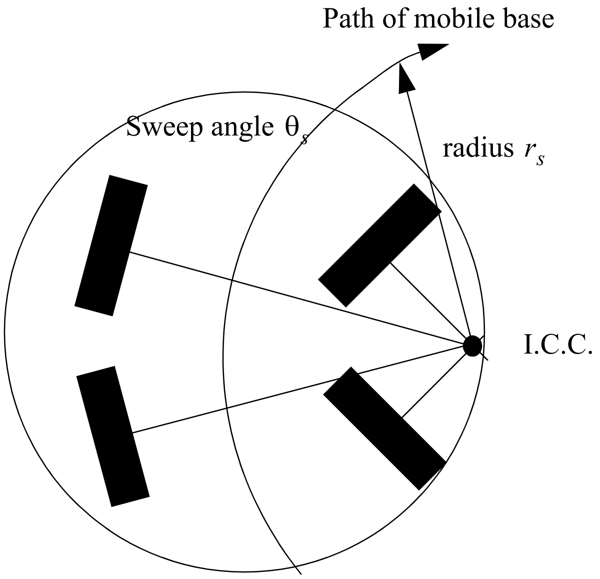

Figure 2-3: The Instantaneous Center of Curvature, I.C.C.

Pneuman has three steering modes: skid, Ackerman, and "crab", and each mode will be explained in detail in this section. Skid steering should not be used due to inaccuracies associated with it. Ackerman steering is commonly used on automobiles, and much research has been done on the theory and modeling of this steering configuration. However, there are kinematic constraints that limit its use. The final and preferred method is “crab” steering where all wheels are capable of changing their orientation. *Pneuman* primarily uses this method of steering.

2.3.2 Skid Steering

Many wheeled robots use “skid steering”. This simply means that the orientation of each drive wheel is fixed, and turning is made possible by varying the speed of each side's drive wheels with respect to the other side. This is an effective and easy solution to steering the robot. However, it is not as accurate as other steering methods; certain characteristics including friction, wheel slippage, and other unpredictable attributes cause problems [26]. This steering configuration is a special case where the bisectors of the wheels do not intersect and the fact that the wheels slip is exploited to cause the robot to rotate. See figure 2-4.

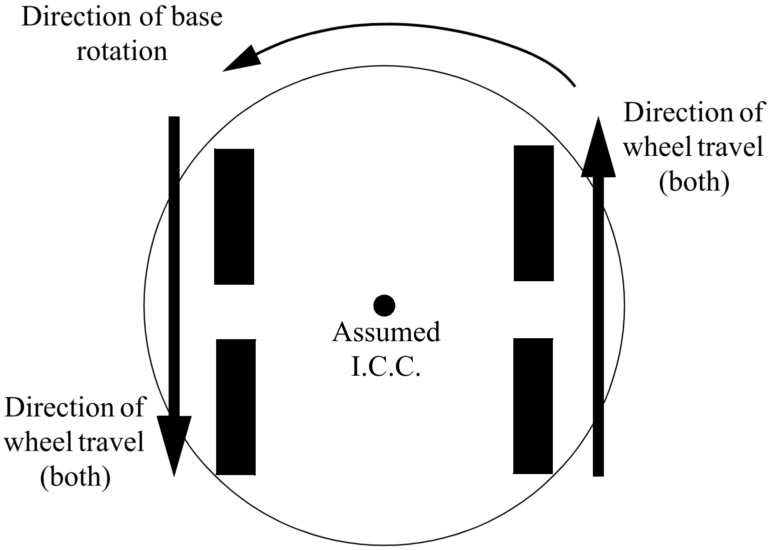

Figure 2-4: Skid Steering. Note that the perpendicular bisectors do not intersect, and the I.C.C. is not exactly known.

2.3.3 Ackerman Steering

This type of steering is used in most automobiles. The two rear wheels remain at a fixed orientation, facing towards the front of the vehicle. This means that the perpendicular bisector is the same for both rear wheels, extending in a line away from the vehicle. The two front wheels change their steering angle to steer the vehicle. Note that the steering angle for each of the front wheels is different to insure that their perpendicular bisectors intersect at the same point along the rear wheel perpendicular bisector. See figure 2-5.

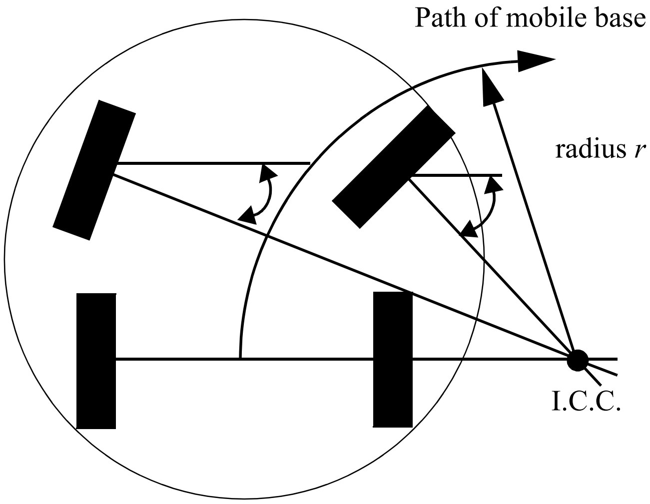

Figure 2-5: Ackerman Steering. Note that the I.C.C. lies along the mutual perpendicular bisector of the rear wheels.

2.3.4 Four-wheel Steering

Four-wheel, or “Crab” steering, has the same requirement as Ackerman steering; all of the wheel's perpendicular bisectors must intersect at a common point to avoid wheel slippage. In this mode, however, all of the wheels are allowed to change orientation. This means that the ICC can be anywhere, not just along the mutual perpendicular of the rear wheels as in Ackerman steering.

A major advantage of this mode is that the turning radius can vary from zero to infinity, and it can lie anywhere in the plane of motion. See figure 2-6.

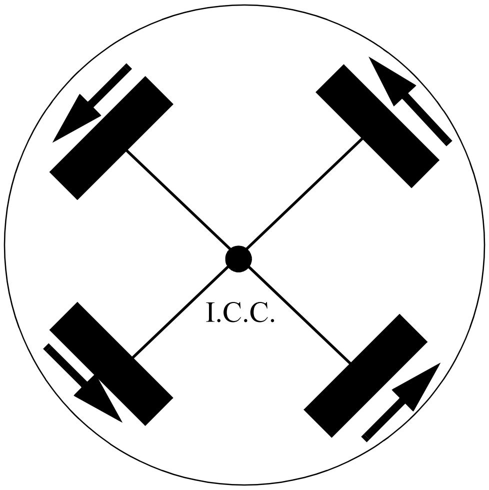

Figure 2-6: Four-wheel or “crab” steering. Note that all four wheels are turned, and the I.C.C. is the center of the base.

2.3.5 Physical Implementation

The base assembly consists of a round aluminum plate with four drive wheel assemblies mounted in a circular arrangement. The large aluminum plate provides mounting space for all of *Pneuman’s* batteries, power supplies, computers, sensors, and for the waist assembly. See Figure 2-7.

Each drive wheel assembly contains two motors; one for steering the drive wheel and one for rotating the drive wheel. The steering motor has an operational range of 180 degrees. This is limited by the wires for the drive motor and for the optical encoder. A limit switch is integrated into each steering assembly to insure that the operational range is not exceeded, which may damage the wires. See Figure 2-7.

Figure 2-7: The base and wheel assemblies.

2.4 Kinematics

2.4.1 Active Stereo Head Design Considerations

Pneuman's vision system consists of a four DOF stereo head with convergence, tilt, and pan. These DOF are needed to allow *Pneuman* identify the location of an object in a 3D space. Each eye can move independently, allowing each camera to converge on to an object. Additionally, each eye uses an optical encoder providing an angular resolution of 0.036 degrees. This will allow *Pneuman* to determine the location of objects with high accuracy. See Figure 2-8.

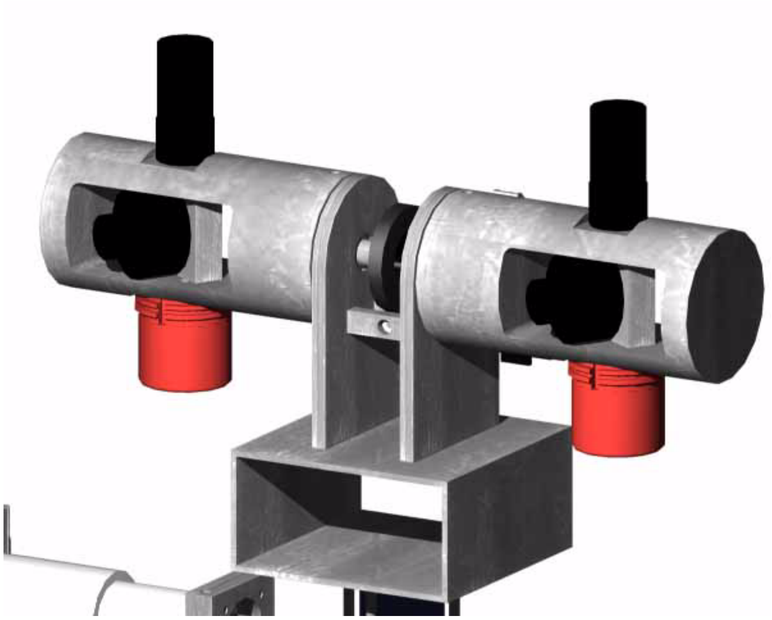

Figure 2-8: *Pneuman's* active stereo head.

The geometry required to determine the location of an object with the stereo head is illustrated in Figure 2-9. Each eye will be able to determine the object of interest using computer vision techniques. After the centroid of each object is determined, each camera will converge on the object such that the center of the image will correspond to the centroid of the object. The disparity between the camera angles, θ_L and θ_R, will allow *Pneuman* to know the location of the object in 3D space.

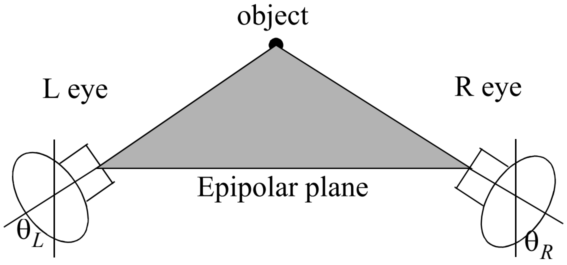

Figure 2-9: Epipolar plane formed by two cameras and the object.

2.4.2 Robotic Arm Design Considerations

The two arms discussed below are five degree-of-freedom (5 DOF) serial link manipulators. Constructed entirely from aluminum, the arms were designed to perform tasks similar to human arms. Upper and lower arm lengths are proportional to that of an adult human. Explosion of kinematics equations were kept to a minimum by aligning the axes of rotations from joint to joint as shown in Figure 2-10. The arms are mirror images of each other and are identical in all other respects [27].

Figure 2-10: One of *Pneuman's* robotic arms.

When designing a higher nth DOF serial link manipulator, one must consider the kinematics equations behind each joint placement. The arm was designed so that joint axis i intersects joint axis i+1, where i is the number of joints in the arm. Each new link is offset from the previous link by 90 degrees as shown in Figure 2-11. Additionally, see Table 2-1 for joint characteristics [27].

Joints ShoulderA, ShoulderB, and ShoulderC are coincident at the shoulder. This alignment allows for the arm to rotate as if a ball and socket joint were implemented. The Elbow and Wrist joints are also coincident. All joints are actuated by planetary gearhead motors [27].

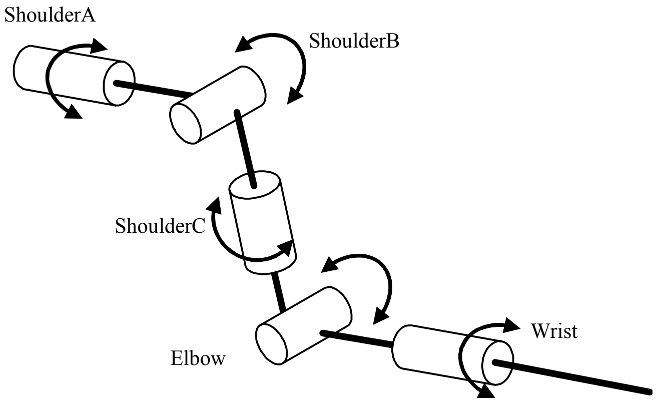

Figure 2-11: Kinematic representation of *Pneuman's* arms.

The forward and inverse kinematic solutions are straightforward due to the fact that the principal axes of all the joints are aligned. Figure 2-12 shows the coordinate frame assignments.

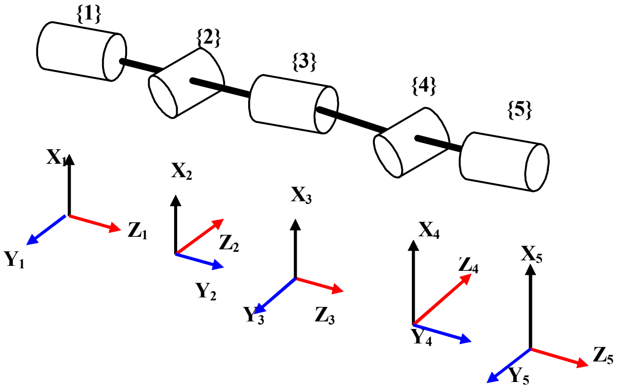

Figure 2-12: Coordinate frames for arms.

Note that frame {0} is coincident with frame {1} when 1 = 0. The DH parameters are shown in the table below.

Table 2-1: D-H Parameters for 5 DOF Arm

I	α_{I-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	$\frac{\pi}{2}$	0	0	θ_2
3	$-\frac{\pi}{2}$	0	d_3	θ_3
4	$\frac{\pi}{2}$	0	0	θ_4
5	$-\frac{\pi}{2}$	0	0	θ_5

Note the base frame {0} is positioned at the shoulder. This is the arm's point of attachment to the body of *Pneuman*. The origin of frame {5} is located at the wrist. A dexterous hand will be attached here in the future [27].

The overall forward kinematics of the manipulator, derived from the DH parameters, is given by the transform (Note: $c_x = \cos(\theta_x)$ and $s_x = \sin(\theta_x)$, where θ_x refers to the position θ of joint x.)

$$ {}^{0}_{5}T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \end{bmatrix} \tag{2-1}$$

where

$$r_{11} = c_5[c_4(c_1c_2c_3 - s_1s_3) - c_1s_2s_4] - (c_3s_1 + c_1c_2s_3)s_5 \tag{2-2}$$

$$r_{12} = -c_5(c_3s_1 + c_1c_2s_3) - [c_4(c_1c_2c_3 - s_1s_3) - c_1s_2s_4]s_5 \tag{2-3}$$

$$r_{13} = -c_1c_4s_2 - (c_1c_2c_3 - s_1s_3)s_4 \tag{2-4}$$

$$p_x = -d_3c_1s_2 \tag{2-5}$$

$$r_{21} = c_5[c_4(c_2c_3s_1 + c_1s_3) - s_1s_2s_4] - (c_2s_1s_3 - c_1c_3)s_5 \tag{2-6}$$

$$r_{22} = -c_5(c_2s_1s_3 - c_1c_3) - [c_4(c_2c_3s_1 + c_1s_3) - s_1s_2s_4s_5] \tag{2-7}$$

$$r_{23} = -c_4s_1s_2 - (c_2c_3s_1 + c_1s_3)s_4 \tag{2-8}$$

$$p_y = -d_3s_1s_2 \tag{2-9}$$

$$r_{31} = c_5(c_3c_4s_2 + c_2s_4) - s_2s_3s_5 \tag{2-10}$$

$$r_{32} = -c_5s_2s_3 - (c_3c_4s_2 + c_2s_4)s_5 \tag{2-11}$$

$$r_{33} = c_2c_4 - c_3s_2s_4 \tag{2-12}$$

$$p_z = d_3c_2 \tag{2-13}$$

where d_3 is the distance between ShoulderB (frame {2}) and ElbowA (frame {3}) and that the origin of the frame for ElbowA is the same as the origin of the frame for ElbowB (frame {4}) [27].

After the forward kinematics solution was determined, the closed form inverse kinematic solution was found for the 5 DOF arm. The solutions for the joint angles are

$$\theta_1 = \operatorname{atan2}(-p_y, -p_x) \tag{2-14}$$

$$\theta_2 = \operatorname{atan2}(\pm\sqrt{p_x^2 + p_y^2}, p_z) \tag{2-15}$$

$$\theta_3 = \operatorname{atan2}[(-r_{12}c_1c_2 + r_{23}s_1c_2 + r_{33}s_2), r_{12}s_1 - r_{23}c_1] \tag{2-16}$$

$$\theta_4 = \operatorname{atan2}\begin{pmatrix}(\pm\sqrt{(r_{31}c_2 - (r_{11}c_1 + r_{21}s_1)s_2)^2 + (r_{32}c_2 - (r_{12}c_1 + r_{22}s_1)s_2)^2}), \\ (r_{33}c_2 - r_{12}c_1s_2 - r_{23}s_1s_2)\end{pmatrix} \tag{2-17}$$

$$\theta_5 = \operatorname{atan2}\begin{pmatrix}(c_3(r_{21}c_1 - r_{11}s_1) - (r_{11}c_1c_2 + r_{21}s_1c_2 + r_{31}s_2)s_3), \\ (c_3(r_{22}c_1 - r_{12}s_1) - (r_{12}c_1c_2 + r_{22}s_1c_2 + r_{32}s_2)s_3)\end{pmatrix} \tag{2-18}$$

2.4.3 Waist Joint Design Considerations

The waist joint kinematics must be considered in addition to the head, neck, and arm kinematics. The waist is a two DOF joint, exactly like a universal joint, providing *Pneuman's* upper torso pitch and yaw movement. As in the arm design, both axes of rotation are aligned to keep the kinematics simple. See Figure 2-13 for a kinematic representation of the waist joint and placement of the reference frames.

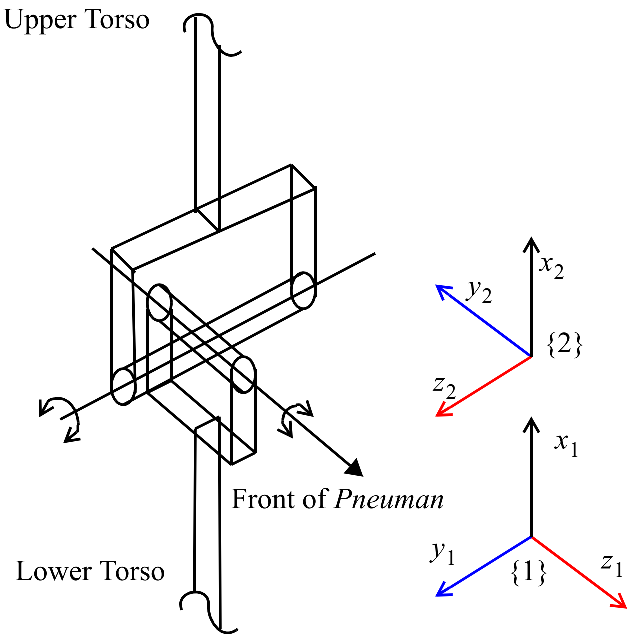

Figure 2-13: Kinematic Figure of *Pneuman's* Waist Joint

The D-H parameters for the waist joint are shown in Table 2-2. Note that frame {0} is coincident with frame {1} when θ_1 equals zero.

Table 2-2: D-H Parameters for 2 DOF Waist

I	α_{I-1}	a_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	$-\frac{\pi}{2}$	0	0	θ_2

The overall forward kinematic transform is

$$ {}^{0}_{2}T = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \end{bmatrix} = \begin{bmatrix} \cos(\theta_1)\cos(\theta_2) & -\cos(\theta_1)\sin(\theta_2) & -\sin(\theta_1) & 0 \\ \cos(\theta_2)\sin(\theta_1) & -\sin(\theta_1)\sin(\theta_2) & \cos(\theta_1) & 0 \\ -\sin(\theta_2) & -\cos(\theta_2) & 0 & 0 \end{bmatrix} \qquad (2\text{-}19) $$

The closed form inverse kinematic solution for the waist was also determined:

$$ \theta_1 = \operatorname{atan2}(-r_{13}, r_{23}), \qquad (2\text{-}20) $$

$$ \theta_2 = \operatorname{atan2}(-r_{31}, -r_{32}). \qquad (2\text{-}21) $$

A CAD drawing of the waist assembly is shown in Figure 2-14.

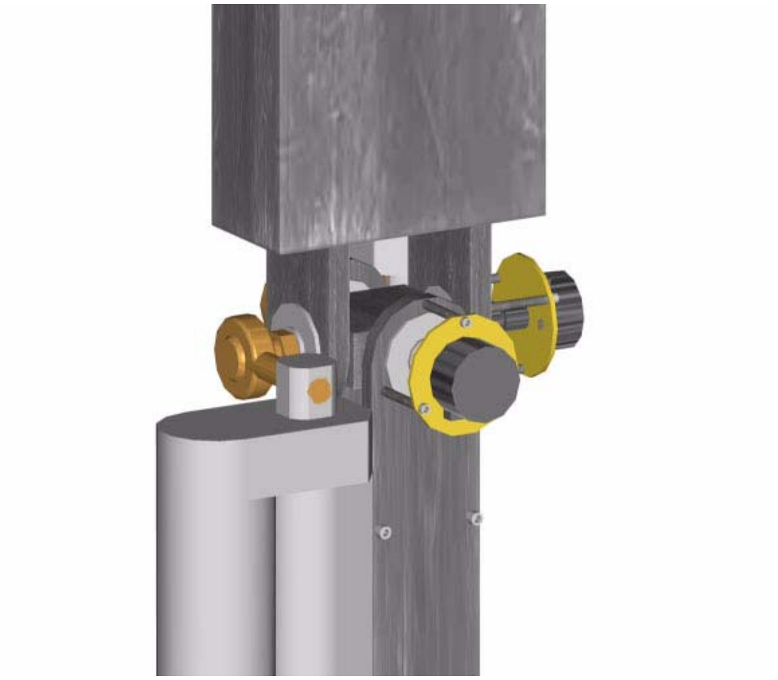

Figure 2-14: *Pneuman's* Waist Joint

2.5 Kinematic Simulation

A kinematic model of the entire structure was simulated in Mathematica.<MORE HERE>.