First Humanoid, Nanotechnology, Information Technology, Communication and Control
Environment and Management (HNICEM) International Conference
March 27-30, 2003, Manila, Philippines

MECHANICAL DESIGN OF AN ANTHROPOMORPHIC BIPEDAL ROBOT

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Abstract

As the study of bipedal walking grows in popularity in recent years, the demand for bipedal robots has also increased. However, a search through literature reveals little about the design process of bipedal robots. The design for the bipedal robot is rather different from conventional robots. There are limits on, among other things, the actuator size and the weight. Therefore, this paper aims to share our experiences in the design process, especially to those new in this area. This is done through outlining the considerations and process taken to design the first protoype of NUS Biped Robot - the NUSBIP-1

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1 Introduction

When we look at terrestrial animals, we notice that most of them move around using legs - be it two, four or more legs. If we compare legged animals and non-legged ones, we often find that the legged ones are typically more agile than their non-legged counterparts - they can traverse more types of terrains. This fact has inspired many researchers to look into building legged systems as an alternative to the wheeled systems that currently dominate mobile robotics and even land transportation systems. Besides, the legged robots will be able to work in human environments better than wheeled robots can [1].

Currently, many institutions around the world are conducting research on legged systems [2, 3, 4, 5, 6,7]. The common legged systems being researched are the two legged (biped), four legged (quadruped) and six legged (hexapod) ones. Arguably, between these, bipedal walking is the most interesting and most di±cult to achieve. Though there are many researches on bipedal walking, sadly, only a handful had succeeded in producing a stable dynamic walk. This only underscores the di±culty in developing a bipedal walking system.

The development of a bipedal walking system actually consist of a variety of research areas - robotics, mechanics, electronics, control and biomechanics all contribute to various aspects of this research. System integration is therefore very crucial to the successful development of a bipedal robot.

Although a lot of research has been conducted on bipedal walking systems, little has been written regarding the process of designing a bipedal robot for research. There are some papers that detailed the design process of particular joints [8, 9]. However, most others mainly described the specifications and the resulting robots, not the design process itself [2, 3, 4, 5, 6, 7]. A good robot design will generally reduce the control e®ort, and will present fewer problems during operation. This paper will address the main considerations taken in designing an anthropomorphic bipedal robot.

2 Robot Specifications

National University of Singapore (NUS) has recently embarked on a project to study bipedal walking. This project is titled NUS Bipedal Robot (NUSBIP). To facilitate the study of bipedal walking, a physical bipedal robot is needed. This robot is to be used as a test-bed to develop and test various walking algorithms. Simulations, however complete, are still insu±cient to prove the algorithm's capability. The application of the algorithm onto a bipedal robot is required to fully test its capability.

For the research to be successfully conducted, the robot need to possess some specified capabilities. These constitute the specifications for the robot. The following is the list of basic specifications for the robot:

To walk dynamically at a reasonable speed: The robot is to achieve walking speed of approximately 1m/s.

To be robust and reliable: This is because various control algorithms are to be developed and tested on this robot. Otherwise, considerable amounts of time need to be spent on reparing, configuring and repairing the robot on a regular basis.

To be easily repaired and maintained: In the event of any breakdowns, it should be easily repaired to reduce downtime.

To have anthropomorphic properties: The robot should have human proportions and weight, to simulate human walking.

To be able to walk in 3D: It should have sufficient degrees of freedom to enable it's legs to move sideways.

3 Design Considerations

There are various design considerations when designing this robot. Among the various factors being considered are:

- robot size selection
- degrees of freedom (DOF) selection
- actuator selection
- loads at joints
- sensor selection
- control hardware

3.1 Robot Size Selection

When we design a robot, we will eventually come to the questions: "What size should it be?" and "How large/tall should we design it?". To answer those questions above, we need to consider various factors that are a®ected by the size of the robot. The space available and the power requirement to move the robot will place constraints on the size of the robot. The robot should not be too small, neither should it be too large. Too small a robot would make it di±cult to maneuver certain terrains (say, walking up stairs). Too large, it would consume more power and require more working space. A large robot would also require a larger actuator, which in all probability, will also be heavier.

However, we know that we want the robot to be anthropomorphic. Therefore, the anthropomorphic data for children and adults were compiled and calculated [10, 11, 12]. Particularly of interest to us are the data of children from age 8 to 16. The data for lengths and weights of children between ages of 8 and 16 are shown in Tables 1 and 2 respectively. The reason why data for children from this age group was chosen was mainly because at these ages, the children are su±ciently large to perform most tasks that adults can perform. However, they are not as large as adults in size, or as heavy in weight. It will thus require less workspace area and less power for actuators. Taking into consideration the two factors of power requirement and spatial constraint, the size of a 10 year-old child was chosen. Its height up to hip is approximately 0.72m, and the weight of the two lower limbs are about 13.7kg.

Table 1: Lengths of lower body segments of children (in meters) from age 8 to 14 years. (Height refers to the height of the robot up to the hip.)

Age	Thigh	Shank	Foot	Height
8	0.2428	0.2637	0.2237	0.5655
10	0.3233	0.3354	0.2430	0.7187
12	0.3819	0.3892	0.2546	0.8311
14	0.4152	0.4206	0.2624	0.8958
16	0.4263	0.4296	0.5680	0.9159

Table 2: Weights of lower body segments and total body weight of children (in kg) from age 8 to 14 years.

Age	Thigh	Shank	Foot	Total Weight
8	2.883	1.466	0.614	28.683
10	4.055	2.008	0.785	37.583
12	5.347	2.550	0.955	48.158
14	6.759	3.092	1.126	60.212
16	8.291	3.634	1.296	73.551

The robot was designed to meet the specified size and weights imposed. The comparison between the robot's segment weights to that of the child is shown in Table 3. As the robot generally has lighter legs, ballasts can be added to increase the weight if necessary.

Table 3: Comparison between segment weights of robot and a 10 year-old child.

Segment	Robot	Human	Difference
Thigh	2.391	4.055	-1.664
Shank	1.397	2.008	-0.611
Foot	1.185	0.785	0.400
Total Weight	*4.973*	*6.848*	*-1.875*

The weight of the lower trunk, including some motors that are attached to the body is approximately 10kg. However, if a heavier weight is required (so that it is closer to the human counterpart), ballasts can be added to increase the weight to the desired value. With the addition of the weight of the lower trunk, the total weight of the robot is expected to be less than 30kg. It's size

also conforms to the spatial constraint in the lab and a suitable actuator can be
found to power the robot.

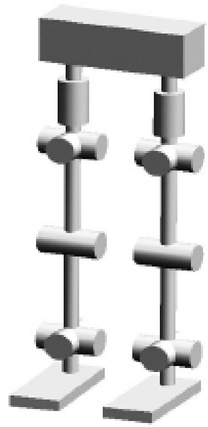

Figure 1: Diagram showing DOFs/joints of robot. Each cylinder represents one joint. In total, there are 12 joints - 3 at each hip, 1 at each knee, and 2 at each ankle.

3.2 DOF Selection

It is specified that the robot be able to move in 3 dimensions (3D). That means that the robot must be physically capable of changing walking directions, walking up stairs, and others similar tasks. To be able to do these tasks, the robot needs to have sufficient DOFs. Say, if we were to only move our legs forwards and backwards (no sideway movements), we would not be able to change our walking direction, and would find walking up stairs very difficult.

Therefore, the robot needs to have at least 12 joints for it to be able to walk in 3D. The 12 joints are listed below. Figure 1 shows the location and the arrangements of the joints on the robot.

Location	No. of joints
Hip	3
Knee	1
Ankle	2
Total/Leg	*6*

The ranges of motion for the joints are modelled after the human joints. Table 4 shows the typical ranges of motion for a human and the robot for all 12 joints.

3.3 Actuator Selection

After knowing the sizes and weights for the robot, a suitable actuator could then be chosen. Nevertheless, some information on the requirements for the actuator is needed before choosing it.

Simulations were performed on the model of the robot, where the data for the torque and speed requirements were obtained. The requirements are shown in Table 5. The actuators preferably should have a high power:weight ratio, and also lightweight.

Table 4: Range of motion of human and robot hip, knee and ankle joints.

	Human		Robot	
Joints	Min. Angle	Max. Angle	Min. Angle	Max. Angle
Hip Yaw	-20	65	-180	60
Hip Roll	-25	40	-50	50
Hip Pitch	-10	135	-30	100
Knee Pitch	-135	5	-125	0
Ankle Roll	-60	30	-45	45
Ankle Pitch	-50	30	-50	30

Table 5: Maximum torque and speed requirements at various joints the robot obtained from simulation data (torque in Nm, and speed in rad/s). Note that the knee's torque requirement is high here, as the simulation was conducted using bent-knee walking.

Joint	Maximum Torque	Maximum Speed
Hip Yaw	10	0.3
Hip Roll	20	3.0
Hip Pitch	50	0.3
Knee Pitch	75	5.0
Ankle Roll	5	2.0
Ankle Pitch	20	5.0

The three most common types of actuators are the hydraulic actuator, pneumatic actuator and electric motors. Hydraulic actuators have good power:weight ratios, but they are definitely not lightweight. Pneumatic actuators are lightweight, but they do not have good power:weight ratios. Further to that, both require a very bulky pump or compressor, which is not feasible for walking robots. That narrows the choices to only electric motors.

Now that electric motors are chosen, the question "Which motor?" comes up. To answer this question, we refer to Table 5 for the torque and speed requirements for each DOF. It is noted that the knee and hip pitch require the highest torques. Fortunately, the maximum torque and speed points do not occur at the same time.

Based on these information, the Faulhaber 3863C

Micromotor was chosen. The specifications for this motor are given in Table 6. There are a few gear ratios that were used - 14:1, 43:1, 66:1, 134:1 – depending on the torque requirement. The higher the torque requirement, the higher the gear ratio used. For the hip pitch and knee joints, gear ratios of 134:1 was used; 66:1 gear ratios were used for hip roll and ankle pitch; 43:1 was used for hip yaw; and finally 14:1 was used for ankle roll. Note that the same motors were used for all joints so as to make maintenance simpler.

Table 6: Specifications for Faulhaber 3863C 24C without any gears attached.

Specifications		
Nominal Voltage	24	V
Output Power	220	W
Efficiency	85	
No-load speed	6700	rpm
Stall Torque	1.25	Nm

3.4 Loads and Stresses At Joints

From previous studies of the human hip and knee joints, it was found that the loads on the hip and knee could reach up to 7 and 4 times the body weight respectively [13, 14, 15]. Say, if the body weight of a human were 60kg, the load imposed on the hip joint would be 4200N (420kg). (Assuming g = 10m=s2). This load is rather significant, and need to be taken into consideration.

The estimated weight of the biped robot is approximately 30kg. For a load factor of 7 on the hip, the load would be 2100N. As for the knee, it would be 1200N. Both loads need to be taken into account when sizing the materials for the hip and knee joints. Further to that, a safety factor is incorporated.

The most critical part is at the hip which takes the highest amount of impact loading. The deflection of the shaft caused by the loading was also taken into consideration.

However, we can reduce the impact load on the joints. This can be achieved by incorporating a shock absorbing material, say rubber, at the feet and at the joints. This will reduce the impact on the joint during landing. Some other robots have incorporated this design on their foot [4].

3.5 Sensor Selection

The next questions to ask are: “What information do we need?” and “What types of sensors are required to read those information?”.

In a typical bipedal robot, we require the joint information - joint position and velocity; body information - body orientation and velocity; load information - force on feet. These can be obtained through the use of the following sensors.

Potentiometer/Encoder. One of the most important information required is the joint position and velocity. These information can be obtained via a potentiometer or an encoder mounted onto a joint. However, choosing between either is not as straightforward. Each has its own advantages and disadvantages.

The signal from a potentiometer tends to be rather noisy. Some filtering might be required before it becomes useful. As for the quadrature encoder, there arises the task of reading the signals (pulses). This can be easily solved by using an quadrature counter. However, the cost of the entire setup (quadrature encoder and counter) could be prohibitive. Same goes for a good potentiometer.

For NUSBIP-1, a quadrature encoder was used at each joint. The signals from the encoder were processed by HCTL-2016 quadrature counters.

Load Cells. Another information that might be of importance is the force information on the foot. This could be used to measure the zero-moment point (ZMP) of the robot. There are sufficiently many ways to measure the force on the robot foot, but one of the most commonly used method is to place load cells on base of the foot. This method is being employed by many researchers [3, 4].

Four Sensotec Model 13 tension-compression load cells were placed on each foot of NUSBIP-1. In the first stage of implementation, they are able to provide the effective force applied onto the leg, and also, position of the center of pressure.

Rate Gyro and Accelerometers. The orientation, posture and speed of the body is also important. This information could be used as a feedback for the robot to retain its stability and maintain its walking speed. To be precise, the information required are the rotations (yaw, pitch and roll) of the body, and also, the velocity of the body in x, y and z axes. These can be obtained by using gyros and accelerometers respectively.

Three rate gyros and a 3-axis accelerometer were used in NUSBIP-1. The rate gyros outputs the speed of angular rotation, where the accelerometer outputs the accelerations. The outputs are then integrated to provide angular position and linear velocity respectively. However, Kalman filters had to be used to filter the noise from the signal.

The components were placed in a fixture and work dependently on each other. The accelerometer uses the information from the gyro to compensate for gravitational effects, meanwhile the gyros obtain readings from each other to compute the actual orientation of the robot body.

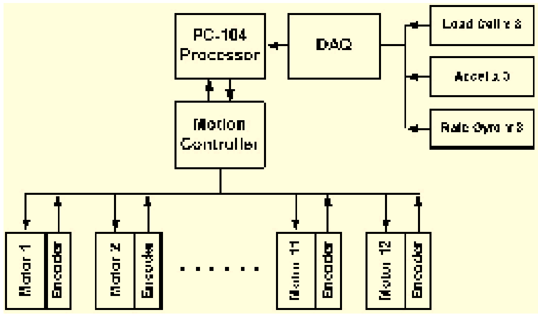

Figure 2: Schematics of the Control Hardware.

3.6 Control Hardware

To perform servo control on the motors, PMAC2-PC/104 motion controllers are used. A 486-100MHz PC/104 processor board is used to compute the highlevel control algorithm, i.e. walking trajectory, and these information are sent to the motion controllers.

Besides that, the signals from the sensors are converted by the analog-to-digital (AD) card and returned to the PC/104 processor board. There are 4 load cells at each feet, 3-axis accelerometers and rate gyros. All these sensors output analog voltage. Figure 2 shows the schematics of the control hardware.

4 Design Philosophy

The driving philosophy behind the design of NUSBIP-1 is the design for maintenance. The maintainability of the robot has an important priority. This is so that the robot can be easily repaired and the downtime minimised.

There are two methods to make the robot easier to maintain - make the design modular, and simplify the design.

4.1 Modular Design

Modularity here is limited to the discussion on mechanical design. The main modules for this robot are the hip, knee, ankle, links (thigh and shin) and body. The robot is made such that the hip, knee and ankle can be interchanged without affecting the other parts of the robot. The lengths of the thigh and shank can also be changed. Each motor can also be changed rather easily. This is very important in the research environment, due to the ever-changing nature of technology and ideas. It also facilitates the changing of components that is unsuitable or has been damaged.

Without any doubt, modularity would help to ease maintenance of the robot, as parts that had been damaged can be changed easily. Each module can be removed and replaced easily, reducing the downtime of the robot.

Furthermore, modularity of the robot would enable ballasts to be added. This is so that the weight distribution is changed, such that its dynamics is altered. This would enable us to fine-tune the robot such that an optimal dynamics can be achieved. For example, we can change the location of the motor so that we change the center of gravity (CG) of the thigh. We can also add ballasts to increase the weight and change the CG.

4.2 Simple Design

The second strategy to make it easily maintainable is by employing a simple design. To create a simple design is not simple! By making the design simple, less things can go wrong. The main task is to simplify the mechanism of the joints, while maintaining its functionality.

Simple design also applies to the joining between two parts or modules. It enables parts and modules to be removed and installed easily, without the need to take the robot apart.

One side benefit from simplifying the design is the the weight is also indirectly reduced. Fewer parts are used and this also leads to a lighter robot.

5 Conclusion

The design steps outlined in this paper provides a systematic approach to design an anthropomorphic bipedal robot. It describes the considerations and the strategy towards achieving the specifications laid out in the beginning. The main design considerations in the creation of a bipedal robots are size, DOFs, actuators, sensors and control hardware. Applying the various considerations listed above, NUSBIP-1 was created.

Acknowledgments

The author would like to thank Kelvin Chan for his contribution and time in collecting the anthropomorphic data used in this project.

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