Critical Issues for Biped Mechanism in achieving Dynamically Stable Legged Locomotion

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Abstract

This paper introduces an experimental small-sized biped mechanism that will be used to perform a dynamically stable smooth terrain walking. Some of the necessary criteria for biped locomotion are thoroughly explored. These criteria are actuator's power, structural weight, leg-link design, and the computing hardware capability. All the criteria are taken into account during the course of constructing the biped mechanism. The resulting design is a 50 centimeter high biped mechanism that weighs about 2000 gram and possesses 14 degrees of freedom. The real-time computing hardware and the power source are off-board. The biped is compared with other selected prototype of the same class. The results are shown in the form of comparison metric and MATLAB dynamic simulation.

1. Introduction

A dynamically stable walking biped has long been a challenging topic in the legged mobile robotics community. Various research topics have sprung up from this balancing problem. The champions among biped robots in the world are undoubtedly Honda P3 [2] and its sibling, ASIMO. These bipeds can walk smoothly in a manner very close to human. Exotic and lightweight structural material such as magnesium alloy is used as the main structural material. The motors used at each joint are specifically design and manufactured to satisfy such a walking character.

The long research program at Waseda University has produced many versions of WABIAN [7]. The biped could walk but at a small step length due to big body weight. SONY Dream Robot, SDR-3X [4], is another offspring of the corporate research. The biped used custom-made high power AC motors with integrated drive circuit and control loop to save weight and space. The latest version, SDR 4X, is now available with some improvement in motion control system and added sensors. On the contrary, ERATO, JST Corporation ([1] and [15]) has concentrated on a low cost, energy efficient, and small-sized biped, dubbed, PINO. The model of the small and cheap actuator was identified and the control experiments were conducted using genetic algorithms (GA) to learn actuator's performance and used the information to generate the most efficient gaits for the biped. Using this approach, it was discovered that the design and construction of a low cost and efficient biped could be done very quickly.

Wolherr, et al [14] is another group of researcher that focuses their research on actuator performance for biped robots. They used the large-scale sequential quadratic programming to optimize the squared input torque performance index and select the appropriate actuators for their biped robot.

Some researchers [12,13] used smart mechanisms like parallel mechanisms for biped legs. The parallel mechanisms have advantages over conventional serial mechanisms. The link could be built with lighter weight since it does not have to endure bending moment, and actuators could be installed at the trunk. It is also simple to calculate the inverse kinematics. Okada, et al [8] arranged the serial mechanism such that the trunk and hip joints merged and could achieve the spherical joint capability. These results enable the biped to walk without resorting to knee bending and hence saving energy.

The bipedal project at the Ministry of Economy, Trade, and Industry (METI) of Japan revealed another effective arrangement of leg joints [6] resulting in the biped legs that could walk in cross-leg fashion. Cross-leg capability aims at repositioning the center of gravity, leading to higher balancing capability of a robot. The legs are also made of magnesium alloy.

With the rapid improvement in the computing hardware, designing the computer-controlled system is easier than ever. Kanehiro, et al [5] applied the scalable/expandable capability of RT-Linux real-time operating system to control a small-size humanoid robot and a life-size humanoid robot. Inaba, et al [3] utilized the full-scale computing power of the SPARC server to remote control the biped. The project, dubbed “Remote Brain System”, moved the computing power off-board to reduce weight of the biped. Salzmann, et al [10] showed the capability of LabVIEW Real-time software in the application of teaching the subject of Automatic Control from long distance via the Internet. The feedback control loop experimental test bed was controlled from long distance. The application could be extended to the case of bipedal control.

Mechanically or structurally, some biped mechanisms are susceptible to foot impact during walking. Lim [7] and Park [9] implemented the software to help the stiff mechanism to act as if it is composed of tunable mass-spring-damper system, i.e., impedance controlled system. The software helped damping out the contact vibration when mechanism interacts with rigid environment.

The organization of this paper is the followings. In section 2, we describe the specification of our small-sized biped mechanism that we design and build at the Institute of Field Robotics (FIBO). The critical issues related to the mechanical designs necessary (but not sufficient) for the biped mechanism to dynamically balance were addressed in section 3. Section 4 discusses the critical issues related to the computing hardware and software. Section 5 shows some simulation results. The conclusion of this paper is in section6.

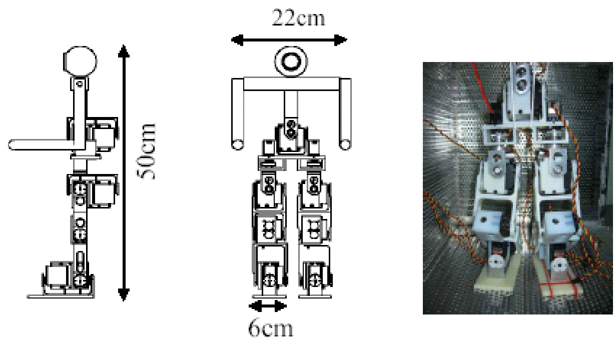

Figure 1: FIBO’s small-sized biped mechanism

2. Hardware Description

The objective of building the small-sized biped robot is to obtain a manageable and versatile experimental setup to explore and collect data to study the biped locomotion. The knowledge obtained from this experimental setup will be used for constructing a better biped robot. Figure 1 shows the FIBO’s small-sized biped mechanism and its major dimensions. The robot has 14 degrees of freedom. There are two motors at each ankle, a motor at each knee, three motors at each hip and two motors at the trunk. The robot will be equipped with 16 force sensitive resistances in order to feel the interaction with ground. Three gyro-sensors will be employed to sense the orientation of the robot body (trunk). A charged couple device (CCD) camera will also be included to incorporate the visual information in a navigation system in the future. Note that the upper half of the body does not have any motors since the research only focuses on the lower extremity analysis. The top part at the moment is only for mocking up reason. All computing hardware is off board in order to minimize its weight. The biped robot is tethered to a controller. It also gets the 6 Volts regulated power off board via a commercial switching power supply. Total weight of the robot is about 2000 gram.

3. Critical Issues Related to Mechanical Designs

From section 1 we can see how the bipedal research community has focused their effort. Lightweight design, high power actuator, smart mechanism, and simple but powerful computing power are the issues that are needed toward the dynamically stable walking. All these points are the prerequisite for a dynamically stable walking biped. This section discusses the issues related to the mechanical design. Section 4 discusses issues related to the computing power. Table 1 shows the important parameters that are needed in the following subsections.

Table 1: Comparison of several parameters of various bipedal mechanisms

	Motor torque [N-m]	Single actuator Weight [g]	Robot Weight [Kg]	Motor Speed [rad/s]
PINO	2.45 (Modified Futaba S3801) #	107.17 †	4.5*	4.028 †
SDR3X	2.35 (ISA-MH) *	143.2*	5*	N/A
WABIAN-RIV	1.3*	>1000	131.4*	N/A
FIBO’s SSBIPED	1.28 (HITEC HS5945) ‡	56 ‡	2	8.055 ‡

Sources:

* *Robolution*, ISBN4-8222-1531-8 (in Japanese), 2001

‡ HITEC R/C servomotor user manual

† http://www2.towerhobbies.com/

From [1]

3.1 Power-to-weight Ratio of the Actuator (P/W)

The biped needs high power-to-weight ratio actuator in order to rapidly drive the system states into either the stable region or unstable region. Conventionally this ratio can be calculated by dividing the power of the actuator (torque multiplied by angular speed) by its weight. The high ratio value signifies the powerful motor that not only can carry its own weight but also be able to carry dynamic loads and others. Considering various off-the-shelf motors, we found that the servomotor, whose type is popular among the radio controlled (R/C) hobbyist, can give out a comparatively high power-to-weight ratio. The motor comes in a small lightweight package with drive circuit and gear reduction. The motor also has a built-in proportional-derivative feedback control loop. The R/C servomotor is much cheaper than the typical motor-gear-encoder package. We decide to use this R/C servomotor as our main actuator. Table 2 shows the P/W comparison between PINO and FIBO's biped. The parameters from table 1 are used in the calculation of P/W ratio. We can see that the motor of the FIBO's biped outperforms that of PINO.

3.2 Structural Weight

The biped should be constructed with the minimal structural weight such that the high ratio of the value of single actuator power to the whole body weight is attained. We have to find the way either through design or through material selection to come up with the lightest possible biped structure.

Although, there are other exotic super materials to be chosen from, to keep the construction cost down, our choices for the biped structure are narrowed down to Aluminum Alloy 5083 (Al5083) and Cast Nylon plastic. Both of them are light comparing with stainless steel or Zinc. They are also easy to fabricate either by way of direct machining or other forms of mass-producing. Aluminum has higher yield stress and deflects less under load than the cast nylon. The cast nylon is among the strongest plastic. Although the amount of deflection is higher than the aluminum, its specific density is almost 50% less than the Al5083.

At the load bearing area such as the ankle joint and the hip joints, Al5083 is used for its minimum deflection. At other places, the thin Cast Nylon plate assembled into a "box" or "frame" is used. We always use "box" or "frame" design to keep the part strong. The use of steel fastener is kept at minimum to further reduce weight. This results in many U-Shape parts or integrated geometrical parts. All parts are machined and resulting in a lot of wasted materials. It is unavoidable since we are still at the prototyping stage and design is not yet finalized. Subsequent version can take advantage of plastic injection molding technology or Aluminum die-casting to minimize wasted material and prepare for mass production.

3.3 Power of a Single Actuator to Weight of the Whole Robot Ratio (PS/WR)

This ratio is similar to the P/W ratio but instead of concerning whether the actuator can carry its own weight, it focuses on the capability of the motor's kinetics and its responsiveness that influence the whole biped. It is a ratio that combines the effect of 3.1 and 3.2 together into a single ratio. This ratio can be calculated by dividing the power of the actuator (torque multiplied by angular speed) by a biped's total weight. We use this ratio extensively in combination with a dynamic simulation during motor sizing process. The ratio is also good for comparing a dynamic walking ability among bipeds. Table 2 shows the PS/WR comparison between PINO and FIBO's biped. The parameters from table 1 are used in the calculation of PS/WR ratio. We believe that the FIBO's biped is able to outperform PINO in bipedal walking.

Table 2: Comparison between PINO and FIBO's Biped

	P/W	PS/WR
PINO	92.084	2.193
FIBO's biped	184.114	5.155

3.4 Link Mechanism Design

The link mechanism needs to be built to facilitate the bipedal locomotion with enough degree of freedom to perform the walk and not too many of them such that they post a difficult control problem. How many degrees of freedom are enough to create efficient bipedal motion? Good review and explanation of this issue are discussed in great details in [11]. We decide to go with 14 degrees of freedom (DOF). 12 DOF, according to [11], are the minimum number for the lower extremity to achieve human-like walking, and we know that human gait is the most efficient form of locomotion. The extra two DOF 's are for body weight balancing in roll and pitch orientation without resorting to the leg DOF's.

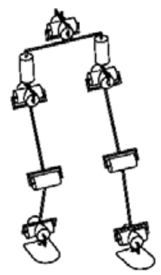

Figure 2: The diagram shows legs and joints orientation of the FIBO's small-sized biped mechanism

As displayed in figure 2, the conventional serial mechanism is still our choice since it is easy to build and it also retains the similarity with real human structure. All joints are designed to intersect at a local point to simplify the kinematics computation and control. Upper leg length equals to the lower leg length to simplify the kinematics. The distance between the left and right hips is also important. If the distance is too close, the legs will hit each other during walking. If the distance is too far apart, the ankle's motors have to work harder in swinging the center of mass from side to side to balance during walking. Note that the optimum values of parameters mentioned in this section are subjected to further study. This subject will be further studied,

4. Critical Issues Related to Computing Hardware and Software

Selecting the right computing hardware and the suitable software environment are very important. The good system should be composed of 1) Fast processor, 2) Compatible peripheral cards, 3) Fast and reliable bus, 4) Suitable operating system (OS) for the task at hand, such as, a deterministic real-time OS, and 5) User friendly

The computing hardware used to control the FIBO's biped is the PXI module. The module is composed of eight-slot chassis, Pentium III 1.2 GHz embedded controller, the multifunction DAQ card, the analog output card, and the timer/counter card. The microcontroller and the other cards are synchronized by 10 MHz system reference clock. All cards are connected by the PCI extensions for instrumentation (PXI) bus. The PXI module runs the National Instrument Real-Time operating system. The diagram of the hardware is shown in figure 3.

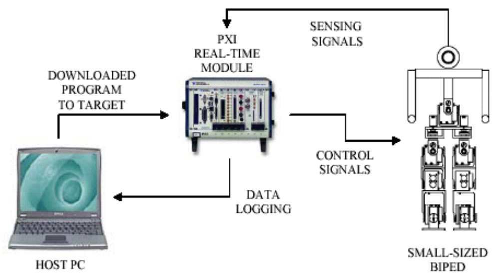

Figure 3: A diagram shows the schematic diagram of all the hardware

LabVIEW graphical programming is the programming language of choice. We choose LabVIEW 6.1 due to its compatibility with all the selected hardware. LabVIEW is also easy to develop because the program (VI) is graphical based, signal oriented, and have innate multi-threading capability. Figure 2 shows a sample LabVIEW VI used to control one axes of the biped.

The main component of the control hardware is the timer/counter card. The card is used to generate a modulated frequency and modulated duty cycle TTL squared pulse train for the R/C servomotor. The digital R/C servomotor needs the TTL squared pulse train to determine the angular position of its next move. There are two conditions to drive the motor. One is that the frequency has to be 50 Hz, 100 Hz, or any multiple of 50 Hz. The higher the frequency the more resolution step the motor can turn. The relationship between the frequency and the resolution step is linear. We have tried various frequency ranges and found that the 300 Hz frequency can give us satisfactory resolution of 441steps/180 degree rotation. The other condition for the motor to turn is that the duty cycle of the pulse has to satisfy the circuitry inside the motor. At the frequency of 300 Hz, the duty cycle has to be in the range of 22.4% to 66.5%, where 22.4% signifies the angular position of zero degree and 66.5% signifies the 180 degrees position.

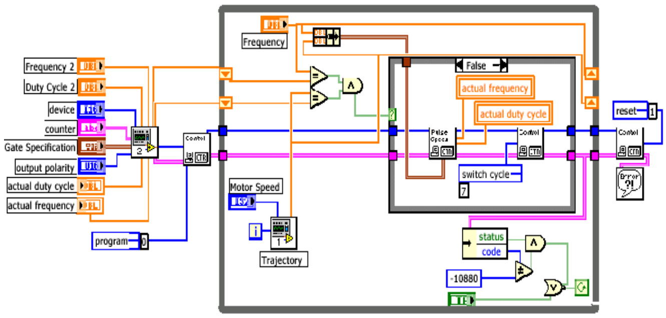

Figure 4: LabVIEW's program (VI) used to control a digital R/C servomotor

We download the program via the Ethernet connection to run on the PXI module Real-Time Target. The PXI module runs Real-Time operating system and, hence, it is headless and can dedicate all the computing power to the task at hand. The PXI module sends out the control signal via its timer/counter card and receives sensing signal from analog input channel. The analog input records signals from the force sensing resistance (FSR) and the three axes gyroscopic sensor. Data-logging route can be utilized to read the sensor readings and monitoring the behavior of the machine on the host PC.

5. Simulation Results

MATLAB's SimMECHANICS and SIMULINK proof the capability of the prospective motors to be used with the biped robot. There are two operating conditions that are parts of the bipedal gait and are the ones that require high torque from the motors. These are the crouching up and down (knee bending posture) and the sway from side to side (ankle swing). Figure 5 shows the stick figure of the simulation. We assume the link geometry to be uniformly diametric cylinder. We also assume that the link has a center of mass at the half of its total lenght.

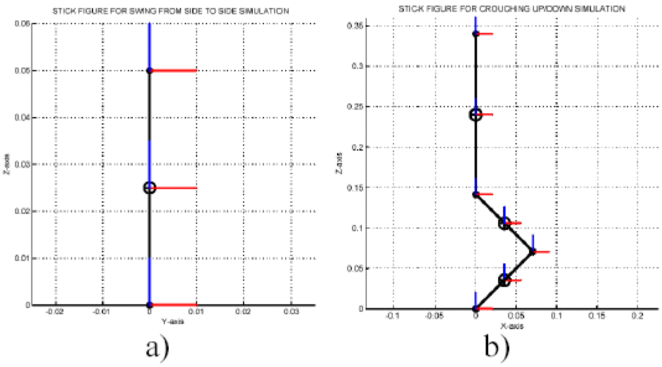

Figure 5: a) Stick diagram shows front-view of biped. Positive Y-axis points to the left of the biped. Positive Z-axis points up from the ground. b) Stick diagram shows side-view of biped. Positive X-axis points to the front of the biped

A sinusoidal command reference is fed into the biped model. We used the simple proportional-derivative controller to track the command trajectory. The controller gains are tuned such that the angular speed of the simulation matches the real specification of the real motor (~1revolution/second, maximum output torque of 1.26 N-m). The mathematical model of the two links (single leg) used in this simulation can be derived using the theory of the Lagrangian Mechanics. The derivation is not shown here in this paper. The saturation function limits the control action to be closer to the real motor. We limit the motor torque to 1.2 N-m.

Table 2: Leg Link's parameter used in the simulation

Parameter	Value	Unit
Mass of a link	0.4	[Kg]
Length	0.1	[m]
Diameter	0.04	[m]
Mass moment of inertia	0.000373	[Kg*m^2]
Gravity along Z-axis	9.81	[m/sec^2]

The simulations (SIMULINK blocks shown in figure 6) run for 40 seconds in both cases of swing from side to side and the crouching up and down postures. All plots are cut and displayed only the first 10 seconds to highlight interesting details. There are two key points that can be extracted from the plot results. The first point concerns the control action. From figure 7a and 8a, the initial 0.4 seconds portions shows bang-bang control characteristic. This is not surprising due to the controller effort to reach the set points as quick as possible while the actuator can only output a limited amount of torque. The bang-bang control action is simple but dangerous. If the starting posture of the biped is too difficult for the controller to bring it to the desired posture, the robot will fall due to the excessive vibration due to controller shattering.

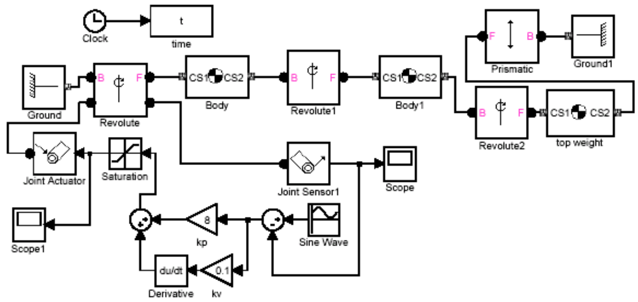

Figure 6: SIMULINK Diagram used to simulate the dynamic response of the single leg of the biped

The second point involves the window of operation of the ankle joint. Note that the case of swinging from side to side is the same as the case when the biped swings the body from back to front and vice versa. Figure 7b shows the range of ankle sweeps from –30 degree to 30 degree (where zero degree is at the center position and the sign is taken from the right-hand rule). The simulation result show that sweeping much more than 30 degree each side is too much for the controller to handle. Figure 8b shows another posture of the ankle joint in the crouching up and down.

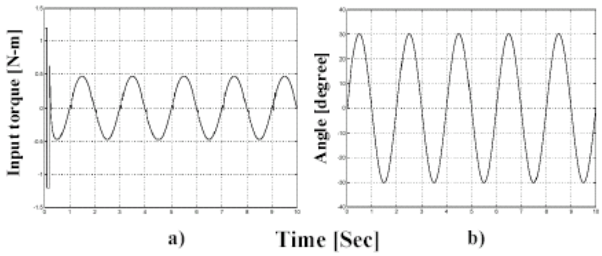

Figure 7: MATLAB's plots a) the control action of the ankle joint during swing from side to side operation and b) the angular response of the ankle joint during the swing from side to side operation

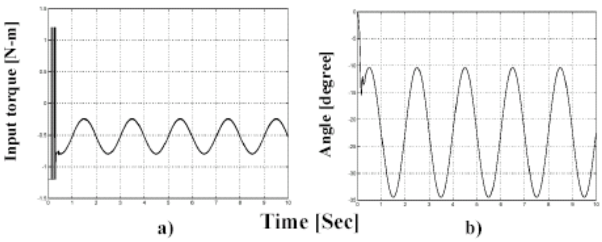

Figure 8: MATLAB's plots a) the control action of the ankle joint during the crouching up-down operation and b) the angular position during the crouching up-down operation.

6. Conclusion

The issues that the biped needs to meet in order to achieve a dynamically stable walking can be divided into two parts- the mechanical design and the computing hardware/control implementation. The weight of mechanical structure of the biped must be light. The actuator must output the highest power at the smallest expense of the actuator weight. The controller must be simple in order to reduce the processor memory storage and computational time. The implementation of the controller software must be in the environment of Real-Time operating system, such that, the response to the external event can be done in the deterministic boundary. This is not to mention the computing hardware must be as simple and as user-friendly as possible to allow more time to tackle the pertinent issue of dynamic walking. The knowledge in designing and constructing the small-sized biped mechanism prototype was obtained from the simulation results and the experiment with the motors. The subject of gait design and the control will be discussed in details in the future work.

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