Sprainy: Design and Prototype Development of an 8-Degree-of-Freedom Walking Biped Robot

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ABSTRACT
Theoretically the birth of the humanoid robot arises from the study of human characteristics of movement. However, following the human model does not mean copying it. It is still a big challenge to develop an advanced humanoid robot. Most researchers have shown an interest in developing an ideal theory to keep the balance in various grounds while walking since it is so important for the survival of biped robots; however, there are very few discussions on optimizing mechanical design to enhance the control of biped robots. In this article, we present the concept, design and construction of a biped robot, called “Sprainy,” and concentrate on the possibility of using optimized mechanical design to improve the workspace of its feet. The desired system criteria, design alternatives, final design selection, kinematics and design of the robot are presented.

Keyword
Biped robot, Sprainy Robot, Humanoid, Zero Momentum Point (ZMP)

1. INTRODUCTION
Thanks to the rapid development in science and technology, robotics has been widely applied to more and more areas. Hence, many kinds of robots have been built to replace humans working in different environments. Among them biped robots still receive less attention, but there is some interest in this field of robots since they offer better adaptability and ability to address complex jobs – and they resemble humans.

In the class of walkers, a distinction is established between three categories. First, “static” walkers, whose projection of the Center of Mass remains constantly inside the polygon that circumscribes one or two soles in support. Second, “dynamic” walkers, whose ankles are actuated in order that the Center of Pressure is situated in the support base. Note that the Center of Pressure (or Center of Ground Reaction Force) is called Zero Moment Point (ZMP) in most articles. Third, “purely dynamic” walkers, whose ankles are non-actuated, or they simply have no feet. In this case, the polygon of contact between the robot and the ground is reduced to a single point during the single support phase and to a single segment during the double support phase.

McGeer has designed a “purely dynamic” walker with 1 theoretical DOF [1]. This biped (Fig. 1) does not possess a pelvis; it has only two stiff articulated legs. It shows therefore in theory only a single degree of freedom (DOF). In practice, these two legs are telescopic so as to allow the swinging leg to rock backward and forward without colliding with the ground surface. So in reality, because of these two translations, this biped has a total of 3 DOF. There is no motion in the lateral plane. In the sagittal plane, the biped moves like a compass made of two links. The main articulation between the two legs is not actuated. Hence, in the double support phase, this walker has no redundancy. The kinematic model is planar. McGeer has been able to complete a symmetrical mechanical construction with respect to the sagittal plane; thus, obtaining a demonstrator representing the planar architecture. This biped activated by the forces of gravity can move on a sloping ground.

Grishin et al. have built a “purely dynamic” walker with 2 DOF [2]. It is composed (Fig. 2) of a pelvis on which two telescopic straight legs are articulated. Among these 4 DOF (two articulations plus two translations), it is necessary to subtract two constraints because

![Figure 1. Biped robot with 1 DOF](image)

The total length of the two legs is constant, and the pelvis is brought into alignment with the bisector of the two legs. Consequently, the real number of DOF is 2. The legs are equipped with passive feet, orientated perpendicularly to the sagittal plane, in order to inhibit lateral fall. This walker presents a redundancy of order 1 in the double support phase. Motors and transmission mechanisms are placed on the pelvis and thighs. This biped walks along a straight line on a planar horizontal surface.

Kajita et al. have constructed a “purely dynamic” walker with 4 DOF [3]. The mechanical architecture (Fig. 3) comes close to be a pseudo-inverted pendulum.
Miura et al. have employed a “purely dynamic” walker with 4 DOF named BIPER-3 [4]. It is composed (Fig. 4) of a pelvis and two stiff legs, articulated at the level of the hips characterized by a flexing-stretching freedom and an abduction-adduction freedom. The motion in the lateral plane involves three links and two articulations; it allows the robot to get lateral equilibrium in single support, and allows the swinging leg to rock backward and forward without colliding with the ground surface. The motion in the sagittal plane is that of a compass. The double support phase is very short and there is no change of posture. This is easy to understand, since during this phase this walker is underactuated and consequently no action allows it to modify its balance.

Furusho et al. have worked out several walkers. The latest is a “dynamic” one with 8 DOF named BLR-G2 [5]. It is composed (Fig. 5) of a pelvis and two legs. The hip and knee have a single DOF in flexing-stretching. The ankle possesses a DOF in flexing-stretching plus a DOF in lateral rotation. The lateral motion is that of an inverted pendulum: the robot functions in its frontal plane as a single rigid solid with a unique mobility about the ankle. It allows for equilibrium in single support and the rocking of the swinging leg. The motion in the sagittal plane involves seven links and six articulations. In the double support phase, this walker has a redundancy of order 6.

Zheng et al. have designed a “static” walker with 8 DOF named SD-2 [6]. The pelvis is long, which gives it the appearance of a trunk (Fig. 6), but it is not a trunk because it does not have functions differing from those of the pelvis. Its two legs are articulated in the motions of flexing-stretching and abduction-adduction while its feet are articulated in flexing-stretching and in lateral rotation. The biped has no knees. The DOFs are equally distributed in the lateral and sagittal planes: in one plane or the other, the motion involves five links and four articulations.

Takanishi et al. have built several walkers with trunks. The latest is a “dynamic” one with 9 DOF named WL-12RIII [8], [9]. The locomotive system of this biped is purely sagittal (Fig. 7). The 6 axis of ankles, knees and hips are parallel. For balance, a trunk is articulated on the pelvis around perpendicular axis (symbolized on Fig. 7 as a spherical joint). In the lateral plane, only the trunk is mobile which creates an inverted pendulum on the pelvis. The motion in the sagittal plane involves eight links and seven articulations.
Gruver et al. have designed a “dynamic” walker with 12 DOF [10]. It is composed (Fig. 8) of a pelvis and two legs whose hips have 3 DOF, knees 1 and ankles 2. The motion in the lateral plane involves five links and 4 DOF. The motion in the sagittal plane has seven links and 6 DOF. As a result of its 2 DOF of vertical axis (at the hips), this walker can potentially change direction.

Honda Motor Co. publicly presented a humanoid robot with two legs and two arms in 1996. The biped shown in Fig. 9 is the Honda robot in its first stage, without arms, as it is described by Honda [11]. The kinematic arrangement is more precisely detailed in [12].

This biped has no trunk, but a very high pelvis which looks like a pelvis-trunk (the arms of the complete humanoid robot are connected in the upper part of this pelvis trunk). It is a “dynamic” walker with 12 DOF: the hips have 3 DOF, the knees 1 and the ankles 2.

2. CONCEPTUAL DESIGN

The basic design concepts and specifications for the biped robot Sprainy are listed as follows:

- Develop a biped robot walker with only lower body; a pelvis and two legs.
- Achieve the static balance and dynamic stability so that it can walk continuously.
- Compact in size and light in weight.

With these main ideas, three conceptual designs have been developed.

2.1 Concept I

The concept of this design is to make the humanoid robot walk like a drunken person. However, it has been verified in later experiments that this way is very helpful to keep the dynamic balance and imitate the gait of human. A robot with 8 DOF is designed for walking [see Fig. 10]. The hip and knee have a single DOF each in flexing-stretching. The ankle possesses a DOF in flexing-stretching plus a DOF in lateral rotation. The lateral motion is that of an inverted pendulum (Fig. 11). The robot functions in its frontal plane as a single rigid solid body with a unique mobility about the ankle. It allows for equilibrium on single support and the rocking of the swinging leg. The motion in the sagittal plane involves seven links and six articulations.

In this design, in order to obtain more freedom we introduce a four-bar linkage mechanism to control the motion of the feet. In later experiments this mechanism is verified to be very successful. The foot moves not only in two planes but in 3D space so that better adaptability for the ground is achieved. This mechanism is shown in Fig. 12 and Fig. 13.
2.2 Concept II
It is apparent that to realize single leg support raising the other leg is the key; however, due to the weight of the 6 motors below the knee, it would be difficult (if not impossible) to raise the leg. Therefore, another concept is developed as an alternative. The change involves reducing two motors at the knees of Sprainy. Then, the biped becomes 6 DOF. This design can still realize a steady walk, but the risk of falling down has increased greatly because of the large strike on the pelvis.

2.3 Concept III
Another way to reduce the weight of the leg is to give up the four-bar linkage mechanism and reduce the four motors at the feet of Sprainy. Such a modification reduces DOF to 4. However, single foot support can not be achieved with this design. The strike to the pelvis becomes larger, but the balance is obtained easily than the other two design concepts.

2.4 Final Conceptual Design
Based on our design concepts summarized above, concept I is selected as the final concept because of the most DOF, the best adaptability and its mechanical advantages although it has the highest cost and the most fabrication difficulty. Thus, the final concept design has the following features:

- Total of 8 degree of freedom:
  - 2 DOF on the pelvis
  - 1 DOF on each knee
  - 2 DOF on each foot
- Controller: Basic Stamp HomeWork Board
- Servo: Futaba S3003
- Materials: Aluminum

3. KINEMATIC DESIGN
Since theoretically the birth of the robot arises from the study of human characteristics of movement, it is necessary to learn the mechanism of kinematics. However, it is almost impossible by just copying the model. Indeed, concerning kinematic mobility, a human being possesses approximately 350 DOF. It is necessary therefore to underline the articulations that are essential for proper walking of the robot: 15 active joints have been found essential for a walker mimicking a human gait (without upper body or arms).

3.1 Analysis of the Robot Kinematic Arrangement
In this work, a robot with 8 DOF is designed for walking (Fig. 10). The hip and knee have a single DOF in flexing-stretching. The ankle possesses a DOF in flexing-stretching plus a DOF in lateral rotation. The lateral motion is that of an inverted pendulum (Fig.11).

For the purpose of optimizing the mechanical design, use of four-bar linkages is considered to enhance the mechanical efficiency and achieve better adaptability. This mechanism is a popular and has been applied to many mechanical equipment. By rotating of the motors installed all over the robot, the kinematic characteristics of the movement of the links are calculated, and; furthermore, easily determined through the mathematical model based on the geometrical relationship between the links.

3.2 Proposed Control Strategy
For simplification purpose, the dynamic model in both sagittal and lateral plane can be modeled as the motion of inverted pendulum. Consequently, the ZMP can be decided in these planes separately. For the model in sagittal plane (Fig 15), the ZMP can be obtained with the method proposed by M. Vukobratovic et al. [13].

\[
X_{ZMP} \approx \frac{\tau_x}{Mg}
\]

\[
\tau_x = M\left[g + \left(\frac{\tau}{LM} - g\sin\theta\right)\sin\theta - \frac{v^2}{L}\cos^2\theta\right]x
\]

\[
\tau_x = M\left[g + \left(\frac{\tau}{LM} - g\sin\theta\right)\sin\theta\right]x
\]

\[
\tau_x = \frac{Mg\cos^2\theta}{1 - \frac{x\sin\theta}{L}}
\]

\[
X_{ZMP} = L\sin\theta
\]
For example, with \( L \) equals to 18 cm and the angle trajectory obtained by the control trajectory below, the ZMP for the supporting leg in lateral plane are plotted in figure 17.

From this figure, we can conclude that the width of the robot foot must be at least 3 cm. As one of the successful control strategies, use of final states of single-leg supporting phase was developed and implemented by T. Furuta et al [14]. Once both the initial and the final conditions of a single step are given, the trajectories of joint angles between them can be generated using interpolation by polynomials. This method has an advantage that the gait generation using polynomials is computationally inexpensive and is suited for real-time gait generation. The angular trajectory is assumed to follow the following polynomial equation:

\[
\theta = \alpha_0 + \alpha_1 t + \alpha_2 t^2 + \alpha_3 t^3
\]

The order of this polynomial is chosen to be three because that is necessary and sufficient for specifying angles and angular velocities on both ends. The coefficients are computed by the set of the boundary conditions. The final state and the time duration for a single step are obtained by the motion of the inverted pendulum.

4. GAIT DESIGN

Gait design is an important procedure to realize the steady walk for Sprainy. With the designed gait it has been possible to control the speed of walking robot. Our design imitates the gait of human walking. Three steps are defined as initial step, walking step and stop step (Fig.18).
Based on this design, the procedure of taking a step is outlined as follows (Fig.19):

- Make the robot stay at the initial position
- Drive the No. 7 and 8 motors to swing the robot to the left.
- Drive No. 1 motor to raise the right leg, drive No. 3 motor to hold the position.
- Drive No. 1 motor to lower the right leg, meanwhile, drive the No. 7 and 8 motors to swing back to the middle position.

Figure 19. Procedures of making one step

5. MECHANICAL DESIGN OF THE BIPED ROBOT

The robot developed in this work has eight degrees of freedom actuating its thirty one links, which are arranged as a hybrid mechanism. On the serial, or open chain, portion of the system, is where the main components are located: the two feet, the two calves, the two thighs, and the hip bridge. The functions of this chain are to move performing the gait as commanded by the controller, and to support the actuators and the components of the parallel portions of the system. These closed chain sections of the robot are located at each ankle, and its function is to control the position of the foot, by inclining it about two horizontal and perpendicular axes, in order to achieve the angular positions required to advance one leg and to balance the robot.

The foot angle control mechanism at each ankle is composed of two six-bar spatial mechanisms, each one actuated by one servo. These two servos are parallel to each other, and they, together with the linkages they actuate, are located symmetrically with respect to a vertical axis positioned along the calf. These mechanisms are spatial, as opposed to planar, because they move in two vertical and perpendicular planes to incline the foot, by means of the use of a link, attached to the crank of each one of the four servos at the two ankles, that has two revolute joints, along perpendicular axes; and three spherical joints for each foot: one for the linkage driven by each servo, and one central to join the foot and the calf together.

The foot of this robot has the contour of the letter “L”, with the objective of maximizing, for a given amount of material, the area of the footprint, defined by the intersection of the lines, extended from the shortest edges of the “L”, enclosing a virtual rectangular area. The hypothesis is that the robot would stay vertically, when supported by only one foot, if the vertical projection of its center of gravity lies inside the virtual rectangle footprint of this single supporting leg.

6. HARDWARE IMPLEMENTATION

6.1 Servo Selection

After a thorough survey of different types of the servos, we selected Futaba S3003 standard servo, as it has the highest torque/price ratio. In addition, it has a torque of 44 oz-in at 4.8 operating voltage and 56.8 oz-in at 6.0 operating voltage. And the weight is 1.3 oz while the size is 1.6"L x .8"W x 1.4"H. The connector is "J" type with approximate 5" lead.

Figure 20. Futaba S3003 standard servo

6.2 Microcontroller Selection

At the early stage of the present work, an SV203 microcontroller by Pontech was used. The SV203 is a microchip PIC16C73 microcontroller based board. It accepts RS232 serial data signal from a host computer and outputs PWM (pulse width modulated) signal to control up to eight RC servo motors.

A 5 channel, 8 bit A/D input is available to read analog voltages between 0 to 5 Volts. Devices such as an analog joystick or potentiometers can be connected to this port and the position can be read by the PC and sent back to the board to control the servo position.

The SV203 processes commands sent by a host computer connected to the serial port. The commands are ASCII character strings that select the board, instruct which servo to control, and the position of the servo.

Due to regulator problems with the SV203 microcontroller, it was replaced with Parallax’ Homework board to control the servos.
7. SOFTWARE IMPLEMENTATION
Robot control software was also developed. As Homework board was used, the code was developed in the Basic Stamp editor by Parallax for the biped walking gait of the robot (Fig. 25).

8. INTEGRATION OF HARDWARE AND SOFTWARE
At the heart of Sprainy's control system is the Basic stamp 2 Homework board. The Basic stamp uses a PIC 16C57 microcontroller. It has a built-in EPROM with a capacity of 2K/500 lines of PBasic code and 32 bytes of RAM. The BS-2 has 16 ports, which can be designated as either input or output, depending on the needs. It connects to the PC using the normal support interface. In the case of the Sprainy, the BS-2 controls all eight servos of the robots joints. The following figure shows how the servos and power source were connected. To start the gait, we input the code into the compiler, which in this case is the Basic Stamp Editor from Parallax.
After the code is entered into the editor, the Sprainy robot’s control board is connected to the computer via a serial cable. The code is then run through the editor and loaded onto the control board’s EPROM. Once this is done, the robot will perform instructions programmed.

9. CONCLUSIONS

The concept, design, construction and software development of a biped robot, called “Sprainy,” especially the possibility of using optimized mechanical design to improve the workspace of its feet are reviewed in this article (Figs. 27 and 28). The desired system criteria, design alternatives, final design selection, kinematics, and design of the robot are included. Initial test runs on the biped have been carried out. Further refinement of the design and development of different gait will be addressed in the future.

10. REFERENCES

