The Design Process of the Unified Walking Controller for the UNH Biped

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Abstract. This paper presents the process that was used to design a new walking control algorithm for the UNH biped, called the unified walking control algorithm. The new algorithm was designed using experiences gained though the implementation of controllers for dynamic and static walking. At the beginning of the design process four major hypotheses were formulated. Next the previously implemented algorithms were examined and compared. Based on the knowledge gained from the comparison seven secondary hypotheses were introduced. The hypotheses were used as the starting point in the design of the new controller. The new controller allows the experimental biped to walk with forward progression velocities in the range of *21 cm/min* to *72 cm/min*. Slow gait speeds require static walking while faster gaits require dynamic walking.

Introduction

One of the challenges of building humanoid robots is implementing biped robot walking. Bipedal gaits can be classified as *statically balanced* or *dynamically balanced* gaits. Statically balanced gaits have the property that if the walking motion is frozen at any instant of time, the biped is stable. This is achieved by keeping the normal projection of the robot's center of mass (NPCM) within the limits defined by the biped feet, while moving slowly enough that the biped dynamics can be ignored. When only one of the two feet is in contact with the ground, the NPCM has to be within the area of that foot. When both feet are on the ground the NPCM has to be within the polygon determined by the outer corners of the biped feet. We can call the above regions the *"stability regions"*. Very slow walking requires a statically balanced gait. Faster walking requires a dynamically balanced gait. In the case of dynamic balance the NPCM is permitted outside the boundaries described above. When the NPCM is outside these boundaries gravity will tend to make the biped fall over, and unless the feet are controlled correctly, the biped could fall on the ground.

Researchers at the UNH Robotics Lab have implemented a balance scheme, called the *unified walking controller*, for handling variable speed gaits on an experimental biped [1, 2]. The biped is able to walk with variable speed gaits, and to change gait speeds on the fly. The slower gait speeds require statically balanced walking, while the faster speeds require dynamically balanced walking. The unified walking controller was based on experiences gained from implementations of controllers for dynamic [3] and static [4] walking for the UNH biped. The goal of this paper is to describe the design process that resulted in the implementation of the unified walking controller. The paper describes the hypotheses of the research, paying special attention to the design of the hypotheses, as well as the resulting controller and the performance of the controller. Additional details and justifications for the individual controllers for dynamic and static walking are contained in the references cited.

Background

Early bipeds walked with static balance, usually with large feet and slow walking speeds. Summary discussion of the early history of biped walking machines has been presented by Raibert [5]. A recent implementation of static biped walking is the work of Yi and Zheng in which they used the SD-2 robot to test a reduced ankle power strategy applied to static walking [6]. Inaba, et al. [7] built an experimental ape-like biped that could perform static walking. These studies relied upon a sufficiently detailed model of the distribution of mass within the structure.

One of the first *dynamic walking* bipeds was built by Miura and Shimoyama. In their 1984 work [8] they reported on two dynamic walkers, BIPER-3 and BIPER-4. The control law was designed by approximating the motion of the robots in the single support phase to the motion of an inverted pendulum. The authors conducted successful walking experiments with the two robots. A more recent research effort that produced a dynamic walking biped is presented in the dissertation of Benbrahim published in 1996 [9]. The author designed and built an experimental biped robot, and developed a reinforcement learning control architecture. The robot can learn how to walk without prior knowledge of its dynamics and with minimum user intervention.

In initial research at the UNH Robotics Lab concerning two-legged walking adaptive control strategies were developed in simulation [10]. The strategies developed in simulation were tested and extended in studies using two generations of experimental bipeds [1, 2, 3, 4, 11].

Toddler the UNH Biped Robot

The biped (Figure 1) is approximately *1 m* tall and weighs approximately *11 kg*. The separation between the legs is *20 cm*. Each foot measures $12x7\ cm^2$, with the ankle attached near the center-rear corner of the foot. Each hip and ankle is actuated by two gearmotors. Each knee is actuated by a single gearmotor. The positions of the ten joints are sensed by optical position encoders. Four force sensing resistors are mounted on the underside of each foot, near each corner. Two piezoresistive accelerometers and two solid state rate gyroscopes oriented along orthogonal horizontal axes are mounted near the top of the body in order to provide two-dimensional body acceleration and rotation rate sensing. The accelerometers and the gyroscopes form two virtual sensors that can detect instantaneous biped body angles in the frontal and in the lateral planes.

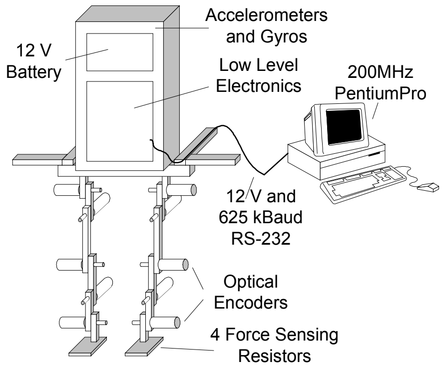

Figure 1. The biped hardware

Adaptive Control of Dynamic Balance Walking

An adaptive dynamic balance scheme was implemented and tested on the UNH biped. Figure 2 shows the basic walking gait of the biped robot. As a result of the distribution of mass within the structure, the biped cannot simply lift a foot without falling. In order to move a foot, it is necessary to first generate a lateral momentum toward the opposite side. The foot can then be lifted and moved to a new location. The resulting gravitational force when the foot is lifted breaks the momentum and allows the biped to fall back on to the lifted foot. Note that, while in single support phase, the biped dynamics can roughly be modeled by an inverted pendulum.

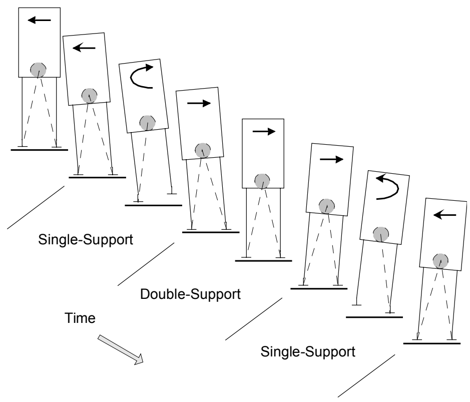

Figure 2. The basic walking gait. The arrows indicate the direction of motion of the body.

A gait generator based on an approximate model of the biped kinematics initiates the side-to-side and foot movement motions in the walking process. The gait generator attempts to create the simple sequence described in the previous paragraph. CMAC neural networks [12, 13] are used to modulate the gait generator output, as a function of desired step parameters (step length and step rate) and immediate sensor feedback. The CMAC neural networks are responsible for the control of side-to-side and front-to-back balance, as well as for maintaining good foot contact. The control system creates smooth motion sequences by superimposing pre-planned elements (provided by the gait generator) and adaptive elements (the outputs of the CMACs).

The gait generator divides the biped steps into three stages: *stepping leg extension stage, stepping leg lift stage,* and *stepping leg relaxation stage*. The lateral momentum necessary to lift a foot is generated in the first stage by extending the stepping leg, and thus tilting the biped. In the next stage the biped takes advantage of the lateral momentum, lifts the stepping foot and moves it forward. In the third stage the stepping leg relaxes and the biped is brought back into its vertical position. After this stage the biped legs exchange roles, and the stages are repeated for the opposite leg.

The gait generator is based on response to sensory triggers, rather than on reactive closed-loop control. It utilizes the concept of phase-locked central pattern generation to conform to, and make use of, the natural dynamics. The sensory triggers are the instances of each foot contacting or breaking contact with the ground, as detected by the foot force sensors. The closed loop system forms a phase-locked-loop that synchronizes the gait generator and the biped dynamics. The phase error is derived from the sensory triggers, and modifying the magnitude and velocity of the commanded side-to-side lean regulates the period of the natural dynamics.

Training of the biped typically proceeds as follows. The CMAC neural networks are first trained during repetitive foot lift motions similar to marching in place. This is typically carried out for five minutes, with different settings for desired foot lift height (in the range *0.5* to *2.5 cm*). Frequent human support is required to keep the biped from falling during the first half of this training, and occasional support is required during the second half. Then, training of the CMAC neural networks is carried out during attempts at walking, for increasing step lengths, and/or for various step rates. Again, frequent human support is required during early training for each new parameter setting, while less frequent support is required after *2* or *3 minutes* of training at a given setting. After about *60 minutes* of total training time, the biped is able to shift body weight from side-to-side while maintaining good foot contact, and to lift a foot off of the floor for a desired length of time, during which the foot can be moved to a new location relative to the body. Using these skills, the biped is able to start and stop on demand, and to walk with continuous motion on flat surfaces at a rate of up to *100* steps per minute, with step lengths up to *6 cm* per step.

Adaptive Control of Static Balance Walking

As in the case of the dynamic balance gait, in order to move a foot using a static balance gait, it is necessary to first counterbalance that foot by leaning the upper body toward the opposite side. The foot can then be lifted and moved to a new location.

Statically stable biped walking is achieved by keeping the robot's normal projection of center of mass (*NPCM*) within the limits defined by its feet. The control architecture of the biped consists of a high- and a low level controller. The high level controller generates pre-planned, but adaptive, sensory triggered, smooth posture sequences. The gait generator, based on an approximate model of the biped kinematics, initiates the side-to-side and foot movement motions in the walking process. CMAC neural networks are used to modulate the gait generator as a function of desired step parameters (step length and rate) and immediate sensor feedback. The low level controller performs three steps. First it transforms the posture sequences, received from the high level control, into actuator angle sequences. The actuator angle sequences are then modified as a result of reactive control of the right-left and front-back angles, and of the active control of the foot contact in double support phase. Finally, the corrected actuator angle sequences are implemented using PID control. The control strategy therefore uses a combination of pre-planned, but adaptive, smooth motion sequences with sensory triggers, and reactive closed-loop control.

The CMAC neural networks are first trained during marching in place. This is typically carried out for five minutes, with different settings for desired foot lift height (*2* to *5 cm*). Then, training of the CMAC neural networks is carried out during attempts at walking, for increasing step lengths, and/or for various step rates. Frequent human support is required during early training for each new parameter setting, while less frequent support is required after *2* or *3 minutes* of training at a given setting. After about *30 minutes* of total training time, the biped is able to shift body weight from side-to-side while maintaining good foot contact, and to lift a foot off of the floor for a desired length of time, during which the foot can be moved to a new location relative to the body. The biped can start and stop on demand, and walk with continuous motion on flat surfaces at a rate of up to *2.2* steps per minute, with step lengths of up to *6 cm* per step (*12 cm* stride lengths).

Unified walking controller design

The *main hypothesis* of this research proposed that identification of the characteristics of dynamic and static walking, and the examination and comparison of these characteristics, could be used to create a new algorithm, which would allow the biped to walk at a range of gait speeds, and switch from any gait speed to any other gait speed within the allowed range, at any given instant of time. The slow velocities would be implementing static walking, and the faster velocities dynamic walking. Following this hypothesis the first step in the development of the new algorithm was to identify the major characteristics of the dynamic and static walking gaits.

Characteristics of Dynamic Walking

During the analysis of the dynamic walking controller seven important characteristics of the gait were identified:

1. The controller utilized the natural dynamics of the robot.
2. The controller lacked reactive control.
3. The biped would continue moving in the right-left direction after it lifted a foot.
4. Centers of force (*CFs*) measured on the feet were not utilized extensively.
5. The supporting foot had to be roughly static under the upper body during stepping with the other foot.
6. The desired front-back lean angle was constant.
7. The controller used simplified frontal and lateral plane kinematics to translate posture commands into joint position commands.

Let us now look at each of the above characteristics individually.

Utilization of Natural Dynamics

The most important characteristic of the dynamic walking gait implementation is that the controller tried to make use of the natural dynamics of the biped hardware. The biped's gait required a right-left swinging motion in order to lift a foot. The controller was programmed to keep the rate of the right-left swinging of the biped in the vicinity of the natural frequency of this swinging motion. This way, instead of "fighting" the biped's mechanical hardware, the controller was making use of its properties. This approach reduced the need to accurately model the biped dynamics. However, the lack of an accurate knowledge of the dynamics represented a problem when the controller tried to reduce the stepping rate.

In single support phase the biped can roughly be modeled as an inverted pendulum. For a two-dimensional inverted pendulum model of the biped, the relationship between the time period the foot spends in the air (*"foot lift period"*), the lean angle at the moment the foot is lifted (*"lean at foot lift"*), and the sideways speed at this moment (*"v"*), is represented by the curves in Figure 3. The dynamic walking controller produced walking rates that resulted in the lifted foot remaining in the air for approximately *0.3 sec*. The corresponding pairs of *lean at foot lift*, and *foot lift period* were in the *natural frequency region* outlined in Figure 3. When the controller was driving the robot at a stepping rate higher than the natural frequency the *"foot lift period"* became shorter. The controller did not have a problem with these stepping rates because they required less accurate control than walking in the vicinity of the natural frequency. This can be seen from the fact that the curves have a smaller slope for shorter *"foot lift period"* values, and the curves corresponding to different sideways speeds *"v"* are closer together. Conversely, for longer *"foot lift period"* values, the curves have a larger slope, and curves corresponding to different values of *"v"* are further apart. Consequently, slow walking requires a more precise control of the biped's position and speed. The dynamic walking controller was not able to provide the accuracy required for slow walking.

Lack of Reactive Control

The dynamic walking controller implemented adaptive closed loop control without reactive control. The controller got better by learning not to repeat mistakes, however it did not have a mechanism that would react to mistakes when they occurred.

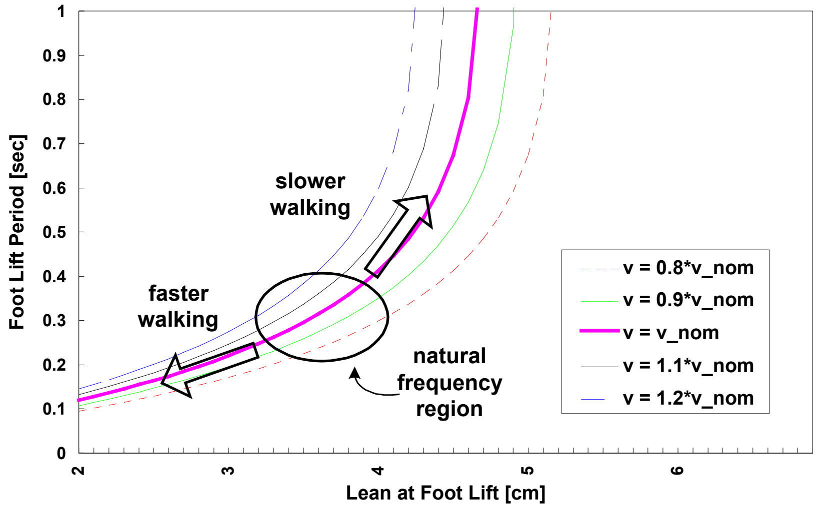

Figure 3. Relationship between the time period the foot spends in the air, and the lean angle and the sideways speed at the moment the foot is lifted

Right-Left Motion Continued After Lifting a Foot

In the case of the dynamic walking gait, a foot was moved by first generating a lateral momentum toward the opposite side. The foot could then be lifted and moved to a new location. The biped's right-left motion would continue in single support phase without explicit control by the walking algorithm. At the moment a foot was lifted the biped body was at a certain right-left angle. The first part of the sideways motion in single support phase was due to the biped body's inertia, which carried it past its position when the foot was lifted. However, the gravitational force when the foot was lifted, broke the inertia and allowed the biped to fall back onto the lifted foot. Thus the second part of the motion was due to the biped falling back toward the lifted foot.

Centers of Force (*CFs*) on the Feet not Utilized Extensively

The dynamic walking controller utilized the *CFs* measured on the feet only to train one of its CMAC neural networks. This CMAC adjusted the positions of the "Ankle Y" joint of the supporting foot to achieve better foot contact in the right-left direction in single support phase.

The Supporting Foot has to be Under the Upper Body

The dynamic gait controller was designed in such a way that the gait generator produced a predefined sequence of posture commands, which were then modified by CMAC neural networks. The predefined sequence was very simple: the biped had to lean to one side, pick up a foot and put it forward, and then repeat the motion to the other side and with the other foot. One important preprogrammed feature of the gait was that, while one foot was lifted, the supporting foot had to be held steady under the biped upper body. The biped was not pushing off with the supporting foot. Moving the supporting foot did not produce stable walking.

Constant Desired Front-Back Lean Angle
The dynamic gait controller aimed to keep the front-back lean angle constant. The controller was designed with this characteristic as a requirement. This meant that the front-back angle was not used to try to achieve better front-back stability. Instead, a constant front-back angle was a criterion of stability.

Simplified Kinematics
The system used simplified kinematics to translate commanded posture sequences into commanded joint angle sequences. The simplified kinematics did not take into account the coupling between the frontal and lateral plane motions. This reduced the complexity of the necessary calculations, while providing good results.

Characteristics of Static Walking

During the analysis of the static walking controller ten important characteristics of the gait were identified:
1. The biped was moving slowly enough that the dynamics could be neglected.
2. Reactive lean angle control was used along with adaptive control.
3. The preprogrammed part of the gait assumed that the biped stopped the right-left motion in single support phase.
4. *Right-left lean* posture command corrections were performed by both a CMAC neural network and a PID controller.
5. The *CFs* measured on the feet were used both in the high- and low-level controller.
6. The supporting foot had to be under the upper body during stepping with the other foot.
7. Integral control was used to provide good foot contact in double support phase.
8. The desired front-back lean angle was constant.
9. The desired front-back lean angle was *9°*, which was less than the desired front-back angle in the case of dynamic walking *(15°)*.
10. The controller was not successful at walking rates of over *2.2 steps per minute*.
11. The controller used simplified frontal and lateral plane kinematics to translate posture commands into joint position commands.

Let us now take a look at each of the above characteristics individually.

Slow Motion Allowed Dynamics to be Neglected
The biped's stepping rate did not exceed *2.2 steps/minute*. This rate allowed the controller to be designed without having to model the dynamics very accurately.

Reactive Control Used Along with Adaptive Control
The low level controller included an algorithm for reactively adjusting the right-left and front-back lean angles to the target lean angles. The adaptive part of the control, based on CMAC neural networks, was not able to implement the exact angles required for lifting a foot. With the presence of reactive control, the lean angles were implemented with sufficient accuracy for static walking.

Right-Left Lean Angle Commanded to be Constant in Single Support Phase
In the case of static walking, in order to move a foot, it is necessary to first counterbalance that foot by leaning the biped's upper body toward the opposite side. The foot can then be lifted and moved to a new location. The right-left lean angle was commanded to be constant in single support phase.

Right-Left Lean Angle Corrections Performed by Both a CMAC and a PID Controller
The *right-left lean* posture command was affected by both a CMAC neural net and a PID controller. The idea was to make the job of the CMAC easier - the CMAC would "learn" to implement the lean angle "almost right", and the PID controller would provide small corrections. The problem with this setup was that the PID control caused instability when the stepping rate was increased.

Extensive Use of Measured Centers of Force (*CFs*)
In the static gait controller the *CFs* measured on the feet were used in three places:

- the integral control of the position of the biped ankle angles;
- a CMAC neural network responsible for right-left balance control;
- the reactive control algorithm.

This extensive use of the *CFs* was important because they are the most reliable measure of the biped's stability. If the biped is falling in one direction the *CF* readings on the feet will clearly show this. The biped's stability cannot be deduced unequivocally from the body lean angles - in different situations different body angles could lead to a fall.

The Supporting Foot has to be Under the Upper body
The static gait controller's *gait generator* produced a predefined sequence of posture commands, which were then modified by CMAC neural networks. The predefined sequence commanded the biped to lean to one side, pick up a foot and put it forward, then repeat the motion to the other side and with the other foot. As in the case of the dynamic gait, an important feature of the static gait was that while one foot was lifted, the other (supporting) foot had to be held steady under the biped's upper body. The biped was not pushing off with the supporting foot. When the supporting foot was under the biped's upper body the metal structure (the "bones") carried a large portion of the weight. When the supporting foot was used to push the biped forward the load on the "Hip" and "Ankle" joint motors of the supporting leg increased to the point where the motors were not able to implement the commanded angles. This is illustrated in Figure 4.

Integral Control Used to Provide Good Foot Contact in Double Support Phase
The low level controller implemented integral control to provide good foot contact in double support phase. Good foot contact was essential in achieving stable walking - without it the biped tended to rock back onto the lifted foot. One problem with having an integral controller in the system was stability. The biped's walking rate was limited by the delay introduced by the integral control of foot contact.

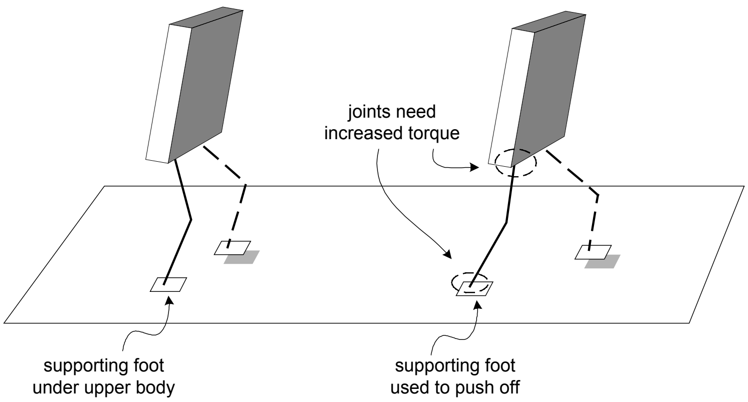

Figure 4. It is important to keep the supporting foot under the upper body

Desired Front-Back Lean Angle Constant

As in the case of dynamic walking, the front-back lean angle was not variable - the controller did not adjust this angle continuously in order to try to improve stability. Rather, the value of the front-back angle was a predefined requirement.

Desired Front-Back Lean Angle Less than for Dynamic Walking

The dynamic walking was implemented with a constant front-back lean angle of *15*°. For static walking the value of the desired front-back lean angle was decreased from *15*° to *9*°. When the lean angle was *15*° in single support phase the "Hip" joint motors could not counteract the torque created by the weight of the upper body and the lifted leg. Figure 5 illustrates how the different lean angles result in different torques on the "Hip" joint. When the biped's front-back lean angle is zero, the torque is also zero. The more the biped leans forward the larger the torque gets - this is true up to the point where the center of mass of the upper body and the lifted leg (CM) are in the same line as the "Hip Y" joint.

In the dynamic walking case the length of time the lifted foot spent in the air was less than *0.5 sec*, while in the case of static walking it was on the order of *5 sec*. The "Hip" motors were strong enough to implement the desired angles with relatively high accuracy for short periods of time, even when the biped was leaning *15*°. However, for longer periods they were not able to supply the necessary torque. Therefore, for static walking the lean angle was reduced to *9*°.

The Controller Could Only Implement Slow Walking Rates

The controller was not successful at walking rates of more than *2.2 steps/minute*. The controller was designed to work at low stepping rates. Mechanisms that performed well at these low rates failed at higher rates. The CMAC neural nets were not geared toward higher speeds, or toward allowing motion at various speeds. The system also had integral and PID controllers in two subsystems - these controllers worked well for low step rates, but became unstable for higher rates.

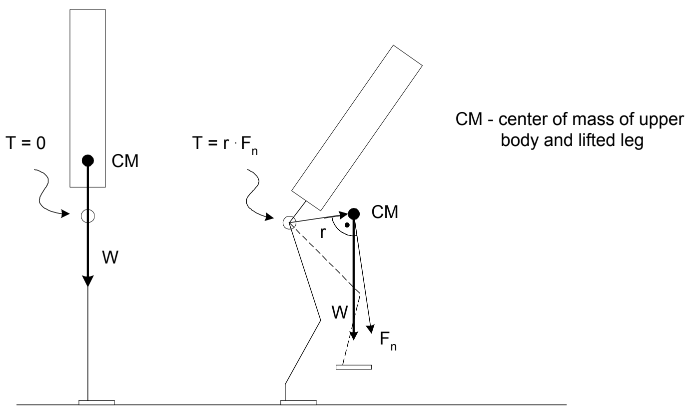

Figure 5. Torque (T) on "Hip" joint due to body lean

Simplified Kinematics
As in the case of dynamic walking, the posture commands were translated into joint angle commands by simplified kinematics, which ignored the coupling between motions in the frontal and the lateral planes. As in the case of dynamic walking, this reduced the complexity of the necessary calculations, while providing good results.

Unified Controller Design Hypotheses

The previous section described the most important characteristics of the static and dynamic gaits. This section discusses how the examination and comparison of these characteristics led to the formulation of three of the major hypotheses and seven secondary hypotheses.

Major Hypotheses

As we said in the Introduction, the statically balanced gait has the property that if the walking motion is frozen at any instant of time, the biped is stable. This is achieved by keeping the normal projection of the robot's center of mass (NPCM) within the limits defined by the biped feet, while moving slowly enough that the biped dynamics can be ignored. When only one of the two feet is in contact with the ground, the NPCM has to be within the area of that foot. When both feet are on the ground the NPCM has to be within the polygon determined by the outer corners of the biped feet. We can call the above regions the *"stability regions"*. Both cases are illustrated in Figure 6, where the regions described above are hashmarked.

In the case of dynamic balance the NPCM is permitted outside the boundaries described above. If the NPCM is outside these boundaries gravity will tend to make the biped fall over. The biped may be falling during parts of the gait, and unless the feet are controlled correctly, it could fall on the ground. The "Zero Moment Point" (ZMP) is the point where the sum of all moments is equal to zero [14]. If the dynamically balanced gait is constrained such that the supporting foot has to be flat on the ground, then the ZMP has to stay within the boundaries hashmarked in Figure 6, that is within the *"stability region"*. If the ZMP left the stability region, the contact foot would rotate around one of its edges. We can call dynamic balance with the above constraint *full foot contact dynamic balance*. Since, in the case of static balance, the NPCM and the ZMP are located in the same point, static balance is a special case of full foot contact dynamic balance.

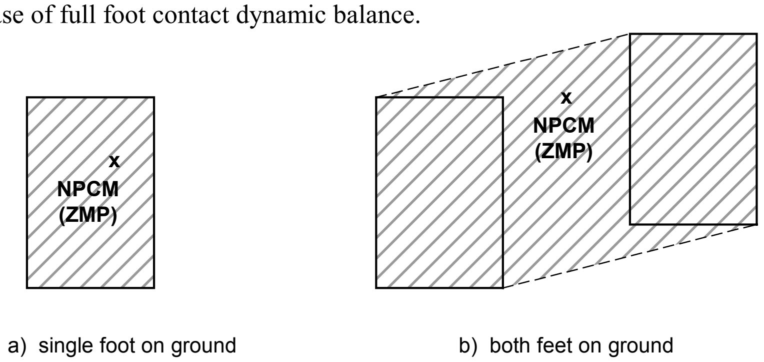

Figure 6. Stability region: Position of the NPCM in the case of static balance, and the ZMP in the case of full foot contact dynamic balance

The *second hypothesis* of this research is that the property of both static walking and full foot contact dynamic walking that the ZMP has to be within the stability region, as illustrated in Figure 6, can be used to create a unified biped walking control algorithm. The hypothesis proposed that the position of the ZMP can be measured, and that the control algorithm should position the ZMP such that the biped is stable. Since the ZMP has to be in the same area for all gait speeds, the controller should not need to distinguish between static and dynamic walking.

Both the static and the dynamic walking controllers were adaptive controllers that improved their performance based on sensor feedback. The *third major hypothesis* thus was that the new controller should be adaptive and improve over time based on feedback from the biped sensors.

The *fourth major hypothesis* of this research proposed that the unified bipedal walking controller should be based on adaptive closed-loop control. The control output should have a pre-planned, but adaptive, component, and a reactive component. This hypothesis was initially based on the property of the dynamic gait controller that slow walking cannot be implemented because the controller utilizes the dynamics of the mechanical hardware and lacks reactive control. The hypothesis was given more credibility when it was found that the low level reactive lean angle control was essential in achieving static walking.

Secondary Hypotheses

The examination and comparison of the characteristics of the two implemented gaits resulted in the following seven secondary hypotheses, denoted *SH*:

SH #1. *In single support phase the body's right-left position should be actively controlled to help smoothly break any existing momentum, which is swinging the biped away from the lifted foot.* In the case of dynamic walking, the gait was designed such that the biped relied on the lateral momentum being broken by lifting the foot off the ground. The right-left angle was not actively controlled. In the case of static walking, the sideways momentum was always negligibly small, thus the biped could be commanded not to move sideways in single support phase. The new controller had to be able to deal both with gaits that have lateral momentum at the beginning of the single support phase, and with those that do not. This hypothesis proposed that the important consideration was how to smoothly break the sideways momentum if it does exist, and it said that this should be done by actively controlling the right-left angle in single support phase, such that its value helps break the momentum in a smooth manner.

SH #2. *If only a CMAC neural network is used to perform corrections of the* right-left lean *posture command, the biped's performance at higher stepping rates will be satisfactory.* It is necessary to perform corrections of the *right-left lean* and the *front-back lean* posture commands in order to implement reactive control of the lean angles in the low level controller. In the case of static walking this was done in the high level controller by a PID controller in combination with a CMAC neural net. However, the PID control caused instability when the stepping rate was increased. This hypothesis proposed that by using only a CMAC neural network the lean angles would be corrected successfully, while avoiding instability at higher stepping rates.

SH #3. *Providing good foot contact in double support phase is necessary for successful walking at variable speeds.* Securing good foot contact in the double support phase was essential to achieving static walking. In the case of dynamic walking good foot contact in the double support phase was less important because, due to relatively large sideways speeds, the biped did not have a problem of rocking back onto the lifted foot. Instead, variations in foot contact resulted primarily in variations in single support duration. Since the new controller would have to deal with both slow and fast walking, it seemed reasonable to expect that good foot contact in double support phase will be a prerequisite for successful walking.

SH #4. *Good foot contact in double support phase can be achieved by correcting the positions of the ankle joint positions by using a CMAC neural network.* In the case of static walking good foot contact is achieved with the help of an integral controller. This controller was not stable at higher stepping rates. This hypothesis says that the integral controller can be replaced by a CMAC neural network that will perform well at various stepping rates.

SH #5. *The preprogrammed part of the gait should keep the supporting foot under the upper body.* For both the implemented static and the dynamic gaits the walking was successful only when the supporting foot was commanded to be steady under the upper body. It was expected that the new controller would perform in the same manner.

SH #6. *Keeping the commanded front-back angle constant at 9° will result in stable walking.* Both implemented controllers used a constant front-back lean angle. In the case of dynamic walking this angle was *15*°, however the static gait walking required a front-back lean angle of *9*°. In order to be able to implement both static and dynamic walking the front-back angle was set to *9*°.
SH #7. *The new controller can use simplified kinematics to translate posture commands into commanded joint angles.* Both the dynamic and the static controller used simplified kinematics with good results. It seemed reasonable to expect that the new controller would perform well with it as well.

The gait and the control architecture of the unified biped walking scheme was based on the major hypotheses and the secondary hypotheses presented in this section. Let us first introduce the biped gait, and then take a look at the control architecture.

Walking Gait

The walking gait of the robot using the unified control algorithm combined elements of both previously implemented gaits. It also took into account the first and the fifth secondary hypotheses (SH #1 and SH #5).

As in the case of dynamic and static walking, due to the distribution of mass within the biped structure, in order to move a foot it is necessary to first lean the biped's upper body toward the opposite side. Since the unified controller has to deal with both static and dynamic walking, it was assumed that the sideways motion will create a momentum that cannot be neglected. Following SH #1, the biped gait was designed to help smoothly break this momentum after the foot is lifted, by smoothly decelerating the sideways motion while the foot is being raised. If the *gait generator* was programmed to stop the sideways motion while the lifted foot is in the air (as was the case for static walking), the upper body would still continue moving away from the lifted foot, with a decelerating motion. The gait generator creates a commanded sequence of postures that takes into account the fact that the upper body will need some time to decelerate. This approach makes the control less abrupt, and results in smoother walking motions. Once the foot reaches the highest point of its trajectory, the right-left angle starts changing to bring the biped back towards the lifted foot. When the foot lands the biped's sideways speed levels off. The right-left speed profile of the sideways motion implementing this idea is outlined in Figure 7. Notice that the profile is designed to be continuous. This is important since a discontinuous speed profile corresponds to jerky motion, which in turn can easily lead to instability, due to its high frequency content.

The biped gait is shown in Figure 8. The biped goes through double support phases, when both feet are on the ground, and single support phases when only one foot is on the ground. The arrows on the upper body show the direction in which the upper body is moving (right or left). The arrows next to the lifted feet show the direction in which those feet are moving (up or down).

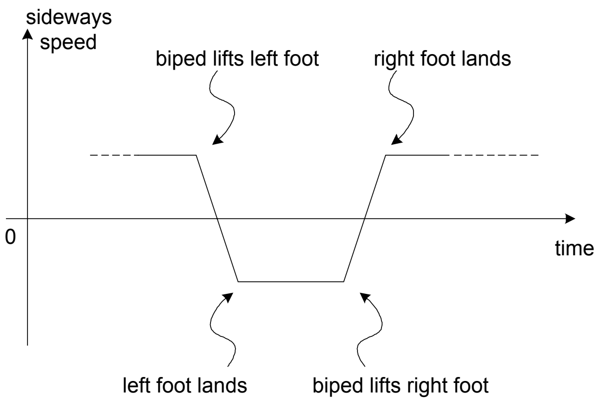

Figure 7. Outline of the preprogrammed sideways speed profile

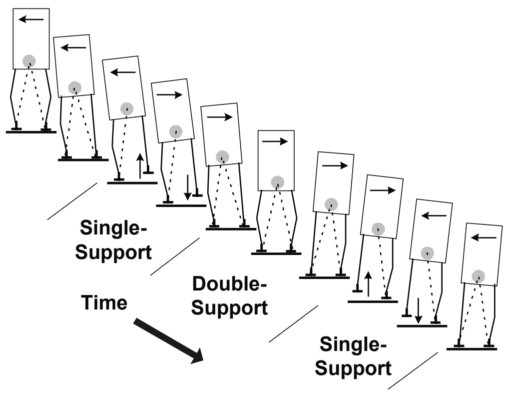

Figure 8. Biped gait used by the unified walking controller

As for both dynamic and static walking, leaning to one side is achieved by starting the biped with bent knees and extending the opposite leg. Bent legs in Figure 8 illustrate this method of leaning. Alternative ways of leaning the upper body are leaning it from the hips or from the ankles, but the biped's DC motors are not strong enough for these. Notice also that, as outlined in Figure 8, in single support phase the biped can roughly be modeled as in inverted pendulum. The biped's walking gait in the unified control algorithm is logically divided into the same six phases as the static walking gait:

1. *extend left leg phase*: In this phase the biped leans from left to right by extending the left leg, in order to take weight off the left foot. The sideways speed is preprogrammed to be constant. In the front-back direction the biped feet are moving relative to the upper body such that at the end of this phase the right foot is under the upper body, and the distance between the right and left foot is the same as at the beginning of this phase.

2. *lift left foot phase*: At the end of the *extend left leg phase* the position of the biped (in the case of static walking), or both the position and the sideways momentum generated by the left-to-right motion (in the case of dynamic walking), allow the left foot to be lifted, and the *lift left foot phase* starts. While in this phase, the upper body is moving away from the lifted left foot with speed decreasing to zero. The right foot is kept under the upper body, while the left foot moves forward.
3. *lower left foot phase*: Once the left foot reaches the highest point of its trajectory this phase starts, and the foot is lowered back onto the ground. At the start of this phase the sideways speed is zero. As time progresses the biped is moving towards the lifted left foot with increasing speed, until the left foot hits the floor. When the left foot makes contact with the ground this phase ends, and the *extend right leg phase* starts. While the left foot is in the air the right foot is kept under the upper body, and the left foot is moved forward.
4. *extend right leg phase*: Symmetrical counterpart of the *extend left leg phase*.
5. *lift right foot phase*: Symmetrical counterpart of the *lift left foot phase.*
6. *lower right foot phase*: Symmetrical counterpart of the *lower left foot phase.*

Note that the motion of the feet is based on the requirement that the biped has to move forward and on SH #5, which proposes that the supporting foot should be preprogrammed to be under the upper body. Following SH #6 the biped's front-back lean angle is commanded to be 9° throughout the gait.

Adaptive Control of Walking

Now that we have introduced the biped gate for the unified control algorithm, let us examine the unified control architecture of the biped. As in the cases of dynamic and static walking, the control architecture consists of a high- and a low level controller. Figure 9 shows in block diagram form how the control architecture, including both the low and the high level control, fits into the overall biped system.

The high level controller generates sequences of desired joint angles. This is done in three steps. First, the controller generates posture sequences based on a simplified model of the biped. Next, these sequences are modified using neural networks. The modified sequences are pre-planned, but adaptive, sensory triggered, smooth sequences of desired postures, called *"commanded postures"* in Figure 9. Taking into account SH #2 only a CMAC neural net is used to correct the right-left lean angle command. The commanded posture sequences are translated into sequences of desired actuator angles. Following SH #7 the translation is done using simplified kinematics. Two of the resulting "*desired angles"* are modified using neural networks to obtain the *"commanded angles"*. These two angles are the right and left ankle angles in the frontal plane. Based on SH #3 good foot contact is necessary for successful walking at variable rates. Following SH #4 good foot contact in the double support phase can be achieved by controlling these angles a CMAC neural network.

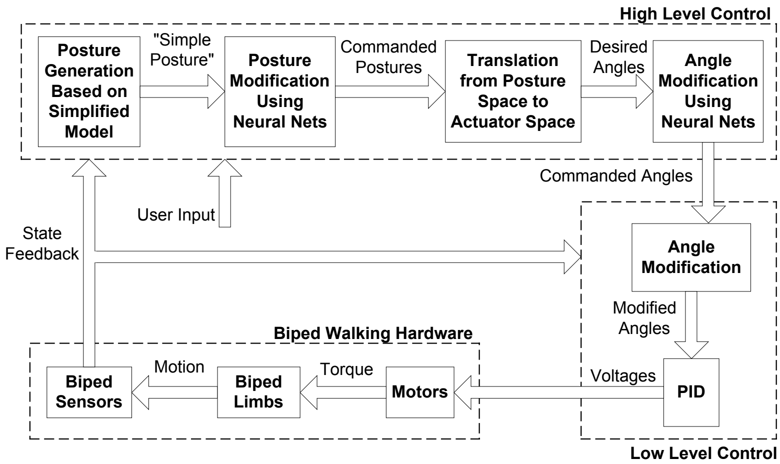

Figure 9. Overall biped system block diagram

The low level controller performs two steps. First, the actuator angle sequences received from the high level controller are modified as a result of reactive control of the right-left and front-back angles. Next, the modified actuator angle sequences *("modified angles")* are implemented using PID control.

The overall control strategy (including both the high and the low level control) uses a combination of pre-planned, but adaptive, smooth motion sequences with sensory triggers, and reactive closed-loop control.

Neural Network Training and Qualitative Results for the Unified Walking Controller

The CMAC neural networks of the *unified walking controller* were first trained during repetitive foot lift motions similar to marching in place (i.e. no attempts were made to translate the lifted foot). This was typically carried out for five minutes, with different settings for the desired foot lift height (in the *2* to *5 cm* range). Then, training of the CMAC neural networks was carried out during attempts at walking (translating the lifted foot forward), for increasing step lengths and gait speeds. Frequent human support was required to keep the biped from falling during early training for each new parameter setting, while less frequent support was required after *2* or *3 minutes* of training at a given setting. After about *60 minutes* of total training time, the biped was able to shift body weight from side-to-side while maintaining good foot contact, and to lift a foot off the floor for a desired length of time, during which that foot could be moved to a new location relative to the body. The biped could start and stop on demand, and walk with a forward progression velocity in the range of *21-72 cm/min*, with up to *9 cm* long strides. Figure 10 shows the UNH robot walking. Movies of the biped walking can be seen at *http://www.ece.unh.edu/robots/rbt_home.htm*.

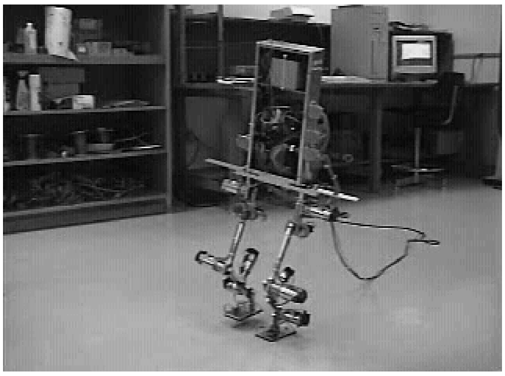

Figure 10. The UNH biped walking

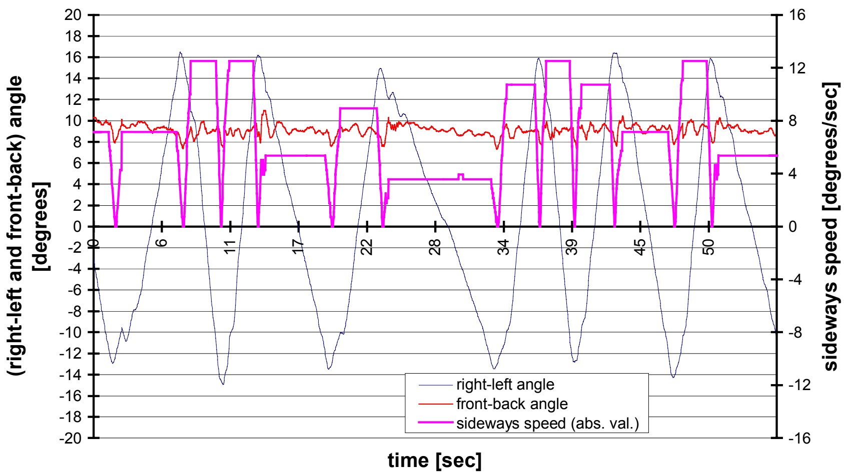

Figure 11. Absolute value of the commanded sideways leaning speed and the measured value of the right-left and front-back angles. The sideways leaning speed is changing "randomly".

Figure 11 shows the absolute value of the commanded sideways leaning speed and the measured value of the right-left and front-back results for walking with "random" changes in the sideways leaning speed. The sideways leaning speed was changed in the range of *3.6 °/sec* to *12.5 °/sec*. By "random" changes we mean that the operator did not deliberately follow a pattern in changing the value of the leaning speed. The data presented in the figure was taken with the stride length set to *9 cm*, and the step height to *4 cm*. The results in the figure show that the walking was stable. The right-left angle was smooth, the front-back angle was centered around *9*°, with excursions of less than ±*2*°. A very important point to make regarding the above results is that the various sideways leaning speeds implemented both static and dynamic walking. The lowest tested sideways leaning speed was *3.6 °/sec* and it required static walking. For higher leaning speeds, some or all phases of the gait required dynamic balance.

Conclusion

This paper presents the process of designing a new walking control algorithm for the UNH biped. The process is described in detail in order to highlight the thought process that led to the new controller, as opposed to describing the end product (the controller) only. Let us now evaluate the major hypotheses of the research, which were presented in Unified Controller Design Hypotheses section.

We said that the ZMP has to be within the stability region for both static and full foot contact dynamic walking. The second hypothesis proposed that this property of the two gaits could be used to create a unified biped walking control algorithm. According to the hypothesis the position of the ZMP can be measured, and the control algorithm should position the ZMP such that the biped is stable. Since the ZMP has to be in the same area for all gait speeds, the controller should not need to distinguish between static and dynamic walking. The measured value of the ZMP is used in two parts of the unified control algorithm. The adaptive control of front-back balance uses the front-back component of the ZMP as the training signal for a CMAC neural network. The CMAC outputs corrections to the commanded positions of the biped's feet with respect to the hips. By moving the feet relative to the hips in the front-back direction the front-back balance is improved. The low level controller also uses the ZMP in single support phase to provide reactive control of the right-left and front-back lean angles. The controller uses the ZMP in both the high- and the low level controller without having to distinguish between static and dynamic walking. Therefore, the second hypothesis was proven to be correct.

The third hypothesis proposed that the new control algorithm can be made adaptive, and that it can improve its performance over time based on feedback from the biped sensors. The high level controller of the unified control algorithm has CMAC neural networks. The output of the high level controller is a combination of pre-planned elements, and outputs of the CMAC neural networks. The neural networks are trained based on sensory feedback about the biped states. The performance of the system improves over time, as described above. Therefore the third hypothesis was correct.

The fourth hypothesis proposed that the unified bipedal walking controller should be based on adaptive closed-loop control. The control output should have a pre-planned, but adaptive, component, and a reactive component. The reactive component should compensate small errors of the controller and some disturbances. The low level controller of the unified control algorithm implements a reactive controller, which controls the right-left and front-back lean angles. The reactive controller compares the lean angles, measured by the virtual body angle sensors, with the desired lean angles and uses the difference between them as the error signal. The modified PD controller is essential to the successful operation of the unified controller, which confirms the fourth hypothesis. Thus the fourth hypothesis was proven correct.

The main hypothesis proposed that, if the static and dynamic walking gaits were analyzed and their important features were identified, one could base the design of a new walking control algorithm on the acquired knowledge. The new algorithm would allow the biped to walk at a range of gait speeds, and switch from any gait speed to any other gait speed within the range, at any given instant of time. The slow velocities would implement static walking, and the faster velocities dynamic walking. As explained above, the examination and comparison of the static and dynamic gait characteristics led to the formulation of three major, and seven secondary hypotheses. These hypotheses were the basis of the design process that led to the implementation of the new *unified biped walking control algorithm*. The new controller was tested, and it was found that, with the new controller, the biped could walk with variable gait speeds, with forward progression velocities in the range of *21 cm/min* to *72 cm/min*, and change gait speeds on the fly. The slow gait speeds implemented statically balanced walking, while the faster speeds implemented dynamically balanced walking. Therefore, the main hypothesis of the research was correct.

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