CONFIRMATION OF PHD CANDIDATURE

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List of Publications:

Wyeth G, Kee D, Yik T, “*Evolving a Locus based Gait for a Humanoid Robot*”, Proceedings of the International Conference on Intelligent Robots and Systems, 2003, (submitted)

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Kee D, Wyeth G, Hood A, Drury A, "*GuRoo: Autonomous Humanoid Platform for Walking Gait Research"* Proceedings of the Conference on Autonomous Minirobots for Research and Edutainment (AMiRE2003) February 18 - 20 , Brisbane 2003

Wyeth G, Kee D, Wagstaff M et al, "*Design of an Autonomous Humanoid Robot*" Proceedings of the Australian Conference on Robotics and Automation (ACRA '01), November 14-15, Sydney 2001

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1 Introduction

1.1 Research Theme

Recent studies have shown an increasing demand for mobile robots to work in domestic and service settings [1], in which the environment is principally designed to meet the ergonomic demands of the human body. Stairs, chairs, offices, kitchens and sport stadiums are all designed with the human body in mind. Wheeled robots, which presently dominate the mobile robot population, do not readily interact with human-shaped spaces. To enable domestic and service robots to become part of our daily lives, it is essential that current human environments be unmodified: rather the robot shape must be adapted. Clearly, the humanoid shape is the logical choice for a robot that will seamlessly integrate with our human-enabled world.

The challenge in shifting to a humanoid platform is to provide locomotion stability and payload capacity to rival the current wheeled robot population. The inherent instability of a two legged robot is the underlying problem that creates this challenge. Unlike multi-legged robots that can benefit from a stable base of three or more contact regions, a humanoid or biped is forced to maintain stability with only one or two contact regions.

Research into two legged robot walking has taken place over the last thirty years, with limited success. Initial research was conducted using bipeds with no torsos, focussing on the leg trajectories required to maintain stable walking. In the mid-80s trunks became more prevalent in the robot designs. Only since the mid-90s, have full humanoid robots (with arms, torso and head) been used for walking research. Surprisingly, the benchmark research institutes in this field of research are two commercial companies; Honda and Sony. Sony’s SDR-4X, standing approximately 50cm tall, demonstrates remarkable agility and balance but is too small to be practical as a domestic robot. Honda’s ASIMO, standing 1.2m tall, is currently the world leader in domestic robot research.

Many aspect of humanoid walking have been solved [2-4], though predominantly in controlled environments and with disturbances kept to a minimum. Hand-tuned sequences of motion are applied which are dependant on repeatable robot dynamics and favourable environmental conditions. While this has found success, it is the transferral of the walking gait from the laboratory to the real world which poses most problems.

High degree of freedom (DoF) systems such as a humanoid robot have enormous configuration spaces. Given a typical six DoF leg on a humanoid robot, there is a wide range of trajectories that will land one foot in front of the other. Only a fraction of these, however, which are practical or stable. While it is possible to hand tune or algorithmically find practical, stable trajectories, the trajectories must be followed accurately due to the sensitive nature of the robot balance problem. Indeed it might not be sufficient to follow the trajectories accurately, as any changes in the robot dynamics (for example, carrying a load) will likely make the trajectory unstable, as will any external force (a strong breeze!) applied to the robot.

Conversely, the human body is continually changing. During the first 20 or so years of life, the length of the limbs increases, and throughout our entire lifetime, body weight fluctuates, sometimes dramatically. Despite this continual change in body dynamics, humans continue to walk without the need to explicitly 'relearn'. Similarly, the human walking gait can readily compensate both for loads to be carried, or disturbances to be rejected.

Can this notion of learning be applied to walking robots? In broad terms, this thesis aims to explore the question:

> *"Given an arbitrary set of humanoid movements, can a learning system be implemented to realise these movements regardless of robot dynamics or environmental disturbances?"*

The ability to control the robot accurately and robustly is paramount to the success of the walking gait. Control problems exist on many levels, from the low level joint control to high level reflexive stabilisation loops.

1.2 Project Aims:

The aim of the research is to implement a control system on a humanoid robot to realise robust and stable locomotion. Due to the high degrees of freedom typical in humanoid robots and the inherent instability of bipedal walking, simple control loops on individual joint are insufficient for robust walking. Higher level reflexive control loops that react quickly to the robots configuration and position relative to the outside world will enable the robot to maintain stability. Changes in robot dynamics, such as an increase in payload, and minor external disturbances, such as incidental human contact, should not necessitate a change in control parameters. Instead, the system will adapt to these changes ‘on the fly’ using a cerebellum model. As there will be several control loops running concurrently there is the possibility that two loops will seek to control the same joint simultaneously. Consequently the cerebellum module will act as a predictive modulator rather than a predictive controller. To achieve these aims there are several major tasks to be undertaken including:

- Identifying various specific control loops and general control techniques that maintain stability in humanoid robots.
- Identifying cerebellum models that propose the cerebellum to function as an adaptive modulator. Addressing the known degradation of controller response due to sensory delay.
- Augmenting the control loops with the cerebellum modules to create a control loop capable of learning system dynamics.
- Evaluating the effectiveness of each control loop and implementing a system comprising a combination of cerebellum based control loops to achieve robust and adaptive control on a humanoid platform.

With this system in place, the robot will learn to perform three successive tasks

- Robust and stable walking along a flat surface.
- Stable walking on an inclined surface.
- Stable walking in the presence of external disturbances.
- Preservation of stability through support polygon control in the presence of excessive external disturbances.

1.3 Test Platform

All work will be carried out on the GuRoo Humanoid robot constructed at the University of Queensland. The GuRoo stands 1.2m tall, weighs approximately 35kg and has 23 Degrees of Freedom. The robot will be equipped with a variety of sensors to measure the interaction with external objects and the robots attitude with respect to the ground. These sensors include:

- Inertial Measurement Unit (IMU), capable of providing acceleration along, and angular rate about, all three axes.
- Force Distribution Sensors, located along the soles of the feet, capable of measuring the ground reaction force.
- Optical joint encoders to provide local positional feedback to each actuator.

The simulator, based on DynaMechs [5] models the robot and the environment, and is capable of simulating the resulting dynamic interaction. The simulator is used as a tool to enable testing of walking gaits without fear of damaging the real robot.

1.4 Outline of Chapters:

Chapter 1	Introduction: General background, project aims and testing platform summary.
Chapter 2	Nomenclature: Terminology and basic concepts within the human biology and humanoid robot research area. Stability concepts and terminology outlined
Chapter 3	Walking Gait Generation: Review of the common techniques employed to generate stable gaits for humanoid robots.
Chapter 4	Stability Control Loops: Review of the common control loops applied to humanoid robots to maintain stability during walking.
Chapter 5	Thesis proposal and Plan: An outline of the control system to be implemented on the GuRoo. The stability loops and support polygon control is describe and possible
Chapter 6	Work to Date: The design and construction of the GuRoo humanoid platform is outlined.
Chapter 7	Work Remaining: The control modules still to be implemented and the associated experiments are described.

2 Nomenclature

Basic terminology with respects to the field of humanoid robotics is drawn from anatomical and robot literature. The terms used to describe pose and motion in the literature vary greatly. This section defines the most common expressions that will be used for the remainder of the document.

2.1 Anatomical Terminology

Humanoid robots, by definition, are anthropomorphic and are best described by the corresponding human anatomical features (for example, hip, knee and ankle). Anatomical literature refers to the axes about the body as the sagittal, frontal and transverse (or horizontal) planes. The anatomical planes are shown in Figure 1. Anterior and posterior descriptors relate to the front and back of the human respectively. Motion around the pitch axis of a joint is termed flexion and extension. Motion of a joint around its roll axis is labelled abduction and adduction.

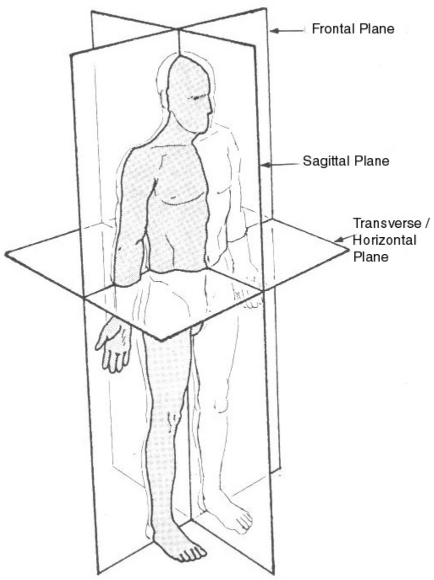

Figure 1 : Anatomical Naming Conventions. Reproduced from [6]

The anatomical literature classifies the state of each leg during walking. The period of time when both feet are in contact with the ground is termed the double support phase. When only one leg takes the weight of the human, it is termed the single support or stance phase. This leg is known as the supporting leg, with the opposite leg termed the swing or free leg.

Many researchers have divided the human gait into phases [6, 7] with Perry [8] regarded as the most definitive. Perry classifies the human walking gait into eight distinct phases as described below.

- **Initial Contact:** At the point of initial contact, the swing leg first contacts the ground through the heel. The knee is straight and the hip flexed. The initial contact is also known as heel strike.
- **Loading response:** During loading response, the body weight is transmitted to the forward leg. The knee is flexed to absorb the weight of the rest of the body.
- **Mid-Stance:** During the mid-stance phase, the supporting leg carries the entire weight of the robot. The hip and upper body pass over the supporting ankle.
- **Terminal Stance:** In the terminal stance phase, the rest of the supporting leg travels over the toes, and the heel lifts from the ground. The opposite foot is now in the initial contact stage.
- **Pre-Swing:** During pre-swing, the heel continues to rise and the knee bends in preparation to lift the foot from the ground.
- **Initial Swing:** The initial swing is when the foot is lifted and propelled forward by flexion of the hip. The knee is further flexed to ensure ground clearance.
- **Mid Swing:** In mid swing, the swing leg passes the support leg. The knee is extended in preparation of the initial contact.
- **Terminal Swing:** At terminal swing, the knee is fully extended in anticipation of the initial contact.

2.2 Biped Robot Terminology

Support Polygon

The support polygon is defined as the convex hull of the contact points of the feet of the robot. During the single support phase, the outline of the supporting foot is considered the support polygon.

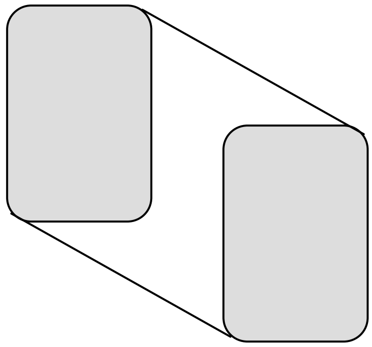

Figure 2 Support polygon for an example double support phase.

Stability Margin

The stability margin is defined as the distance between the zero moment point (ZMP, described below), and the nearest support polygon boundary.

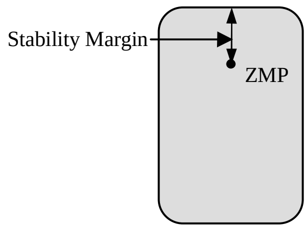

Figure 3 The stability margin during an example single support phase.

Zero Moment Point (ZMP)

The concept of a Zero Moment Point (ZMP) was put forward by Vukobratovic [9] in the early 1970's, based on D'Alembet's principle that the sum of all moments and forces on a body in equilibrium is zero (a corollary of the Newton-Euler laws of motion). The ZMP is a similar concept to the Centre of Gravity, but with the additional forces caused by the motion of each link within the robot taken into account. Vukobratovic's work proves that if the ZMP remains within the support polygon, the robot will be dynamically stable.

Figure 4 shows the difference between a ZMP stable, and a ZMP unstable configuration. When stable, the ZMP resulting force (Fz) is counteracted by the ground reaction force (FR). In this case, the foot remains stable by applying a force at the toes. If Fz leaves the support polygon, FR can only move as far as the polygon boundary. A moment is created between FZ and FR and the robot becomes unstable, tipping about this polygon edge.

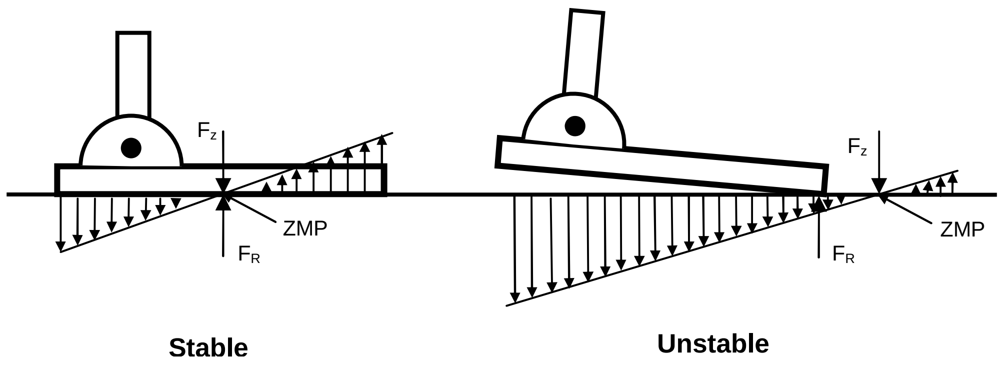

Figure 4 Interaction of the support base with ground surface about the ZMP, illustrating ZMP stability.

The calculation of the exact ZMP for a humanoid robot is computationally demanding. Typically the calculations are simplified by modelling each link as a point mass. With this assumption the free-body analysis simplifies to:

$$\overbrace{\sum_{i=1}^{a}(\mathbf{r}_i-\mathbf{r}_p)\times m_i(\mathbf{g}+\ddot{\mathbf{r}}_i)}^{\text{contribution from particle masses}} + \overbrace{\sum_{j=1}^{b}(\mathbf{r}_j-\mathbf{r}_p)\times\mathbf{F}_j}^{\text{external forces}} + \overbrace{\sum_{k=1}^{c}\mathbf{M}_k}^{\text{external moments}} + \overbrace{\mathbf{r}_p\times\mathbf{F}_R}^{\text{reaction moment}} = 0$$

where;

- r_i , r_j , r_p are the positions of the point masses, external forces and ZMP respectively,
- m_i are the masses of each particle,
- g is the gravity vector,
- F_j are the external forces,
- M_k are the external moments, and
- F_R is the reaction force.

If the links were not modelled as point masses, the first expression would also need to include the contribution from the rotational properties of each link making the overall expression intractable. If further assumptions are made that:

(i) a Cartesian coordinate system is set so that the plane of the X and Y axes is equal to the plane of the floor, and

(ii) the floor is a rigid plane that cannot be moved by any force or moment,

then the coordinates of the ZMP can be calculated by:

$$r_{px} = \frac{\sum_{i=1}^{a} m_i \left(\left(\ddot{r}_{iz} + g_z \right) r_{ix} - \left(\ddot{r}_{ix} + g_x \right) r_{iz} \right) + \sum_{j=1}^{b} \left(r_{jz} F_{jx} - r_{jx} F_{jz} \right) + \sum_{k=1}^{c} M_{ky}}{\sum_{i=1}^{a} m_i \left(\ddot{r}_{iz} + g_z \right) - \sum_{j=1}^{b} F_{jz}}$$

$$r_{py} = \frac{\sum_{i=1}^{a} m_i \left(\left(\ddot{r}_{iz} + g_z \right) r_{iy} - \left(\ddot{r}_{iy} + g_y \right) r_{iz} \right) - \sum_{j=1}^{b} \left(r_{jz} F_{jy} - r_{jy} F_{jz} \right) - \sum_{k=1}^{c} M_{kx}}{\sum_{i=1}^{a} m_i \left(\ddot{r}_{iz} + g_z \right) - \sum_{j=1}^{b} F_{jz}}$$

3 Walking Gait Generation

This section presents a brief overview of locomotion generation techniques currently used by humanoid robot projects around the world. Whilst there is considerable literature within the biped walking domain, the emphasis of this review is towards full humanoid platforms.

The generation of humanoid locomotion sequences are generally classified into three distinct approaches.

- Offline, pre-defined generated leg motions, with torso stabilisation
- Inverted pendulum / point mass assumption
- Neural network or evolved locomotion sequences

3.1 Pre-Defined/ Torso Stabilised gaits

The most basic of walking gaits is a completely pre-defined sequence of motions, explicitly designed to achieve stable walking. A set of motions for the legs are pre-planned to mimic the motions required to walk. Huang [10] used a 3rd order spline interpolation, given a toe-off angle, heel strike angle, maximum step height and step length, to generate the motion of the foot through the swing stage. Inherent in these movements is a ZMP path that may not necessarily be stable. A torso motion is generated to compensate for the error between the actual ZMP and the desired ZMP path. This method relies on the assumption that the assumed ZMP, the one calculated given each link state, is the same as the actual ZMP experienced by the robot. With data pertaining to the acceleration and physical mass of each link, it is possible to calculate the overall ZMP path of the robot. The torso motion is derived analytically.

Takanishi et al [11, 12] uses a point mass assumption for each link to determine the resultant pitch and roll moments on the torso given a sequence of leg motions. Provision for the effect of external forces and moments within the force calculations are made, although how these moments are sensed is not explained. As the torso motion is periodic, the solution can be represented by the coefficients of a Fast Fourier Transform (FFT). An offline iterative technique applies the solution to the approximate model and measures the resultant deviation from the desired path. The FFT coefficients are modified and the process repeated until the errors fall within an acceptable limit. During walking, the torso motion is modified to compensate for external forces and moments. Yamaguchi et al [13] extended this work to deal with the yaw motion generated by the legs. Conversely, Lim et al [14] uses finite difference methods to solve the simplified equations of motion of the torso, and to determine the appropriate path of the torso, to cancel the generated roll and pitch moments.

Nagasaka et al [2], after analytically determining the moments resulting from the arbitrary leg motions, employs a genetic algorithm to determine the required torso motion. An initial torso motion, heuristically designed to maintain static stability is applied to a simulator, and a fitness function dependant on ZMP deviation is used to evolve appropriate torso motions. A suitable solution was achieved after 24 hours on a PentiumIII computer. The final gait was then transferred to their real humanoid, 'H5' with successful results.

3.2 Inverted Pendulum

Kajita et al [15] modelled their biped as a linear inverted pendulum, with an effective point mass located at the centre of mass of the robot. This mass represented the mass of the entire robot and was located on a massless post with the origin at the ZMP (as shown in Figure 5).

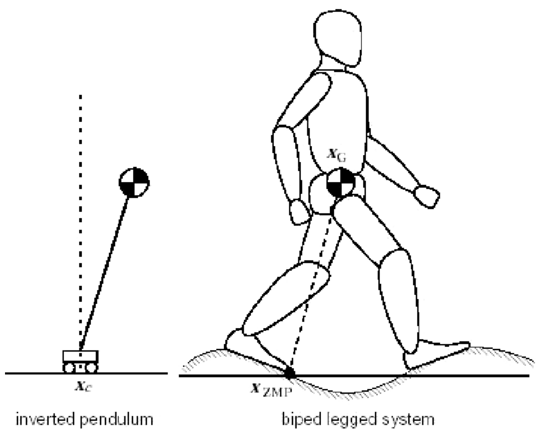

Figure 5 Inverted Pendulum assumption for a humanoid robot

Given a pre-defined ZMP stable path, it is possible to analytically derive the motion necessary to achieve this ZMP path. Problems occurred for Kajita with the fact that the robot's legs, far from being massless, accounted for 47.4% of the total mass of the robot.

Park et al [16] realised this failing of the inverted pendulum assumption and proposed a Gravity Compensated Inverted Pendulum Mode. It was realised that the mass and inertia of the swing leg was not insignificant and was the overriding factor preventing Kajita's above work from success. Park extended the point mass assumption to consist of 2 point masses, one representing the swing leg and the other representing the rest of the robot. Given the path of the swing leg, it was possible to determine its effect on the ZMP and plan an appropriate path for the main mass.

3.3 Neural Network

Two main learning approaches have been applied to humanoids; the genetic algorithms to generate each and every joint trajectory and Cerebellum Modelled Articulation Controller (CMAC) used to develop behaviours relevant to walking.

Genetic Algorithms

Yamasaki et al [17] used a genetic algorithm to generate the joint motions required to make the robot walk. Using a simulated version of PINO, a 26 DoF robot [18], he applied a population of 50 different joint motions and measured the resulting locomotion of the robot. The ZMP was calculated using a 4^{th} order runge-kutta method applied to the robot model. Torque generated by each motor was also analytically determined and a walking failure defined as when the torque generated by any motor exceeded a pre-defined limit. Distance travelled by the robot before falling became the fitness function for the GA. After 50 generations, the fitness function was changed to reflect the ratio of the distance walked to the energy consumed. Yamasaki found that should the energy component be introduced in the first stage, a robot that stood still, and hence very energy efficient, would evolve. Using a two stage fitness function allowed only walking gaits that promoted walking to be further evolved to minimise energy consumption.

Shan [19] used neural oscillator central pattern generators to generate the sinusoidal patterns necessary for walking. Each joint consisted of a CPG with the shape of the output dependant on the connections with other CPG's. These weights were generated using a multi-objective genetic algorithm, with fitness functions incorporating the ZMP as well as the body inclination and forward velocity.

CMAC

The other learning approach to gait generation uses the Cerebellum Model Arithmetic Computer (CMAC) neural network to train various behaviours. Kun et al [20] implement three such networks, each responsible for learning a particular behaviour which in turn modifies an initial gait based on heuristics and a simple biped model. Common inputs among all CMAC's were user defined gait parameters including step length, step frequency and step height.

The first CMAC was responsible for learning the side to side swaying motion necessary for the transfer of weight between legs during the double support phase of the gait. A predefined lean angle of 9 degrees is set, with the leg lifting off the ground at each extreme. Force sensitive resistors located on the feet measure the time the feet remain off the ground, the error between the measured time and a pre-determined desired time forms the learning signal for the CMAC learning process. The second CMAC is responsible for position of the feet relative to the hips in the sagittal plane. The ZMP, as inferred from the force sensors on the feet, is used as the training signal, ensuring front to back stability. As the gait generator uses a simplified model of the robot, CMAC's 3 and 4 are used to learn the specific dynamics of the robot. Due to errors in the model and possible deviations in joints, during the double support phase of the gait, each foot may not be flush with the ground. CMAC 5 seeks to achieve the best foot contact possible by rotating the ankle to balance the force seen along the whole area of the foot.

Smith's [21] work on CMAC's was applied to a 18 degree of freedom simulated humanoid. Eighteen different behaviours were trained, 8 for both the left and right side, and 2 global behaviours to control the overall twist in the yaw axis and the drift from the desired path. Main behaviours for each leg included balance in the sagittal and frontal plane, placement of the leg and toe collision. Behaviours for swinging each arm were also applied. In the simulation, Smith was able to make the humanoid walk in a straight line and up and down inclines. It was found that the performance of the robot did not increase in a linear fashion, but rather went through various training stages, each with a different failure mode. With so many different behaviours, the CMAC's are highly coupled leading to long training times.

4 Stability Control Loops

This section will review different techniques used to maintain the stability of humanoid robots as they walk along flat surfaces. From previous research, it is possible to divide the most common control techniques into several categories:

- Direct ZMP control
- Body attitude control
- Landing foot control
- Scheduled control

4.1 Direct ZMP Control

The most common control technique for humanoid robots is the direct control of the ZMP. The ZMP is either inferred from the information provided by external sensors, or calculated based on the assumed acceleration and mass of each link. The difference between various ZMP control loops lies in the action taken to resolve any resulting error between the desired ZMP and the measured ZMP.

Using an off-line generated ZMP stable gait, Li [22] implements a learning control that modifies the motion of the torso to maintain a ZMP stable gait. The actual ZMP experienced by the robot is measured via two six axis force sensors located in the lower legs of the robot. As the walking gait is periodic in nature, the motion of the torso can be characterised by the coefficients of its FFT. These coefficients are adjusted proportionally to the magnitude of the error signal between the measured ZMP and the desired ZMP.

Hirai et al [4] employs an inertial measurement system located in the body of the robot to infer the actual ZMP of the robot. The body is then accelerated forward or backward to drive the actual ZMP towards the desired ZMP, as determined by the walking pattern generator. Whilst this will control ZMP in the sagittal plane, there is no reference to control in the frontal plane.

Yokoi et al [23] implements a similar ZMP control scheme, but with the actual ZMP acting on the robot calculated from 6-axis force sensors located in each foot. Acceleration of the body forward or backward results in movement of the actual ZMP experienced by the robot.

Huang et al [24] applies a more flexible approach to ZMP control, based around a pre-defined valid ZMP stable region as opposed to a ZMP stable path. Manipulation of the ZMP is achieved by rotating the supporting foot to apply pressure to either the toes or heel by an amount proportional to the distance between the actual ZMP and the stable region. Huang speculates that if the ZMP is controlled to strictly follow a single path, the stability margin is always at its greatest but the control does not allow the robot to move quickly. Applying control only when the ZMP exceeds the stable region allows more flexibility when walking. Stability regions can be calculated dynamically in response to environmental disturbances.

Park et al [25] accelerates the torso in a vertical direction to prevent the need to recalculate the leg landing position in the direction of travel.

4.2 Body Posture Control

Body posture control is designed to keep the torso at a pre-defined attitude. While it is theoretically possible to have dynamically stable gaits with the torso inclined to large angles, maintaining a distinct posture produces a gait that is aesthetically pleasing. A stable upright torso also provides a suitable base for the location of additional sensors such as a vision sensor.

Using a pre-determined ZMP stable gait, Huang [24] implements a control loop responsible for maintaining the torso attitude. Information describing this attitude is provided to the controller via a collection of accelerometers and angular rate sensors. The body posture control loop modifies the pitch components of the hip to maintain an upright position. Only change in the hip pitch actuator of the supporting leg effects a change in torso attitude. Consequently, after a change in the torso attitude, the hip pitch joint of the swing leg is adjusted to maintain the gait of the planned trajectories.

Yokoi et al [23] extends this control technique to take into account the inclination of the whole body. A desired torso inclination is implicit in the off-line generated ZMP stable walk. The corrective input necessary to maintain the desired body inclination is achieved by rotating the supporting foot accordingly.

4.3 Landing Foot Control

Humanoid stability is arguably at its lowest as the swing leg makes contact with the ground and the robot moves into the double support phase. The implementation of a control scheme during this phase seeks to reduce this instability. These schemes generally do not does not control the ZMP, but seek to reduce the disturbances of the landing leg as it contacts the ground.

Huang et al [24] implement a control loop based on the pre-calculated time that the foot is expected to make contact with the ground. Three possible scenarios are outlined:

- Foot contacts earlier than expected
- Foot contacts later than expected
- Foot contacts on time

If the foot contact time was less than expected, the robot is either tipping forward, or the ground is higher than expected. Stability is maintained by quickly lifting the leg relative to the rest of the robot. Should the foot not have made contact with the ground by the expected time, the robot is either deemed to be tipping backwards or the ground is lower than expected. The leg is then lowered by a pre-set amount and again tested for contact. No control is applied to the walking gait if the foot contacts the ground at the expected time.

Hirai et al [4] utilise a foot position control loop to compensate for torso motions due to ZMP control. If the torso has been accelerated forward or backwards, the geometric relationship between the torso and the landing foot is changed. Foot landing control is employed to recalculate the position of the landing foot to ensure continuity of the walking gait.

4.4 Scheduled control:

Scheduled control involves the use of control loops that vary their parameters dependant on the phase of robot’s gait.

Lim et al [26] employs an ankle controller that varies a standard proportional control loop dependant on the point in the gait cycle. When the ankle is in the swing phase, a simple proportional position control is employed. As the swing leg contacts the ground and the robot enters the double support phase, the control law is augmented to implement a high viscosity component. This allows the leg to absorb the large contact force present especially during the heel strike phase. This high compliance of the joints is maintained throughout the first half of the single support phase to encourage smooth motion as the body is propelled forward. During the second half of the single support phase authority is returned to the position control to steady the body in preparation for the next heel strike.

5 Thesis Proposal and Plan:

The proposed system will use cerebellum augmented control loops to realise robust humanoid walking. A basic open loop walking motion that is theoretically ZMP stable will be known to the robot. A control system comprising joint controllers and stability loops will be implemented with adaptive components, designed to learn the dynamics of the robot and reject disturbances from the external environment.

5.1 Control Architecture

This architecture proposes is shown in Figure 6 and consists of four major control loops:

- Joint Compensation
- Ankle Compliance
- Active Balance
- Support Polygon Control

The input to the whole system is a *Desired Configuration*, which could represent joint angle, velocity or acceleration, as generated by the *Gait Generator* and which is dependant on time. The *Gait Phase* signal is an indication of the current location of the robot within one complete walking cycle. The *Desired Configuration* is successively modulated by the first three control loops before a motor controller converts the signal into a voltage to be sent to the robot. The IMU, FSRs and Encoders convert the resulting motion of the robot into *Inclination*, *Ground Reaction* and *Actual Joint Configuration* data respectively. The *Support Polygon Control* adjusts the *Gait Generator* to implement a new support polygon, should the stability margin of the current configuration be inadequate.

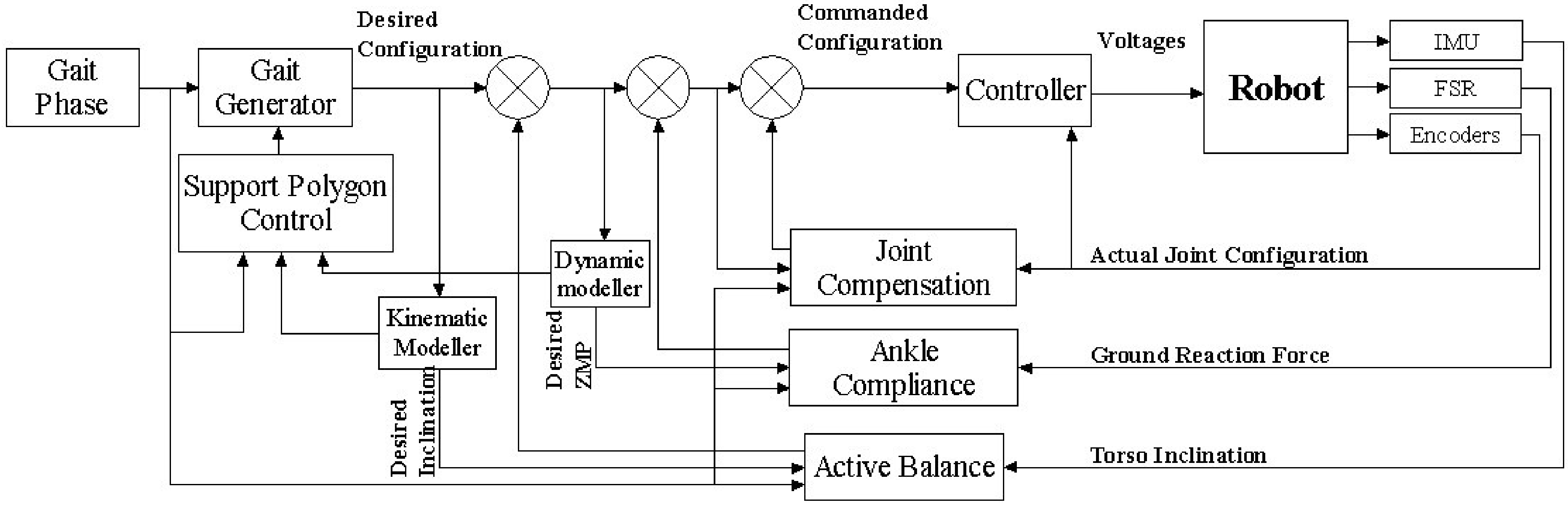

Figure 6 Block diagram of proposed Control System

Joint Compensation:

Due to the cyclic nature of walking, joint trajectory errors are typically dependant on the current point of the gait cycle. A standard motor control loop such as a Proportional controller can only react to errors. With the *Gait Phase* as an input, the *Joint Compensation* control loop is used as a predictive modulator. With knowledge relating the joint error with a particular gait phase, the *Joint Compensation* loop modifies the *Desired Configuration* command appropriately. Given a ZMP stable gait and a well tuned *Joint Compensation* loop, the robot will be able to walk robustly on smooth, flat surfaces.

Ankle Compliance:

Should the terrain be inclined, simple joint compensation is insufficient to maintain stability. In Figure 7, the robot is walking on an incline surface. Without compliance in the ankle, the robot would rotate around the contact point, in this case the toe, and fall backwards. Whilst the *Desired ZMP* might be located in the ground projection of the support polygon, unless the foot is in contact with the ground at the ZMP, the *Ground Reaction Force* will be located at the point of contact. This separation of *Desired ZMP* from the *Ground Reaction Force* results in a tipping motion. By servoing the ankle motors to resolve this error, the foot makes better contact with the ground ensuring the *Desired ZMP* and the *Ground Reaction Force* are coincident. This ankle control is performed in both the frontal and sagittal planes.

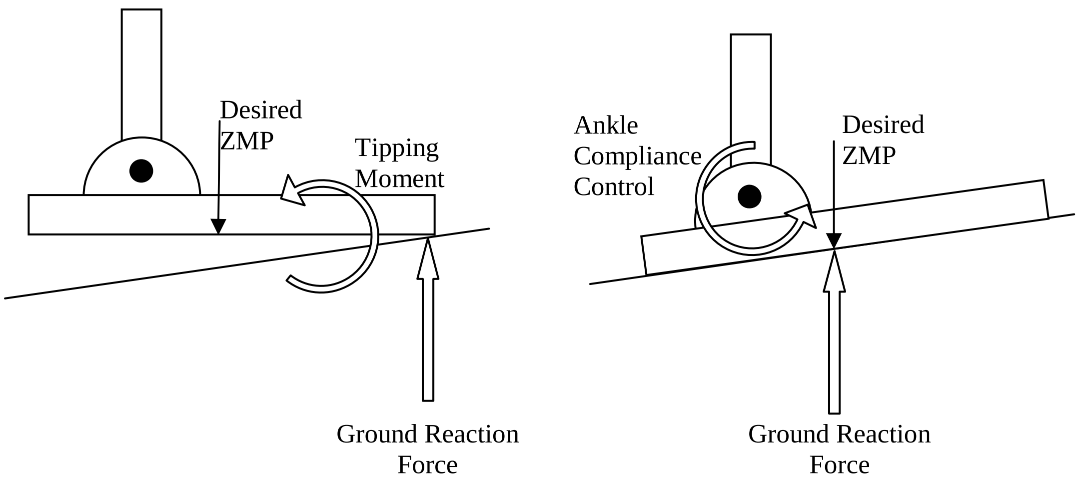

Figure 7 Ankle Compliance control executed while walking on an inclined slope

The *Desired ZMP* is estimated by the *Dynamic Modeller* based on the *Desired Configuration* of the robot. Successful implementation of *Ankle Compliance* control will enable stable walking on inclined or undulating terrains.

Active Balance:

The previous two control loops are designed to maintain stability in a controlled environment without external disturbances acting on the robot. The *Active Balance* control loop is designed to reject sudden and unexpected disturbances. This loop seeks to maintain torso dynamics, both position and velocity as defined by the *Kinematic Modeller*. External disturbances experienced anywhere on the robot will ultimately be manifested in unwanted motion in the torso. Using the *Desired Configuration*, the *Kinematic Modeller* derives the desired torso motion and it is the error between this desired motion and the motion sensed by the IMU that drives the control loop. A sudden push to the chest in the sagittal plane will move the *Ground Reaction Force* backwards. Consequently, the *Active Balance* control loop will shift the *Desired ZMP* in the same direction. Realisation of this new ZMP can be achieved by accelerating the torso forward. Acceleration of the swing leg, both arms and even the head can contribute to the ZMP. The resulting motion directly opposes the external disturbance.

Support Polygon Control:

As long as the desired ZMP stays within the support polygon, the robot will be able to maintain stability without the need to change the support polygon. Should the desired ZMP falls outside the current support polygon, the robot must change the output of the gait generator to realise a suitable support polygon.

In Figure 8, the robot is standing still with both feet together and an external force is applied to the torso in a backwards direction. The *Active Balance* component drives the ZMP backwards by accelerating the torso forwards against the disturbance. Should the disturbance be greater than the *Active Balance* can reject, the ZMP will fall outside a suitable stability margin. A new support polygon is calculated and the robot takes a step backwards to realise this configuration. The S*upport Polygon Control* loop does not directly modulate the desired configuration, as the realisation of a new support polygon requires a set sequence of movements.

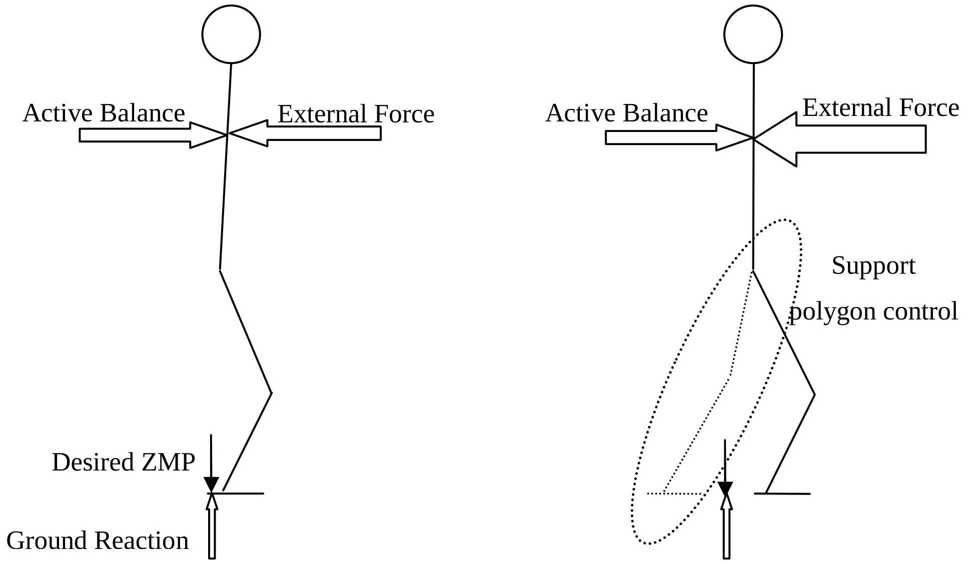

Figure 8 Support Polygon Control. If the desired ZMP falls outside the current support polygon, the robot configuration is changed to effect a new support polygon.

5.2 Tuning the Controllers:

Classical control techniques require accurate system information to be effective. The dynamics of the system must be characterised either through measurement or analytically derived. The loads that will be experienced by the system must also be able to be characterised. The strength of classical control techniques are often based on the accuracy of this system model. If the system can be precisely modelled, classical control is relatively straightforward to implement. Techniques such as sliding mode control and gain scheduling can be employed when the expected loads vary in a predictable fashion. Control parameters are closely dependant on the system, and are often hand tuned or calculated with a set of heuristically derived rules.

Classical control's major failings occur when the system model is inaccurate or has been changed. A humanoid robot with many degrees of freedom poses a difficult system to model with multi-link kinematic chains (single support phase) and closed kinematic loops (double support phase). Disturbances measured at one location are reflected throughout the robot. Change in the system model can occur with the simple addition of more batteries. For these reasons the use of classical control is avoided.

5.3 Cerebellum Models:

The cerebellum has long thought to be the main component of motor skills learning in humans. Brindley [27] put forward the concept that the higher level motion decisions are performed by the cerebral cortex and it is the cerebellum that is primarily employed to execute these motions. One model suggested implies the cerebellum acts as a reflexive action, modulation the sequence of commands generated by the cerebral cortex. Collins et al [28] proposed a cerebellum based method that counters the effect of sensory delay in the feedback path. The adaptive nature of these models enables a complex system such as a humanoid to realise a solution without the need to hand tune the control parameters. High generalisation also allows an appropriate response to be generated, even if the disturbance experienced has not been previously seen. Cerebellum models that act as predictive modulators have found success in mobile robotics [28] and as such investigations into their suitability in the control loops proposed are continuing.

Adaptive Control Loops:

Figure 9 outlines the generic block diagram for the first three control loops proposed. The cerebellum module is at the heart of the system, and generates a signal that modulates the desired configuration as supplied by the gait generator. The error between the Actual control parameter and the Desired control parameter drives the learning process. The Actual Control Parameter and the *Gait Phase* serve as inputs to the system. In the case of *Joint Compliance* control, the *Desired Joint Configuration* is taken after both the *Active Balance* and the *Ankle Compliance* control loops have modulated the signal.

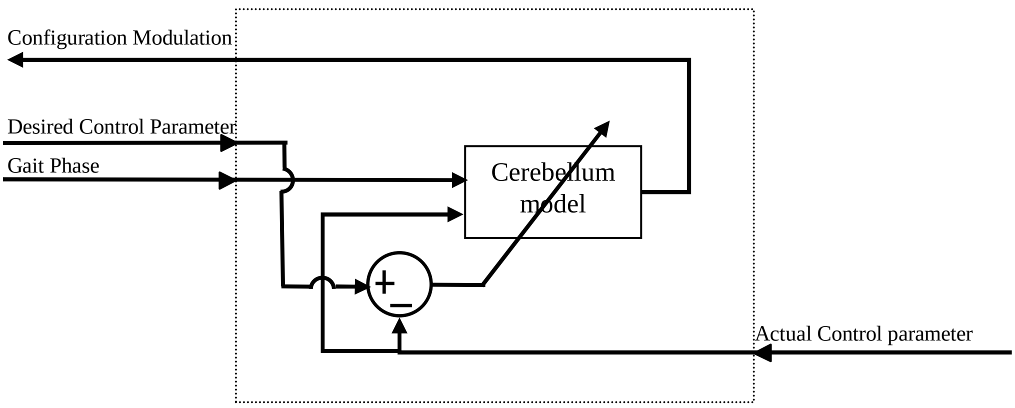

Figure 9 Adaptive Cerebellum based controller

To obtain a *Desired ZMP* for the *Ankle Compliance* control requires the use of a *Dynamic Modeller*. Similarly, the torso inclination information is provided to the *Active Balance* control by the *Kinematic Modeller*. These processes use the current desired configuration of the robot, and estimate the position of the ZMP and the torso inclination respectively. This implies that both modellers have some prior knowledge of the robots dynamics.

It is suggested that given a reasonably accurate model of the robot, the high generalisation of the adaptive control loop will be able to cope with minor variations between the robot model and the robot itself. It may also be possible to include an adaptive component to each of these modellers so that the robot dynamics can be learnt.

While the concept of support polygon control has been suggested, it's method of implementation still requires investigation. The inputs driving the loop include the gait phase and the desired ZMP, but it is unsure if other information present in the system, such as torso inclination, can be of use to the control loop. When the support polygon control is activated, a new set of gaits must be generated to realise the resulting change of support.

5.4 Research Plan

Literature Review:

A detailed review of current humanoid stability techniques and cerebellum models is necessary.

Robot Platform:

Research into walking gaits requires the use of a humanoid robot. This thesis will focus on applying techniques and obtaining results from a real robot as opposed to a simulation.

Simulator:

The use of a simulator as a development tool is crucial. Using a simulator, it is possible to develop walking gaits rapidly with no need to set up the real hardware. Hardware needs maintenance, and due to the unstable nature of bipedal locomotion possible falls result in significant equipment downtime for repairs. Development using a simulator can be done on any computer and allows untested gaits to be performed without the fear of damage to the robot.

Implementation of open loop walking:

Open loop walking will be implemented to test the robot platform for ‘proof of concept’. An open loop walk which is only marginally stable will indicate that robust and stable walking with an appropriate closed loop control system is feasible.

Controlled walking on a flat surface:

The successful implementation of the adaptive joint compensation control loop will result in stable walking on a flat surface. Essentially, this is accurately realising the joint motions as specified by the gait generator..

Controlled walking on inclined surfaces:

Once the robot can accurately follow the generated gaits, Ankle Compliance control will be introduced. Success of this stage of the research will be evident in the robust walking along surfaces inclined about the frontal and sagittal plane.

Controlled Walking in the presence of external disturbances:

Minor disturbances, such as incidental contact with humans, will be rejected by the Active balance loop.

Preservation of stability:

Should work will integrate the polygon support control with the above system. Major disturbances to the robot will result in a change of support polygon to ensure continuing stability.

6 Work completed

6.1 Platform

The design of a humanoid robot at the University of Queensland began in March 2000 [29]. In June 2001 the mechanical and structure was realised, the electronics installed and it's first tentative steps taken. The robot, dubbed GuRoo, consists of 23 degrees of freedom, arranged in an anthropomorphic configuration as can bee seen in Figure 10.

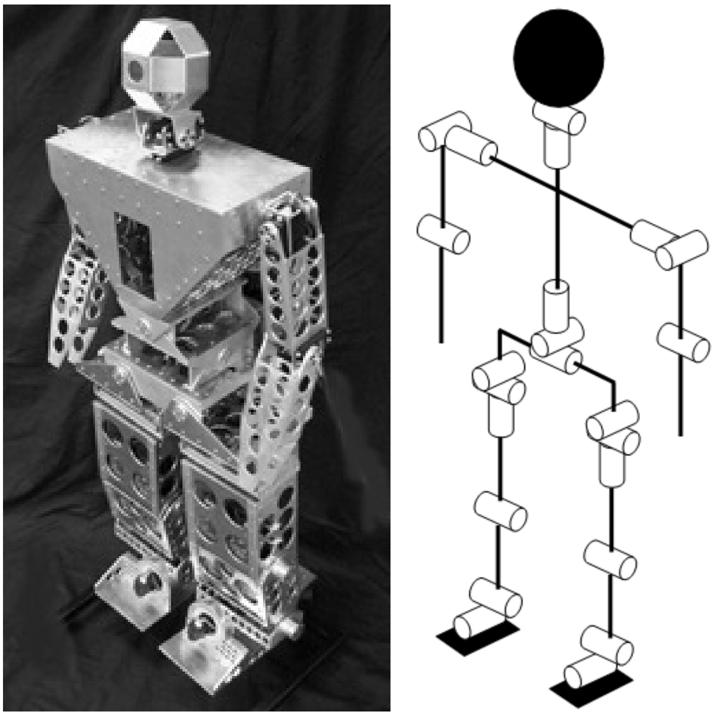

Figure 10 The GuRoo robot and the location and axis of actuation for each degree of freedom.

In choosing type and location for each actuator, a balance of form, function and cost was necessary. The chosen electro-mechanical system consists of 8 low powered RC servo motors, responsible for actuating the arms and head, and 15 high powered brushed DC servo motors to actuate the spine and lower legs.

The electronics consists of 5 identical motor control boards, one servo motor board and one communications board. Each DC motor board is responsible for the local control of three brushed DC motors. High level velocity commands are sent from a PC via a serial link to the communications board, which in turn distributes the commands over a Controller Area Network (CAN).

Currently there are no global sensors, although provisions exist on each control board to accommodate further sensors such as Inertial Measurement Units (IMU) and foot pressure distribution sensors.

6.2 Simulator

A high fidelity dynamic simulator has be built, based on the Dynamechs package by McMillian[5]. The Denavit-Hartenburg parameters of the GuRoo are modelled, along with the geometry and mass distribution of each link. The motor characteristics of the high powered DC motors are also modelled, including stiction, armature resistance and damping co-efficient. Characteristics of the terrain are controllable, from the geometry of the ground to the co-efficient of friction between the foot and contact surface. Figure 11 shows a typical graphical display of the robot.

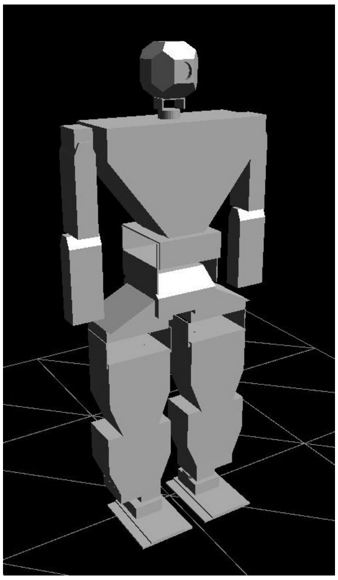

Figure 11 Typical graphical display from the Dynamechs package

The simulator has been written to accurately reflect the robot. The control loop on each board is simulated along with the CAN network. The simulator environment has been set up to enable the high level walking commands to interface with both the low level dynamic simulation or the actual robot.

The results obtained from the simulator accurately reflect the results gathered from the real robot. This establishes a high confidence that gaits generated in simulation can be easily transferred to the real robot.

6.3 Gait Generation

Currently two different approaches to gait generation have been applied. The first method centres on the concept that the robot can be thought of as an inverted pendulum in the frontal plane. Side–to–side swaying motions are generated and hand tuned in an attempt to match the natural frequency of the robot. At the extreme point at both ends of the swaying motion, the robot would lift and lower its legs, in a fashion similar to marching on the spot. Twist introduced into each yaw axis actuators propelled the robot forward.

The second gait generated comprises a ZMP stable gait obtained by linear interpolation of a series of ZMP stable key frames. These key frames themselves were generated using a genetic algorithm with a fitness function proportional to the deviation of the measured ZMP path from the desired ZMP path. The simulator model was reduced to a simplified 10 degree of freedom biped to reduce computation time. On a Pentium 4, 1.8GHz machine, a stable gait was realised in 3 minutes.

6.4 Results

The first walk generated was primarily a ‘proof of concept’ experiment, providing confirmation that the robot hardware was capable of meeting the mechanical and electro-mechanical requirements of walking. The walk was heavily tuned by hand and as such was quite fragile, prone to failure with only the smallest disturbances. The robot lacks global feedback and as such was totally dependant on human intuition to generate a viable walking gait.

The second gait was applied to the robot with considerable success. No tuning of any parameters was required, with the robot able to transition smoothly between key frames. The walking was marginally stable, with favourable environmental conditions resulting in unsupported open loop walking. These results demonstrated the benefit of the simulator, with all gait generation tested in simulation before implementation on the real robot.

6.5 Current Control

At present, control loops around each joint motor have been developed and verified. A Proportional-Integral law applied to the velocity commands is currently used with the PI constants tuned by hand to give the best performance while the leg is in a supporting role. When the leg is in the swing phase the load experienced by each actuator in that leg is considerably smaller than during the support phase. The high gains relative to the small load results in noticeable oscillation of the joint.

7 Work remaining:

7.1 Robot Platform:

The mechanical construction of the robot is complete and the GuRoo possesses enough electronics to servo the joints into any mechanically realisable configuration. An encoder on each motor provides positional feedback. This, however, is not sufficient to enable robust walking. The robot needs global information to measure its interaction with the external environment.

Global Sensing

An Inertial Measurement Unit (IMU) has been made available by CSIRO and needs to be mounted and interfaced to the robot. This sensor is capable of measuring acceleration and angular rate along 3 axes.

Sensing the distribution of force along the soles of each foot can be achieved with Force Sensitive Resistors (FSR). The current design of the feet does not include FSR's, and will need to be redesigned. The design of the foot is crucial as it serves as the contact with the environment during walking. Appropriate FSR's from Tekscan capable of measuring up to 45kg of force, have been sourced.

7.2 Simulator

The simulator needs to be updated to reflect the addition of IMU and the FSR's. Global data such as accelerations and force distribution needs to be extracted from the dynamic simulation. Virtual sensors which take this raw data and pass it to the main controller in the same form as the real sensors must also be coded. The simulator is to be used as an aid to the research, with simulator results not a valid substitute for real walking data.

7.3 Controlled walking on a flat surface:

Determination of the cerebellum model to be used in all three stability loops is necessary. Implementation of the Joint Compensation control loop will allow the robot to walk on a flat surface.

7.4 Controlled walking on inclined surfaces:

Implementation of the Ankle Compliance control loop will allow the robot to walk on inclined surfaces.

7.5 Controlled Walking in the presence of external disturbances:

Implementation of the Active Balance component will allow the robot to continue to walk stably and robustly in the presence of minor disturbances. Disturbances which result in the ZMP staying within a pre-defined stability margin will be rejected.

7.6 Preservation of stability:

The detailed structure of the Support Polygon Control needs to be formulated. Appropriate algorithms to calculate the desired sequence of movements necessary to realise a new support polygon are required. Once determined, the complete control strategy is to be implemented on the robot and evaluated.

7.7 Resources Required

The following resources are required for the completion of this thesis:

- Humanoid Platform
- Global Sensors
- Computer suitable to run the simulator

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