A survey on dynamic locomotion control strategies for legged vehicles

by

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Abstract: This technical report which has been performed at the Mechatronic department in the Royal Institute of Technology, it is a part of a larger program which goal is to investigate and build a autonomous mobile robots for outdoor terrain. The program is sponsored by the Foundation for Strategic Research (SSF), under the supervision of the Centre for Autonomous Systems, CAS. The report is divided in two main parts. The first part is an introduction to different, but general approaches for dynamic gait, and walking control of legged robots and how they are described mathematically. The second part is an overview of some specific research groups which are working with dynamic locomotion of legged robots.

1.0 Introduction

This survey makes no attempt to cover all research on the control systems of legged walking vehicles, mainly because of the vast material available. The aim has been to concentrate on two and four legged vehicles, which have at least one phase in the locomotion cycle where at the most two legs are used for ground support, i.e. there exists a statically unstable phase in the gait. Another limitation in the investigated material is that only groups that actually have implemented a control system and performed experiments on a robot are described. Further only groups using traditional, but sometimes modern control theory are selected. Neural network controllers, Fuzzy logic, genetic programming etc. are left to those with more knowledge about these topics, than the author of this survey.

The difficult question of how many legs a walking vehicle should have to locomote in difficult terrain can be discussed and debated a lot, but is not done here. Within the Centre for Autonomous Systems, CAS it has been decided that four legs is optimal for a walking vehicle, optimal in a sense that it is the least complex mechanical design that allows for static stability. The survey therefore concentrates on quadruped vehicles, but because the dynamic control of the vehicle is the main focus of the survey material on biped control systems is also included. Some of the problems in quadruped dynamic walking are very much the same as those for bipeds. Smooth control of the vehicle walking on an unknown terrain is such a topic, the impact forces from the interaction with the environment must be controlled so that an active suspension of the vehicle is achived.

Methodology and general design approach

Pratt (1995) makes a list of actual problems with dynamic control of legged vehicles, they are:

- Nonlinear and operate throughout the range of their state space
- Act in a gravity field
- Interact with a semi-structured, complex environment
- Are Multi Input, Multi Output (MIMO)
- Exhibit time variant dynamics with zeroth and first order discontinuities as support modes are transitioned (e.g. single support, double support, ballistic phase, etc.)
- Require both continuous and discrete control (for step-to-step transitions)

There are two main approaches within the research on walking vehicles, which does not say that some research groups do not work with booth. One is to analyse humans and animals with respect to gaits, torques, forces and compliance and joint trajectories. The second is a more robotic inspired way, a mathematical model of a walking man made vehicle, is built. The model is analysed with respect to kinematic and dynamic properties. The purpose of the model is not so often to design a feedback control system for the complete gait, but rather the model is simulated with self designed joint trajectories. The trajectories are iteratively refined until a smooth and efficient gait is found, which conforms to the available joint torques. The designed trajectories are then implemented on an actual vehicle with local position feedback at each joint. In general it is possible to state that the Japanese research groups frequently uses the second approach and that the biologically inspired way is more frequently used by research groups in North America. This survey primarily concentrates on the robotic approach and only some of the work done with the first approach, by those who actually build robots, is summarised below.

Pandy et al. (1988) investigated a Nubian goat by measuring the ground reaction forces and joint torques for three different gaits: walking, trotting and jumping. They found that for all three gaits, *(i)* the forelimb forces and joint torques exceed those of the hind limbs. *(ii)* Both vertical and horizontal ground reaction forces increase with speed, as do the joint torques. *(iii)* The energy of the for and hind hip is primarily used to locomote the animal, while the fore and hind knee is used to damp the motion at touch-down.

How the leg stiffness, or its inverse, the compliance is used by animals for energy storage is investigated by Alexander (1990), McMahon (1985) and Nanua (1995). They try to find optimal gaits for minimum energy consumption at varying speeds. A high energy efficiency is of course very important for legged locomotion, but is within CAS at this moment of secondarily importance.

Mathematical models of walking vehicles

Mathematic modelling of the non-linear dynamics of the closed kinematic chains of a walking vehicle should be done as correctly as possible. The control design can then be tested on the model using simulation. It is often better to test a new controller on a simulated robot to avoid a lot of unrelated problems that always will exist with the real robot. Besides the complex model most control system designers use a simplified model for design and analysis of the controller. The simplified model is also sometimes used in for feed-forward generation of reference signals by a high level controller. The reference signals are then fed to local feedback loops at the joint level. An important topic is thus what the simplified model should look like. Different levels of simplification are used. First one would linearize the equations around some operating point. Depending on how many different leg support patterns there are in a gait there would also have to be a set of linearized models, so that each support pattern has its own model. Even so the equations are of relatively high order and are still difficult to understand for the control system designer. Therefore the order of the model is often reduced by trying to find dominant modes of the model, and reducing the model to these modes. This can be difficult without modification of the vehicles parameters or actual behaviour. If the dynamic influence of the transfer legs, and the mass of the supporting legs are neglected, then a model of second order in the plane with the dynamics of an inverted pendulum can be derived. This is the most frequently used model for the control of dynamic gait.

Another model frequently used is a model which consists of a rigid body with springs and dampers as legs with only one joint at the hip. Nanua and Waldron (1994) and Alexander (1990) uses such a model. More examples of simplified models will be given in the following sections.

In high accuracy industrial robotics, high order models are sometimes used to calculate the inverse dynamics to linearize the robot. The reason that it is possible to control a walking vehicle by using a relatively simple model for reference signals and feedback is that the performance of the robot is not measured in position accuracy. Pratt (1995) lists the following performance measurements.

- Biological similarity
- Efficiency, i.e. Distance travel per unit energy input
- Locomotion smoothness
- Top speed
- Robustness to rough terrain

Definition of dynamic and static gaits

An important characteristic of a gait is whether it is static or dynamic. There are different definitions of static and dynamic gaits, one definition is:

- **static walk**: the center of gravity is projected inside the polygon formed by the supporting legs.
- **dynamic walk:** the centre of gravity is not necessarily projected within the polygon formed by the supporting legs. However, dynamic balance is to be maintained.

Another definition that includes walking speed is by Hirose (1993). ‘Under static walk, the static stability will be maintained, and planned walking will be continued even when walking speed is reduced. Under dynamic walk, the robot will begin to fall and will be unable to walk as planned as the walking speed is reduced to a level such that the dynamic effect of walking can no longer be expected. “

The first dynamic walk definition implies that there is at least one support phase in the locomotion cycle which uses none, one or two supporting legs, with the rest of the legs translating without ground contact. These supporting legs have to transfer the Centre of Gravity, CG from a point situated on one side of the supporting legs to the other side in the direction of walking. If the kinetic energy of the CG becomes to small, with decreasing speed, it will no longer move to the other side of the supporting legs in a controlled way. The robot will lose its balance and start falling in an uncontrolled manner. In this dynamic free falling phase the CG is often modelled as an inverted pendulum. When there is only one supporting leg the rotational point for the CG of the inverted pendulum is the contact point of the leg with the ground. With two supporting legs the CG will rotate around the line connecting the contact points of the respective legs with ground support.

Another way of defining dynamic walk is by Adachi et.al. (1993) who provided a more complete definition and also a description of many different possible gaits. If three assumptions are imposed on the gait .

1. Each leg must have identical stroke.
2. Each leg have the same duty factor.
3. The velocity of the CG is constant.

The duty factor, β is the time ratio between support period and locomotion cycle time or gait period *T*, of a leg, i.e. $\beta = 0.75$ means that a leg has ground contact 75% of the gaits time period and is in the air 25% of the period. If a quadruped vehicle is considered and only gaits with symmetry between the two front legs and the two rear legs respectively are used, meaning that the left and right leg are half a period out of phase. Furthermore if the phase difference between two diagonal legs e.g. front right and left rear is called ϕ, then all gaits can be characterized by the two parameters β and ϕ for a quadruped vehicle. With a stride length λ m, and a gait period *T* s, the gait is completely described. Note that the same gait can be performed within a range of λ and *T*.

With $\beta \geq 0.75$ the gait is called static, by varying ϕ from 0 to 1 with β larger than 0.75, 12 different gaits can be realized. All of them have a four legged and a three legged supporting period but some of them also have a two legged supporting period and would therefore not be considered as static gaits. There are also 12 different gaits with $.5 \leq \beta < 0.75$. Also in this range there exist gaits with two, three and four legged support periods, but they all have at least one two legged support phase and are therefore dynamic gaits. Note that even a dynamic gait can thereby have static stable support phases. $\beta < 0.5$ means that a zero legged supporting period has to exist in a locomotion cycle and is not considered in the paper by Adachi.

Realizing that similar support patterns are repeated at varying duty factors it would be natural for the control system of a quadruped vehicle to be divided into several states. Each state would then control a different support period in the locomotion cycle i.e. two, three or four legged supporting periods.

A problem within the often not so biologically well educated legged vehicle research community are the names of the different gaits e.g. trot, walk, gallop, pace, rack, pronk, running etc. The same names are often used for different gaits by different groups, or one gait is called one name with one group and something else by another group. One attempt to categorize the gaits is done by Hildebrand (1965). He only considers symmetric gaits so gaits like gallop is not described. There are 44 theoretically possible support sequences for a quadruped using symmetric gait. If the duty cycle of the forefeet can be shorter than the duty cycle of the hind feet, which is often the case with horses, then there are 60 additional support sequences. From the total of 104 possible sequences about 55 are known to be used by horses, other support sequences than those used by horses are used by other quadruped animals.

An measure often used to analyse the dynamic stability is the Zero Moment Point (ZMP). Vukobratovice (1970) was the first to use the ZMP in dynamic analysis. One definition of ZMP is by Yoneda and Hirose (1995): Assuming that the CG of a vehicle is moving over a horizontal surface, that the friction between the feet/foot and the ground is high, and that the CG of the vehicle is affected by a force and a moment at a certain instance, then the ZMP is the point on the ground at which the force and the moment acting on the CG can be resisted by applying a simple force without a moment.

$$x_{ZMP} = \frac{\Sigma m_i(\ddot{z}_i + g)x_i - \Sigma m_i \ddot{x}_i z_i}{\Sigma m_i(\ddot{z}_i + g)} \qquad (1)$$

$$y_{ZMP} = \frac{\Sigma m_i(\ddot{z}_i + g)y_i - \Sigma m_i \ddot{y}_i z_i}{\Sigma m_i(\ddot{z}_i + g)} \qquad (2)$$

where x_{ZMP} and y_{ZMP} are the coordinates for the ZMP and m_i the mass and x_i, y_i, and z_i the position of link i. For the simplified one mass inverted pendulum model equation 1 and 2 are,

$$x_{ZMP} = \frac{x_{cg} - \ddot{x}_{cg} z_{cg}}{\ddot{z}_{zg} + g} \qquad (3)$$

$$y_{ZMP} = \frac{y_{cg} - \ddot{y}_{cg} z_{cg}}{\ddot{z}_{zg} + g}. \qquad (4)$$

Impact control

Besides static and dynamic control of the walking vehicle there is a third major challenge for a successful implementation of a control system on the robot. It has to control the interaction between the robot and the environment in which the robot is performing. The robot has to make smooth and in a force sense, controlled touchdowns with its feet on the ground. Otherwise the impact forces will destabilize any well performing controller. There are a lot of research on impact control in the industrial robotics field, where manipulators at often high speeds have to pick up objects with controlled grasping and impact forces.

A smooth locomotion do not only depend on a good impact controller. Even with perfect impact control the motion of the vehicle can be jerky. As a foot is placed and the other is lifted the vertical velocity component changes discontinuously, there can be an infinite or at least very high vertical jerk component.

Important problems to solve for good interaction with the environment are.

- Timing of the touchdown
- Ground velocity matching
- Vertical acceleration control at change of support.
- Posture control of the manipulator (feet) with the slope.
- Force regulation in the vertical direction, to handle payload and inertial forces.
- Force regulation in the horizontal direction, utilizing maximum friction between foot and ground.

There is certainly a trade-off to achieve good environment control between a complex mechanical foot including the necessarily sensors and actuators, and a passively damped light weight foot. The dynamic interactions between DOF in the robot are lower with light legs. As will be described below many research groups assumes massless legs in their control design. Another advantage is that higher walking speeds are possible with lighter legs, assuming the same hip and knee actuators. The actuators have to give enough torque to carry the weight of the walking vehicle and the inertial forces. With high gear ratios the actuators maximum speed will be limited, and will thereby set a limit on the gait period. In e.g. a static walk with $\beta \geq 0.75$ the transfer leg has to move at three times higher speed than the supporting legs. High static walking velocities would therefore need an actuator with sufficient high torques and high no load velocities. With a heavy leg this is of course even more difficult to achieve.

Even though a light weight leg is important there are some robots with actuated feet. Mainly two different concepts have been investigated, either to try and match the vertical and horizontal velocity of the foot at touchdown with the walking speed, or to utilize a well damped impact controller.

In the next chapters the research of some academic groups is described in more detail.

2.0 Research overview

2.1 Gifu University

At the faculty of engineering at Gifu University legged locomotion has been a research topic for over 20 years. In 1991 a biped robot called BLR-G2 walked dynamically with a walking speed of 0.18 m/s with a stride-length of 0.25 m. Recently both hexapod and quadruped robots have been built. The quadruped robot COLT-3 trots with a speed of 0.21 m/s and SCAMPER realizes a simplified gallop at 0.85 m/s. First the biped research is described and then the quadruped robot which has a compliance control system.

Biped walking

The walking experiments were performed with the biped BLR-G2 which is 0.97 m in height and weighs 25 kg. It has articulated joints at the knees hips and ankles. Each foot also has a DOF in the roll direction to control the lateral motion of the robot.

The control system is a hierachical controller, with low level local feedback at each joint and a higher level trajectory generator. The higher level controller is based on a reduced second order inverted pendulum type model for the single leg support phase. The reduced order model is derived by applying high gain feedback at each joint and looking at the root locus for the biped. Furusho and Masubuchi (1987) showed that all the eigenvalues move to the far left hand side in the complex plane except for two eigenvalues which stay at ±3.48. The influence of the transfer leg dynamics and the supporting leg dynamics on the reduced order model is,

$$\ddot{\theta}_{CG} - 3.48^2\theta_{CG} = -k_1\theta^T + k_2\dot{\theta}^T \tag{5}$$

were θ_{CG} is the angle between the vertical line at the contact point and the centre of gravity, θ a vector with the joint angles and k_1 and k_2 vectors with derived numerical values. It is seen by the magnitude of the coefficients in k_1 and k_2 that the biped locomotion system is affected considerably by the other joints. The most common used inverted pendulum model is the left hand side of equation 5 with a torque input on the right hand side. By using equation 5 it is possible to callculate the error from the simple version of the inverted pendulum model.

The actuated ankle is mainly used for four things. In the single support phase the CG angular momentum is controlled through ankle torque control, to follow a reference trajectory of the CG angular momentum, Sano and Furusho (1991). Just before the hind foot lifts up from the ground the ankle is position controlled to lift the heel so that the foot is up on its toes. The robot thereby rotates around the toes which makes the hind leg longer and decreases the vertical acceleration at touchdown of the front leg, Furusho and Sano (1985). The landing foot is force controlled by the ankle which is necessarily to avoid slippage which otherwise would occur with the uncertainty of a realistic walking surface.

In three dimensional walking the lateral motion is controlled by the roll DOF in the foot. A simple feedback based on a one-link model is designed using optimal control. The motion in the lateral plane is simply a repetition of tilting to place the CG above respective supporting leg.

The sensors of the biped are described in Furusho and Sano (1990). The reaction forces from the ground are measured by strain gauge pressure sensors. The ankle torque sensor is built in at the pully between the ankle motor, which is located in the hip, and the ankle, i.e. at the knee. The posture and speed of the robot body is detected by a combination of sensors. An angular rate gyro and inclinometers measures the angles and angular velocities in the roll and pitch axis. An external ultrasonic speed sensor measured the body velocity by the doppler effect An accelerometer is used to extrapolate the velocity signal from the ultrasonic sensor which only is updated every 20 ms. Finally the motor angles are measured by encoders and the joint angles by potentiometers which then gives the compliance between actuator and manipulator, i.e. between hip and ankle.

Quadruped

A 8 DOF quadruped robot with articulated joints at the knees and hips is used for trotting in the sagital plane. A trotting speed of 0.21 m/s with a stride period of 0.7 s is performed by the robot called COLT-3. It weighs 45 kg and has a leg length of 0.52 m. It is further described in Sano, Furusho and Hasaguchi (1993).

The duty factor and phase in the trot gait is such that there are four three legged support states and two, two legged support states in each locomotion cycle. The authors point out the importance of not using position feedback with high gains at those joints that are on the ground or are just about to touchdown or leave the ground. They propose and utilizes a compliance control at those joints. Desired joint torques are calculated by the high level controller so that the leg behaves as a spring and damper system with respect to the body. Very much like the virtual control concept at MIT (section 1.6). First the reference forces $F(F_x, F_y)$ in vertical and horizontal directions are calculated as

$$F_{ref} = K_s(x - x_{ref}) + K_v(\dot{x} - \dot{x}_{ref}) \qquad (6)$$

were x is the relative position in two DOF, P(x_1, x_2) between the point on the body were the leg is connected by the hip joint and the point on the ground were the foot is, see figure 1 . K_v and K_s are predetermined spring and damping ratios of the leg body system. The forces are then transformed into joint torques, τ by

$$\tau_{ref} = J^T F_{ref} \qquad (7)$$

were J is the Jacobian. The local torque controller has torque feedback with a feed-forward compensation of the back EMF of the DC-motor. Without including the gear ratio the control law is

$$u = K_D(K_T(\tau_{ref} - \tau) + (\dot{\theta}_{ref} - \dot{\theta})) + K_F\tau_{ref} + K_{EMK}\dot{\theta}_{ref} \qquad (8)$$

where K_T is the torque feedback, K_D a differential feedback gain, K_F a torque feed forward gain and K_{EMK} the back EMF. The torques are measured as described above in the biped part.

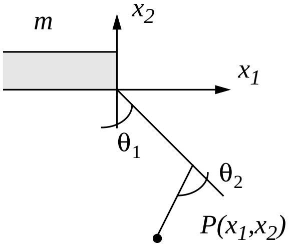

FIGURE 1. 2-link model, from Sano et al. (1993).

The high level controller is further divided into separate states depending on, which phase the vehicle is, i.e., three or two legged support state, if a foot is just going to land or leave the ground. For a complete locomotion cycle the reference trajectories x and $\dot{x}$ are calculated in advance, depending on the state of the locomotion cycle the low level controller will either be in the position mode control or in compliance control mode but still using the same reference signals x and $\dot{x}$. The compliance mode is actually used just before lift of a supporting leg and just before and during touchdown of a transfer leg. Further the trajectories are generated so that just before touchdown for each leg the vertical velocity is set very low or at zero and the horizontal velocity is matched to ground velocity. This action should enable a smooth landing of each leg. The stiffness in vertical direction in compliance mode is set relatively high so that the knee not will bend down too much. In the horizontal direction the stiffness is relatively low to avoid slippage on the partly unknown surface.

In a later paper by Furusho et al. (1995) a smaller and lighter quadruped vehicle is described. The weight is 20 kg and the leg length 0.35 m. The higher power to weight ratio allows the authors to investigate and implement a bounce gait of the robot. The reason to choose a bounce gait instead of gallop is according to the authors that a bounce gait has much simpler dynamics because there is more symmetry in the gait compared with gallop.In the proposed bounce gait the left and right fore legs and the left and right rear legs move with the same phase. A running cycle consists of two, two legged support phases, one four legged support phase and one flying phase.

The reference trajectories are generated in advance through simulation of the robot. The high level controller switches between position, velocity and a free rotation mode, (force control with zero force input) depending of the state of the robot. The robot has a bounce period of about 0.6 s with a speed around 0.85 m/s.

2.2 Tokyo Institute of Technology

The department of Mechano-Aerospace Engineering at Tokyo Institute of Technology is probably one of the most successful research centres for walking robots. Several four and six legged robots have been built at the department. There is an emphasis towards practical usage of walking robots and many possible applications where it could be an advantage with legged vehicles are shown, Hirose and Yoneda (1993). The authors stress maybe more than other research groups the importance of smooth high speed walk without jerkiness to be able to carry a payload.

One of the latest quadruped robots TITAN VI and its control system will be described below. The reason for choosing TITAN VI is that most of the dynamic walking experiments has been performed with TITAN VI. It has reached a maximum speed of 1 m/s with a trot gait on a flat surface. On a terrain which the authors describe as 105 mm up and down rough terrain it walks with 0.125 m/s.

In figure 2 the leg design of TITAN VI is shown. It consists of an Evan mechanism, Hirose et al. (1995) and a pantograph mechanism giving each leg three DOF with a cylindrical coordinate motion of the foot. The first two DOF, radius and rotational motion are in the horizontal plane and the third is a linear vertical motion of the foot. Besides the three DOF in each leg TITAN VI has a linear DOF at the vertical axis in the centre of the body. The height is about one meter and the total weight is 195 kg. 120 W DC motors are used to drive the joints. To increase the speed of the transfer leg motion one of the DOF uses double motors. One motor with high reduction ratio (28.85) is used during the support period and a second motor with low reduction ratio (2) is used during the transfer leg period of the locomotion cycle. The motors connect to a ball screw through an electro-magnetic clutch.

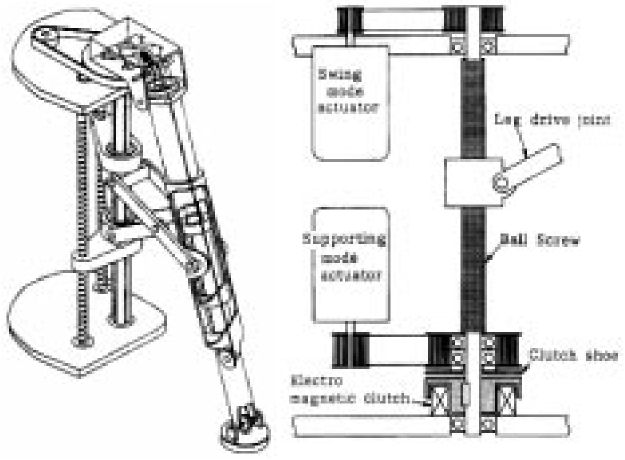

FIGURE 2. Left, the three DOF leg of TITAN VI with a cylindrical coordinate system, and to the right the dual drive mechanism controling the z-axis. Fom Hirose: http://mozu.mes.titech.ac.jp/research/walk/TVI/TVI.html

It is important to walk as smoothly as possible both with a slower static gait and with a faster dynamic gait. Also important is a smooth and continuous change of velocity when going from a static to a dynamic gait. Yoneda and Hirose (1995) call this gait transfer a 'dynamic and static fusion gait'. The gaits used are a static gait with $\beta = 0.75$and $\phi = 0.125$ and a dynamic trot gait which in a later paper is called extended trot with $\beta = 0.625$ and $\phi = 0.125$. With $0.625 < \beta < \dot{0}75$ there is a three legged support period and a two legged support period in the locomotion cycle. As β decreases from 0.75 towards 0.625 the two legged supporting period will increase continuously and the three legged supporting period decrease correspondingly. The vehicle controller is thereby able to change the walking speed in a continuos manner.

In Yoneda et al. (1996) they change the strategy and use $\phi = 0$ and call it an intermittent trot with $0.5 < \beta < 0.75$. The intermittent trot does not have a three legged support period, instead it has two and four legged support periods. With $\beta = 0.75$ and $\phi = 0$ there is still no three legged support only two and four legged support, which would not qualify for a static gait. How the authors solve this problem is not explained in the paper.

The reason of changing the strategy is because with $\phi > 0$ they have problems with dynamic influence from the transferring legs in their walking control, which on a smooth surface only is based on feed forward control i.e. without feedback, except for the local joint feedback. The transfer legs produces unwanted roll and pitch moments on the body. In a diagram they show that with $\phi = 0$ the pitch and roll moments from the transfer legs are about a factor five smaller than with $\phi > 0$. Their explanation is 'when the legs transfer together for any duty factor, β their dynamic effects almost cancel each other'.

Before the controller design is described a dynamic effect must be explained, which influences their design. The two legs supporting the vehicle in a trot is always a diagonal pair, and the line that connects the supporting points is called the diagonal support line. To avoid slippage and the use of high torques a control strategy would be to keep the ZMP on the diagonal support line. Further the most natural approach would be to keep the ZMP at the point were the diagonal support line and the linear trajectory drawn as a straight line in the direction of motion of the CG intersects, see figure 3 . To achieve this the controller must accelerate the CG of the vehicle, when the CG is in-front of the diagonal support line and when the CG is behind the diagonal support line, the controller must decelerate the CG, so that there will be a step in acceleration of the CG as the support legs change place. The acceleration step is something unwanted because it will not give a smooth ride of the vehicle. If the quadruped robot's CG is controlled to move not only straight forward but also sideways, and this sideway motion of the CG is on the diagonal support line then the 'distance' to the next diagonal support line is short and the acceleration step will decrease, or even better it will only be discontinuous. In figure 3 a CG trajectory with a velocity part perpendicular to the heading direction of the vehicle, called sway, is shown together with the resulting acceleration of the CG. The control strategy is thereby to find an optimal trajectory for the CG for all used duty factors and all vehicle velocities.

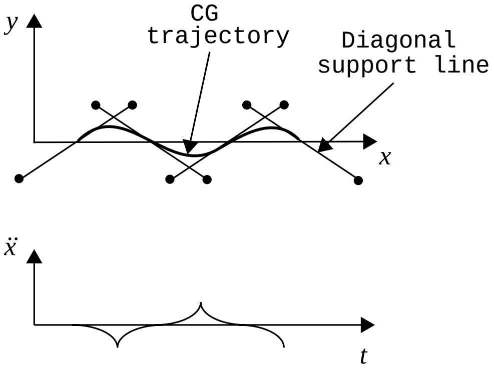

FIGURE 3. Proposed path for the CG incorporating sway to keep the ZMP near diagonal support line and thereby decrease the acceleration step of the CG as shown in the lower graph, from Yoneda and Hirose (1995).

The feed forward control sequence, which is calculated before each step is:

1. Landing points for the new transfer legs are calculated from the desired vehicle velocities $\dot{x}_{ref}(t)$ and $\dot{\theta}_{ref}(t)$, and from any, in advance, known obstacles.
2. Smooth trajectories $q(t)$, for the individual transfer leg actuators, are generated in order to bring the legs from the actual to the in step 1 calculated landing position.
3. A trajectory for the CG, $x_g(t)$ and $y_g(t)$, were $y_g(t)$ is called sway, using the ZMP trajectory $x_z(t)$ and $y_z(t)$ and the equation of the diagonal support line of the vehicle is generated
4. Body rotation velocity $\dot{\theta}_g(t)$ is set constant and to fulfil 1.
5. Body motion is translated into leg joint coordinates.

2.3 Mechanical Engineering Laboratory Tskuba

At the robot department at MEL, biped research has been ongoing since the end of the 80's. Kajita et al. (1992) developed first a 4 DOF biped robot and later a six DOF robot with actuated ankles, knees and hips, Kajita and Tani (Feb. 1996). The biped robot is thereby restricted for a 2 DOF walk in the sagital plane. The robot is approximately 40 cm high and weighs 4.7 kg. It can walk with a varying step length of 10-16 cm with an approximate step time of 1 s, e.g. it can walk with an adaptive gait. It can walk up and down on steps with a step height of 3.8 cm without prior knowledge of the ground surface. A sonar is used to get information of the walking surface. It measures the height of the floor 30 cm ahead of the hip joint, Kajita and Tani (April 1996).

FIGURE 4. Meltran II, a six DOF biped with an ultrasonic sensor to measure the height of the floor 30 cm ahead of the hip joint. From Kajita: http://robby.caltech.edu/~kajita/biped.html

The control uses local feedback at the individual joints and is based on an inverted pendulum mode were the dynamic model assumes massless legs of the robot as shown in figure 5 .

Clearly, they use an extremely simplified model of the robots dynamics. According to the authors 47% of the total weight is in the legs of the actual robot. One of the reasons it still works is that the CG of the robot is close to the hip joint and that a constraint control of the hip joint is used.

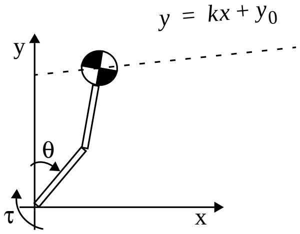

FIGURE 5. Inverted pendulum model consists of a point mass and a two link massless leg. The point mass is controlled on the constraint line $y = kx + y_0$.

The linearized equations of motions in cartesian coordinates with locked knee are

$$\begin{aligned} m\ddot{x} &= \frac{y}{r^2}\tau \qquad (9) \\ m\ddot{y} &= -\frac{x}{r^2}\tau - mg \end{aligned}$$

with *r* being the distance of the CG from the origin. If the CG is controlled at the constraint line

$$y = kx + y_0 \qquad (10)$$

then equation 9 can be modified at the x-axis to

$$\ddot{x} = \frac{g}{y_c}x + \frac{1}{my_c}\tau. \qquad (11)$$

If the knee and hip joints are used to keep a specified height above floor level, y-direction and the CG moves forward along the x-axis by actuating the ankle and using the inertial and gravitational forces, the difference in the proposed dynamic model and the motion of the real robot is quite small.

The idea is to use inverse kinematics with local feedback on the knee and hip joints and let the ankle joint follow the reference position generated by the equation $\ddot{x}_{ref} = (g/m)x_{ref}$ using a PID feedback.The constraint trajectory of the hip and knee joint is calculated from the equation $y = kx + y_0$ of the CG. The coefficients in the above equation k and y_0 are calculated from the ultrasonic sensor information of the ground height 30 cm in front of the robot and the height of the present foothold.

A foot placement algorithm was developed by Kajita and Tani (1996) which as input uses a reachable and possible foot landing position two steps ahead of the present foothold. This means that an obstacle must be recognized at least two steps ahead of the robot to be able to plan a suitable step length and height, which takes the robot safely past the obstacle.

2.4 Waseda university

At the department of mechanical engineering at Waseda university studies on biped walking began in 1969. In 1972 the first biped prototype was built, it had a static gait with a step time of 40 s and was the first computer controlled walking biped in the world. Since then, they have built many prototypes and advanced from static via quasi dynamic walking, until today where full dynamic biped walking in three DOF on an unknown surface is performed. The maximum speed is 1.28 s/step with a 0.3 m step length. Deviations in surface height of ± 16 mm and in tilt angel of ± 3° are managed by the control system, using sensor information from the foot. In figure 6 the latest version WL-12RVI is shown, the size of the robot is approximately that of a human and the weight is around 100 kg (even though they use carbon fibre reinforced plastic as construction material). The joints are all rotational and powered by hydraulic motors. The hydraulic motors are controlled by valves.

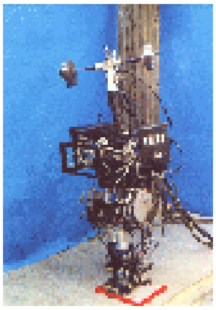

FIGURE 6. Biped robot WL-12RVI, from: http://www.shirai.info.waseda.ac.jp/humanoid/group_c/index.html

Since 1992 is the walking control group part of the larger “Waseda Humanoid Project”, they continue the development on anthropomorphic robots. The goal of the project is to: “develop a Humanoid which will comprise sensing, recognition, expression and motion sub-systems to enable robots and humans to build common mental and physical spaces cooperatively”.

The control can be separated in several parts where the lowest level is the trajectories of the lower limbs which are programmed in advance for a specific walking task e.g. only using local servos at the individual joints to track the specified trajectory.

1. Leg trajectory in the transfer phase for flat ground.
2. Ankle torque and position control in the change over phase.
3. Balancing trunk motion calculated from 1. and 2.
4. Obtain information on the landing surface and if needed recalculate 1. and 2.

Steps 1-3 are calculated before walking and step 4 during walking.

In step 1 time trajectories for the knee and hip DOF’s are calculated using the Zero Moment Points (ZMP) which are the points under the sole of the robot were the sum of gravitation and inertial forces are zero.

In step 2, the change over phase, the goal is to use the ankle to first, damp the impact forces caused by the fore foot and second to control the Centre Of Mass (CG) so that the predefined ZMP trajectory is performed, using a inverted pendulum model of the robot. Only the ankles are active during this phase. In the damping phase a torque feedback is used and in the trajectory phase position control of the ankle.

Takanishi et al. (1985) had the robot walking using only step 1 and 2. The next version included step 3, to balance the robot using an active trunk, Takanishi et al. (1988) and Takanishi et al. (1990) compensated for the dynamic disturbances in the pitch and roll axes. Because of a sideways drift of the robot, which finally made the robot fall they built a refined version, Yamaguchi et al. (1993) has also dynamic compensation in the yaw axis. ´The reason is to separate the walking and the balancing functions of the robot. An iterative algorithm is used to calculate the motion of the trunk from the periodic solutions of the ZMP.

The authors report two main causes of falling when the robot is walking on a planar surface without the special foot mechanism described in Yamaguchi et al. (1994), Yamaguchi et al. (1995) and Yamaguchi et al. (1996). The first is deviation in landing time of the transfer leg compared to the simulated robot, caused by unevenness in the planar walking surface. The second is deviation of the landing position, which with high local feedback gains in the ankle produces high impact forces on the legs making the second (already on the floor) foot slip.

In step 4. sensors in the foot mechanism sense the offset in landing position (height and gradient) compared to the in advance calculated trajectory, and recalculates in real-time the trajectories from that information. It also damps the impact at landing when the timing or position of the landing does not correspond exactly to the landing in the trajectory.

The special foot shown in figure 7 consists of two parallel duraluminium plates in the vertical direction with a shock absorbing mechanism between the plates. The shock absorbing material consists of **a)** a memory foam material which has excellent shock absorbing characteristics and **b)** polyurethane rubber on teflon resin and a silicon foam arranged in parallel to imitate the human non-linear characteristics of the ankle and foot.

FIGURE 7. Foot mechanism with shock absorbing material and sensors for landing surface detection, Yamaguchi et al. (1996).

The authors say that without the shock absorbing mechanism it is impossible to obtain information on landing position and gradient because of the structural resonance of the foot, which they now have overcome with the special foot design.

To conclude, the control of the biped is mainly done off-line and only partly on-line in real-time. First an arbitrary leg trajectory is designed using the ZMP to assure stability, then an iterative algorithm is used to calculate the three DOF motion of the trunk, which balances the robot for the desired walking pattern. Observe that the leg trajectories are not limited to a special walking pattern, e.g. changing step length, making steps up and down, choosing non vertical footholds and turning of the robot can be performed. Interesting to notice is that the amplitude of the balancing motion of the trunk decreases with higher walking velocity, which seems to be correct if one compares with human walking. In the double support phase only the ankles of the robot are active with a combination of position and torque control, were the paths are derived from simulations and experiments. The double support phase is actually divided into four subphases were different control is used in each subphase. To make the walking more robust a special foot mechanism was developed, which can adapt and damp the robot in the landing, double support phase and the leg transfer phase.

The authors do not say anything about future work but the natural task would of course be to try to do the trajectory planning on-line from the information of on-board range sensors like laser scanners or cameras.

In a late paper, Yamaguchi and Takanishi (1997), describe their newest biped, WL-13. It has completely new knee, ankle and hip joints. Firstly, they use AC motor drives, secondly these joints are driven with two motors each. One motor for the tension of the joint and the other for flexing the joint. The motors are connected in series with a special nonlinear spring mechanism between them. Thereby it is possible to control two outputs at each joint, the *position* and the *stiffness*. The stiffness is theoretically possible to change from zero to infinity. They do not describe the control strategy with their new biped in this paper, only that it will appear in a later paper.

Recently the authors have started a joint research project together with KIST (Korean Institute of Technology) which aims at developing a quadruped vehicle with a trunk called “CENTAUR”. The function of the trunk is the same as with the biped robot, to stabilize its walking on uneven surfaces and to compensate for an arbitrarily planned motion of the legs. Takanshi et al. (1995) showed from simulations that the yaw moments are very small for dynamic walking by the quadruped, consequently they only plan for a 2 DOF compensation in the pitch and roll axes.

2.5 Dep of Electrical and comp Eng Yokohama

A more traditional robot control concept is presented by the Department of Electrical and computer Engineering at Yokohama National University. They have only simulated biped robot walking, so actually they should not qualify for this report. There are mainly two reasons to write about their work, where the first is a interesting model of the contact between the foot and the ground. Secondly they use theories that are often used with robotic tool manipulations, e.g. utilizing a force controller between the tool and the environment. Another modern trend in robotics is to use a robust joint controller when workspace coordinates are transformed into joint coordinates, i.e., disturbance observers and variable structure controllers (VSC). The advantages compared with a computed torque method are a lot less of code execution and compared with simple PD controllers a much higher performance.

To use simulations in the development of mechanics and controllers of a robot is obviously in todays research. A difficult task is to choose the right level of complexity in the simulated model, because the model may not only be used for pure simulation, it can also be used to design the control system or on-line feed forward compensation. One important part of modelling walking machines is the ground contact and the impact conditions.

The most commonly used method to model the contact between the foot and the ground is to use a ground model consisting of linear or non-linear springs and dampers. This is probably sufficient when a robot with point feet is used, but with a robot with a revolute ankle and a foot were there are multiple and arbitrary point contacts as shown in figure 8 it is probably not enough.

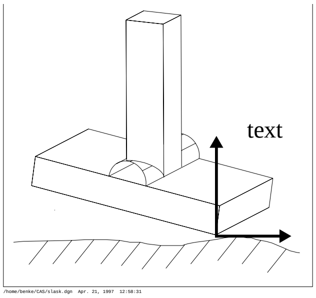

FIGURE 8. A possible scenario at touchdown of the transferring leg that has to be modelled for a correct simulation.

Another method presented by Fujimoto and Kawamura (1995) is to add three DOF of position and three DOF of rotation to the base link of the robot, i.e., the foot with ground contact. These virtual links have no mass or length and augments the dynamic model of the robot with six states, the general dynamic equation of motion of the robot is then.

$$\begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \ddot{x}_0 \\ \ddot{q} \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} \tau \\ 0 \end{bmatrix} + \begin{bmatrix} K_{r1} \\ K_{r2} \end{bmatrix} F_r + \begin{bmatrix} K_{l1} \\ K_{l1} \end{bmatrix} F_l \tag{12}$$

Where H is the mass and inertia matrices, q is the traditional robot generalized coordinates, τ the applied torques or forces, x_0 specifies the motion of the body expressed in a global coordinate system, three positions and three angles. F_l and F_r are 6x1 vectors with the external forces and torques at the centre of each foot (becomes zero when a foot is in the air). K_{*i} are the transform matrices from external forces to forces and torques at the body and b_i denotes the non-linear terms Coriolis, gravitation etc.

Typically a control system either tries to suppress the effects of F_r and F_l on the system, (robust control) or an adaptive feed-forward strategy is used to cancel out the effects of F_r and F_l.

The interesting aaspect of this work is that they try to use F_r and F_l as control inputs for controlling x_0, the pose of the body. This is done with a force reference generator and a hybrid position/force controller, see figure 9 . The reference force is calculated from the error in body pose using a linear controller restricted with a set of force constraints on the allowable friction forces and forces derived from the ZMP. The force controller uses H_∞ control, which gives the body states with respect to the position of the foot on the ground, x_r or x_l, depending on which foot that has ground contact. The transfer leg trajectory is also transformed to x_r or x_l coordinates and is position controlled. In the lowest control level x_r and x_l are transformed to joint coordinates q using inverse kinematics, which then are controlled with a robust servo controller based on a two DOF control and sliding mode control, Fujimoto and Kawamura (1995).

At the highest level a position trajectory for the transfer leg is generated with a three DOF inverted pendulum model of the robot and a foot placement based on a state feedback controller with CG position and velocity as internal states, Fujimoto and Kawamura (1996).

The first problem one sees with this concept is that an accurate force and torque measure is needed for the contact forces between the foot and the ground. The authors simplify their force generator a little so they only need the two friction forces in the plane of the foot, the vertical force and the twisting moment around the vertical axis.

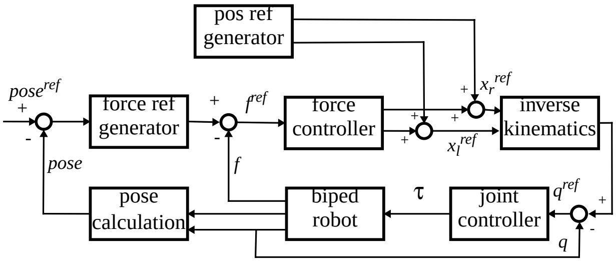

FIGURE 9. Control system.

Recently it seems that they have built, or are building a biped for experiments. So far there is nothing published about the biped and no results are available.

FIGURE 10. Biped under construction for investigation of the proposed control algorithms. From: http://www.kawalab.dnj.ynu.ac.jp/~fujimoto/biped.html

2.6 MIT Leg Laboratory

In the leg lab at the Massachusettes Institute of Technology research of legged robots have been going on since late 70’s. Raibert (1986) has built a whole series of successful running robots with one, two and four legs. They all used prismatic legs and performed hopping and running gaits. The control strategy is fairly simple and does not differ much with the number of legs. The quadruped robot runs with a “one legged hopping gait”.

In the last 10 years they have taken a new approach at MIT leaving the hopping robots with prismatic legs. Now they build robots that can both walk and run and have revolute joints in knee and hip.

They have a lot of ongoing work with different prototypes and simulated robots. There will not be a complete description of their work only on what they call virtual model control and a few words about a project where the contact between foot and ground is studied.

Virtual model control

As mentioned above Raibert (1986) was very successful using very simple controllers. The idea behind virtual control and virtual actuators by Pratt et al. (1996) is to have a set of low level tools which simplifies the design of higher level control. When the virtual model controller(s) are designed, it should be intuitive for anyone how to use them and build their own high level controllers in global coordinates and not having to think about joint space controls.

The concept is a sort of hybrid position/force control were both position and forces can be controlled between specific and in advance decided points on the robot or between a point on the robot and another point in the environment. For example if we have a complex robotic structure with many DOF but only want to control it in a couple of DOF in workspace, we have to design as many *virtual components* as DOF we want to control. How to chose the proper points on the robot that connects the virtual components are up to the designers experience. The virtual components can be designed as linear or non-linear springs and dampers with the force from the springs and dampers acting as *generalized forces* on the robot. The time trajectory of the generalized forces are reference values from the higher level control.

In figure 11 a simple 3 DOF leg is shown with a one link foot, two links for the upper and lower part of the leg and one link for the trunk. If the only goal is to apply a force f_z and a torque f_θ on the trunk using only the hip and knee actuators, we can easily derive an explicit expression for the knee and hip torques τ.

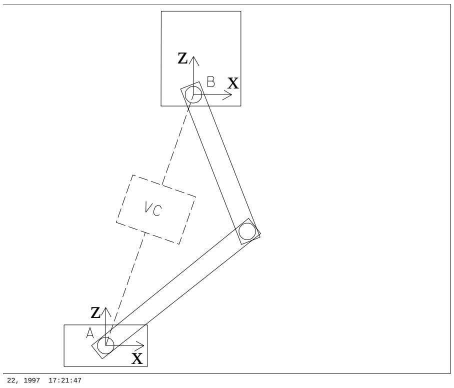

FIGURE 11. A 3 DOF leg with a foot. A virtual component, VC is designed for virtual control of the forces between coordinate system A and B.

First the kinematic map from A to B is

$$x = f(\theta) \tag{13}$$

a partial differentiation of the function *f* gives the Jacobian,

$$J = \frac{\partial f}{\partial \theta} \tag{14}$$

which relates the velocity between frames A and B,

$$\dot{x} = J\dot{\Theta} \tag{15}$$

and the force to joint torque,

$$\tau = J^T F \tag{16}$$

were $F = [f_\theta, f_z, f_x]$. By solving equation 16 for the desired forces f_z and f_θ the desired expression for the hip and knee torque is derived. Now the characteristics of the virtual component can be designed, for example by choosing f_z to be

$$f_z = (l_0 - l_c)k_f + v_c k_v \tag{17}$$

were l_o is the rest length of the virtual component, l_c the actual length, k_f the spring constant, v_c the velocity of the virtual component and k_v the damping ratio. A static force equal to the gravitational force could be added to equation 17 if the static height of the trunk is important.

This simple example is not so interesting because the relations could have been derived without any knowledge about virtual components or virtual control, the interesting part starts when the concept is applied to a complex robotic mechanism, especially when there are parallel chains in the structure such as any multi leg robot possesses.

Torres (1996) derives a virtual controller for a hexapod with six equal legs having the configuration from above. The legs are connected to a common body and a single force from a single virtual component connecting a point on the ground and the CG of the body is desired. Equation 16 is then still valid but the sizes of τ and F are now six times higher. The desired single force on the body is the sum of the individual generalized forces, the system is overdetermined and force constraints must be decided. Some of the constraints will arise due to the relative direction of the actuators, of which certain individual force directions not are available. These constraints can be determined by examining the row space of the individual Jacobians. Others will arise from constraints on the robot such as unactuated joints. The rest of the constraints can be used as design degrees of freedom, such as that two individual serial chains should produce the same force in a specific direction. The constraints can be written in a square matrix, *K* which relates the single force F_s and the individual sub-forces F_i

$$F_s = K[F_1 F_2 ..... F_n]^T \tag{18}$$

if *K* is inverted it is possible to solve for the individual sub-forces and use equation 16 to solve for the joint torques.

A method is used to help to construct the constraint matrix and to invert it. The method is based on defining a set of constants,

n	dimension of the generalized force to be applied
p	number of serial paths of the parallel virtual component
l	number of constraints in each serial path
d=n-l	number of non-constrained degrees of freedom in each serial path
r=pd-n	number of redundant serial path virtual force components, equals the number of design constraints

Pratt (1995) points out that to succeed with the proposed method it is probably important how the virtual components are chosen and what characteristics they are given. It must be better to chose them in such a way that the natural dynamics of the robot is not influenced to much. This implies that the designer needs a good knowledge of the robot dynamics and about proper walking strategies.

Transfer of support in a dynamic walking robot

A smooth transfer of support from one leg to the other is important to achieve a stable and animal like motion of the walking robot. Other advantages are that the impulsive loads are reduced, which reduces the chance of structural damage. During rough terrain locomotion, a gradually loaded foot has a better chance of recovery.

Bailey (1993) has built a robot called GeekBot especially to investigate the leg support transfer. A method called "ground speed matching" is proposed. Actuated ankles are used to servo the striking velocity to zero at touchdown. Experiments show that the impulse forces are reduced with a factor of two with the method compared to a free falling foot.

The method is used with a foot, which is built as an arc on the lower side. At touchdown the ankle is positioned so that the foot will strike on the edge and during the exchange phase rolls over the arc by servoing the ankle after a precalculated geometric path. The ankle of the stance foot is also positioned during exchange to maintain the absolute distance between the feet.

2.7 Harvard

At Harvard University a biped walking strategy is presented, based on a set of conditions which ensure that no instantaneous change in velocity is experienced at exchange of support. In contrast to the work in Yokohama which is based on force control Harvards method is based on the use of appropriate leg length and leg length velocities. It could be called a kinematic solution to achieve finite vertical acceleration from the impact between ground and foot at touchdown.

A velocity and step length control similar to Raiberts (1986), hopping robots is used in the gait controller. The difference is that the gait is walking and not running or hopping as with Raibert. Dunn and Howe (1994) report that they can have 30% of change in desired walking velocity and 25% change in desired step length with their control method.

The robot is quite small and simple about 35 cm in height and a mass of 5.6 kg. It consists of a pair of prismatic legs with point feet joined to a body with rotary hip joints and is thereby constrained to walk in the sagital plane. The prismatic leg actuators are pneumatic cylinders and the rotary hip joints are actuated by DC motors.

The gait with such a configuration is called compass gait because it rolls over the point foot as an inverted pendulum. The only driving forces with a constant leg length are the inertial and gravitational forces.

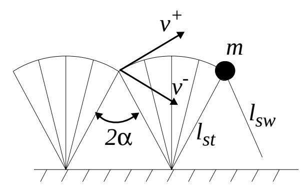

FIGURE 12. The model of the compass gait. At exchange of support there is a discontinuous change of velocity from v^- to v^+

In figure 12 the compass gait is shown, the hip follows an arc of the circle with the radius of the leg length during single support phase. At touchdown there is an instantaneous change in linear velocity of the hip, v^+ and v^- in figure 12 are the velocities just before and after touchdown. Without leg compliance the hip would experience an infinite acceleration at touchdown (discontinuous jerk). Humans control this with an active change of leg length at touchdown. The front leg is shortened at touchdown by ankle flexion and the rear leg is lengthened from ankle flexion, knee extension and foot supination. This leg length change reduces the discontinuous velocity change at touchdown (together with compliance).

Three necessary conditions are derived by Dunn and Howe (1996) to achieve a smooth exchange of support with $v^+ = v^-$ at touchdown, they are

$$\begin{bmatrix} l'_{sw} \\ l_{sw} \end{bmatrix} = \begin{bmatrix} \cos 2\alpha & -\sin 2\alpha \\ \sin 2\alpha & \cos 2\alpha \end{bmatrix} \begin{bmatrix} l'_{st} \\ l_{st} \end{bmatrix} \qquad (19)$$

$$l'_{st} + l_{st}\tan\theta_{sw} = 0 \qquad (20)$$

were l_{sw} is the length of the transfer leg, l_{st} the length of the stance leg, θ the angle between respective leg and a vertical line, 2α is the angle between the legs and the prime denotes the derivative with respect to θ.

If the step length is controlled with the angle between the legs ($2\alpha = \theta_{st} + \theta_{sw}$) and using equations 19 and 20 there are seven variables and four equations. Values for any three of these variables must be known in advance.

The relation between θ_{st} and θ_{sw} is used for velocity control in a simple way as

$$\theta_{st} - \theta_{sw} = G(v_d - v) \qquad (21)$$

were G is a feedback gain and v_d and v the desired and actual velocity.

Important to notice is that even though the above strategy gives (without a compliant structure) zero vertical acceleration at touchdown it can give high horizontal acceleration. Simulations show that the horizontal acceleration is in fact discontinuous, but bounded to some level.

In a real implementation there are other things like compliance, and that it is not possible to achieve an instantaneous exchange of support (double support phase) which will greatly influence the motion of walking and thereby the described strategy. In the only plot from real walking it is seen that the hip trajectory does not behave as good as in the simulations.

2.8 Universitè Pierre et Marie Curie

In Laboratoire de Robotique de Paris a quadruped walking robot called RALPHY has been designed and built. RALPHY has pneumatic actuators and revolout joints, two joints at each leg, one at the knee and one at the hip. Each one of the two links in the legs are composed of a pneumatic cylinder which piston drives a cable attached to pulleys, thereby is the linear piston motion converted into a rotational joint motion.

The controller is hirarchical and composed of three main levels. At the highest level, the supervisor level, is the general gait and main motion decided. The middle level, the coordinator level, ensures the global stabillity and the realization of the desired gait of the robot. Desired leg trajectories and distrubution of leg to platform forces are also calculated at the coordinator level. At the lowest level, the leg level a dynamic control of each leg is utilized.

Coordinator level

The reference signals from the suprevisor level are duty factor β, the relative phase of a foot ϕ, the stride length λ and the stride frequency *f*. They are used to calculate the CG trajectory of the body. A foot trajectory is also calculated at this stage. Villared et al. (1993) proposes a foot trajectory based on a cycloid motion (relative ground) in the transfer phase and an arc of a circle in the support phase. The motivation using such trajectories are that they reduce the impact forces at touchdown. Later Villard et al. (1995) uses linear trajectories for the foot.

From the body CG acceleration, a_{co} the acceleration at each hip joint is callculated, which then is the reference acceleration to the leg controller, and together with the foot trajectories defines the joint trajectories.

A feedback for the bodys CG trajectory is used to make the body robust to external disturbances. If the desiered CG trajectory is $x^d(t)$, were x^d is the usual 6x1 vector with three positions and three angles, and the measured trajectory is $x(t)$, a corection of the CG acceleration, $\ddot{x}^c(t)$ is calculated as

$$\ddot{x}^c = \ddot{x}^d + K_v(\dot{x}^d - \dot{x}) + K_x(x^d - x)\,. \qquad (22)$$

were K_v and K_x are appropriate constant feedback gains. From $\ddot{x}^c(t)$ is then the acceleration at each hip a_0^k, with k=1..4, is calculated from the kinematics as.

$$a_0^k = a_{CG} + \dot{\omega}_{CG} \times r^k{}_{CG} + \omega^d_{CG} \times (\omega^d_{CG} \times r^k{}_{CG}) \qquad (23)$$

with

$$\ddot{x}^c = \begin{bmatrix} a_{CG} \\ \dot{\omega}_{CG} \end{bmatrix} \qquad (24)$$

The desired forces on the bodys CG are

$$F_0 = m_0\ddot{x}_c + m_0 g \qquad (25)$$

where g is the gravitational acceleration and m_0 the body mass. F_0 must then be distributed out to each leg. That is, the sum of the forces, F_i on the body from all four legs must equal F_0 to fullfill equation 22 . This can be achived with many different combinations of leg forces, Villard (1995) uses a simple constraint to solve for F_i, they choose to generate the same vertical force on the left side of the robot as on the right side. Friction constraints are also used to calculate the F_i.

Leg level

The input signals to each leg from the coordinator level are the corrected accelerations from equations 22 and 23 and the desierd force F_i from equation 25 and the distrubution algorithm. The accelerations a_0^k are transformed to joint torques by using an Inverse Dynamic Model (IDM) of each leg with F_i as external force on each grounded foot.

The IDM is the standard Newton Euler algorithm. First the velocities and accelerations of each link including the acceleration of the CG of each link

3.0 Conclusions

The overall conclusion of the last section must be that there is still a lot to do before four legged walking robots will actually be used and perform work within the industry or elsewhere, and not only be research platforms for interesting scientific problems. One could ask whether this is because of missing technology and experience in designing and building them, or if the problem is just a lack of interest from the sponsors of such projects. Why should we spend a lot of resources in building walking vehicles when there already exists vehicles for almost every purpose and every terrain using traditional locomotion, e.g. wheels or tracks?

There should be a need for robotic researchers to get out of their research labs and build dynamically controlled walking robots for their real niche, which must be outdoor terrain. This also calls for building in a larger scale than the normal size robot, which must have a convenient size for indoor research. With a larger scale robot it is possible to use conventional power sources such as combustion engines to provide energy for the robot, with indoor robots the power source will always will be a major obstacle for practical usage because of current battery technology.

I believe that the technology for building successful dynamically walking robots for outdoor terrain is already available and that the main problem is to be found with the complexity and size of such a project. Mechanical design, computer hardware and electronics, software and control and user interaction have all the same importance for a succesfull design. A research team will have to master all these issues to be able to build something useful. One underestimated problem is probably the robustness of the robot. When control strategies are tested on the robot in its natural environment it will often fail, and having a couple of hundred kilogram robot tumbling down a slope could be a disaster for most research platforms. Looking at four legged animals learning to walk and run it is obvious that stumbling and falling must not lead to anything worse than a couple of bruises and that they all have to learn from their own mistakes.

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