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Hannu Lehtinen

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ABSTRACT

Force control of legs of evolving walking machines is assumed to be essential in natural soft and uneven terrain. The main duties of a leg are to support and propel the vehicle in co-operation with the other legs. Force control fills the support requirement also when a leg or many legs penetrate the terrain. It also prevents rolling of the body due to lift-off or placement of legs.

Due to the relatively large mass and inertia of the body, dynamic equations of a free object are a basis for "computed-torque" based calculations of desired body forces to move or participate in the applications as desired. The large and varying amount of friction in the leg mechanisms while the body is carried and the practical delays and saturation in the hydraulic system increase the complexity of the process to be controlled.

The main contributions in this thesis are as follows. The body forces are transformed to the supporting legs in two phases: sets of minimum forces perpendicular to the resultant body force and forces parallel to the same resultant. This method minimizes the possibility of slippage with walking machines, where the desired body force is often close to vertical due to the weight of the body.

A load adaptive PI force control method for the hydraulic actuation system of MECANT I consisting of an asymmetric cylinder and a symmetrical valve has been developed. The I term of the controller is changed according to the desired load.

A rule based altitude controller and a dead-zone and saturation based attitude controller have been designed. The first tests with force controlled vertical actuators show the usability of the method and fast responses to deviations in body orientation. The deviations are usually corrected within 1 second.

PREFACE

This research has been carried out between 1988 and 1993 within the "Basic Technology of Walking Machines" project headed by the Helsinki University of Technology (HUT) and in co-operation with VTT Laboratory of Automation and Electrical Engineering.

The work has been supervised by Professor Aarne Halme. I am deeply grateful to him for discussions on the thesis, many interesting ideas concerning walking and for his support during the academic process.

I also wish to thank many of my friends and colleagues for advice and help concerning the various fields of technology need in walking machines. Among them are Riku Linna, Kari Rintanen, Timo Ropponen, Heikki Seppä and Raimo Soudunsaari, who have been able to devote their busy time to my numerous questions. I am also grateful to Professor Matti Vilenius for checking the chapters dealing with hydraulics and grateful to Professor Heikki Koivo for several improvements.

The financial support of The Technical Development Board (TEKES), VTT, HUT and the Academy of Finland is also gratefully appreciated. The patience of the funders and my superiors, especially Kari Koskinen, has been note-worthy and created, together with my colleagues a pleasant and challenging atmosphere for research work.

Espoo, March 1994

Hannu Lehtinen

LIST OF SYMBOLS, SUBSCRIPTS AND ABBREVIATIONS

$\boldsymbol{A}$	transformation matrix from six d.o.f. body force vector to vector of all leg tip forces
A_a	larger effective area of an asymmetric hydraulic piston
A_b	smaller effective area of an asymmetric hydraulic piston
A_1, A_2	membership function types of a fuzzy controller
$\boldsymbol{A}^+$	pseudoinverse of matrix $\boldsymbol{A}$
a	acceleration
a_c	commanded acceleration
$\boldsymbol{B}$	transformation matrix from three d.o.f. vector of horizontal components of body force to a vector consisting of all horizontal components of leg tip forces
B_{oil}	compressibility of hydraulic oil i.e. bulk modulus
b_v	damping factor
$\boldsymbol{C}$	transformation matrix from three d.o.f. vector of vertical components of body force to a vector consisting of all vertical components of leg tip forces
C	cut-off value of output variables of a fuzzy controller
c_v	leagage factor of linear hydraulic actuator
d	distance
dr	small deviation vector
F	force
$\boldsymbol{F}$	force vector
$\hat{F}$	estimated force provided by an asymmetric piston

$\boldsymbol{f}$	six d.o.f. force (F/T) vector
F_c	constant force, c either x,y or z
F_{co}	Colombian friction force
F_n	centripetal force towards the center of a circular path
F_{pmax}	maximum absolute value of a utility force in one dimension
$\boldsymbol{F}_u$	utility force vector in a coordinate system parallel to horizontal level and the horizontal projection of the X axis of the body coordinate system
$\boldsymbol{F}_{ub}$	utility force vector in the body coordinate system
g	gravity (9.81 ms^{-2})
h	a symbolic height needed in a fuzzy controller
$\boldsymbol{I}$	identity matrix
I	performance index
$\boldsymbol{I}_t$	inertia tensor
I_{cc}	diagonal elements of the inertia tensor; c is x, y or z
$\boldsymbol{J}$	Jacobian: partial derivates of joint angles in respect to perpendicular coordinate position and orientation
k	factor (real value)
$\boldsymbol{K}$	stiffness matrix
$\boldsymbol{K}_a$	gain matrix of position error of accomodation control
K_f	flow factor based on valve data
K_{fe}	gain of force error in hybrid control
$\boldsymbol{K}_{fi}$	gain matrix of integral of force error
K_{fm}, K_{fm2}	gains of force models of hydraulic actuator
k_{leg}	compliance of a leg mechanism
$\boldsymbol{K}_p$	gain matrix of position error
K_p	gain of position error in hybrid control

$\boldsymbol{K}_v$	gain matrix related to speed
L	cut-off value of input variables of a fuzzy controller
M	virtual mass of accomodation control or reduced mass
m	mass
M_v	mass of the vehicle
N	last index, related to supporting legs
p	instant power
p_a	pressure of a hydraulic cylinder in the chamber limited by the larger effective area of the asymmetric piston
p_b	pressure of a hydraulic cylinder in the chamber limited by the smaller effective area of the asymmetric piston
$\boldsymbol{p}_{ref}$	six d.o.f. position reference vector
$\boldsymbol{p}_{cg}$	position of the center of gravity
$\boldsymbol{Q}$	a weight matrix
q_{ii}	diagonal elements of a diagonal weight matrix
q_v	leakage flow of a hydraulic actuator from the chamber of larger pressure to the chamber of smaller pressure
$\boldsymbol{R}$	resultant force vector
r	radius
$\boldsymbol{r}_u$	attachment position of utility equipment
$\boldsymbol{r}_1$	position of the leg tip of the 1st supporting leg in the body coordinate system
s	differential Laplace operator
$\boldsymbol{T}$	torque vector
T	torque
t	time
T_{cntl}	control interval

$\boldsymbol{T}_{ub}$	torque caused by utility force in the body coordinate system
$\acute{T}_c$	sum of body torque reference and torques caused by the horizontal forces of legs (c is x or y)
U,u	control voltage of valves
$\boldsymbol{u}_g$	unit vector of gravity in the body coordinate system pointing downwards
u_x, u_y	operator given real values between -1.0 and 1.0
V	volume
v	speed
$\boldsymbol{v}_n$	velocity vector
$\boldsymbol{v}_{ref}$	velocity reference vector
v_x	translational speed along X axis
W	symbolic width of a fuzzy controller
$\boldsymbol{W}$	six d.o.f. F/T vector
$\boldsymbol{w}$	measured F/T vector
X, Y, Z	axes of the rectangular body coordinate system
$\boldsymbol{x}$	position or vector
$\boldsymbol{y}$	vector
$\boldsymbol{\alpha}$	angular acceleration
$\acute{\alpha},\acute{\theta}$	orientation angles of force reference in respect to the body coordinate system
Δ	change within a short interval
ω	angular speed
τ	time constant
$\boldsymbol{\tau}$	F/T vector of joint actuators
θ	orientation angle of an object

In addition, several auxiliary variables in order to speed up calculations:

> *sx, sy, sz, s2x, s2y, s2z, sxy, syz, sxz, detBBt, detCCt, ns2xy, sxsy, xpx, ypy, nsx, nsy, np2*, k_1, k_2, k_3, k_4, k_5, k_6

Subscribts

alt	deals with force based altitude control
att	deals with force based attitude control
b	deals with body
c	either x,y or z referencing to different components in the body coordinate system
d	reference value
est	estimated value
fric	deals with friction
hor	horizontal
hose	deals with the hoses of the hydraulic system
oil	deals with hydraulic oil
oper	operator given reference value
p	path
ref	reference value
t	terrain
w	deals with gravity compensation of supported mass
v	deals with velocity
e	error

Abbreviations

CAN	controller area network
CPU	central processing unit
F/T	force/torque

GRASP	a three dimensional modeling and simulation program package
HUT	Helsinki University of Technology
IC	integrated circuit
I/O	input/output
ISO	International Organization for Standardization
MACSYMA	MAC's SYmbolic MAnipulation system and programming - program package for symbolic calculations
MATLAB	interactive software package for scientific and engineering numeric computations
VME	Versa Module European
VTT	Technical Research Centre of Finland

CONTENTS

1 INTRODUCTION

Walking has been quite an unresearched area in technology mainly due to the invention and succession of wheels. Various types of wheel based vehicles have also been developed for transportation in a natural environment, although wheels usually require a specially prepared environment i.e. roads. Wheeled vehicles have limited access to natural environments. Therefore new and interesting research subjects could be found in the technology of mechanical walking. As a matter of fact, it can be said, based on careful and even pessimistic considerations, that walking machines will gain, in ten or twenty years, a considerable share in the economies based on forestry. Other factors improving the possibilities of walking machines are the evolution of hydraulic systems and their control possibilities.

Walking is an obvious alternative to wheels on uneven terrain. Multi-legged (more than two legs) walking has been studied frequently since the beginning of the 60's. Chung (1985) listed, in his survey, 15 machines between 1960 and 1985. The development and the usability of the developed machines has been constantly improved, aided by the improvements in computer technology. The total control of movements of a walking machine is a calculation intensive task, as will also be seen in later chapters.

Advantages of walking on natural terrain

Walking is, theoretically and quite surprisingly, more energy efficient than tracked or wheeled locomotion on soft terrain, since walking does not distress or mechanically damage the terrain. This is important for the minor roots of plants and trees. Energy efficiency, directional dexterity, the ability to move on sand or on a terrain, the surface of which gives support only in some locations, are the main advantages of walking compared to wheeled locomotion (see for example Todd (1985)). Force controlled walking would give additional advantages by increasing energy efficiency by the reduction of internal forces between legs and providing the desired support forces regardless of the behavior of the terrain walked on.

The main attraction of wheels is the mechanical simplicity of them. Bearings have been made from elementary wooden parts for carriages pulled by bulls. However, wheels would have been more difficult for evolution in nature.

Another motivation for force control and a belief in its superiority also comes from nature. Several years ago I saw a horse pull a set of logs up a hill slope inclined about 20 degrees. The autumn day was rainy and the stones of the path slippery. The rear legs of the horse caught my attention. While pulling the logs the horse did not care, where the legs were exactly, but was more concerned, that the legs could provide sure footing. This could be seen the instant a leg started its support period. The leg searched, by testing and rapid lateral movements, for a supporting grip before the weight was exerted on that leg. Losing the supporting grip in the middle of a step did not seem to bother the horse at all. It could compensate for the slippage by bending the other two supporting legs. In conclusion it can be said, that the legs of the horse were more force than position controlled during their support phases. The leg was naturally changed to a position control at the limits of its area of reach, where the leg had to be lifted.

Driving cars (exception "cruise controlled" cars) is actually a case of force control. We actually control the force provided by the engine (traction force) with the accelerator pedal. The speed of the car stabilizes, when the friction and wind resistances are equal to the traction force. We request a larger force by pushing the pedal downwards when the car is supposed to take us up the slope of a hill.

As we all know, actuators can also produce force or torque during the movement caused by the force or the torque. The actuator force is a function of a physical control quantity. Current is the control quantity with electric motors. The valve control voltage is typically the control quantity with hydraulics. The control voltage steers the relative opening of the valve channels for oil flow in the case of MECANT I.

The theoretical difference between force and position control is rather small. The control quantity is calculated based on the position error with position control and based on force error with force control. Histories of these errors and previous control quantities can also be used. Control quantity may also be based on several errors.

The accuracy of, for example, industrial robotics is not needed in walking machines nor is it economically motivating. Low adaptivity to the environment is the problem of position control. A position controlled leg of a walking machine would either move in the air without producing any forces for the body or exert all the forces available in the case of uneven terrain. The latter possibility happen, when there is a position error. The inevitable compliances in the mechanisms of the legs, however, ease these difficulties.

The main subject and the main contribution of this work is force related control of walking machines. Both force based movements and utility work done with the body forces are considered. Walking on naturally soft and uneven terrain, like in forests, is the main goal. The force control presented here solves the problem of penetration of one or many legs into the soil during the support phase of it or any of them. Some of the methods presented can be integrated with the existing gait and locomotion control methods.

Benefits and possibilities of force control for walking have been analyzed in this work. Force control is assumed to be a valuable addition to locomotion control on soft and uneven natural terrain. Two main ways to integrate force control have been analyzed and tested. The body of the walking machine can be asked to provide the desired forces to the environment. These forces are called utility forces. The motion control of a walking machine based on force control is another subject. The position of the body is used to calculate the intermediate control quantity, body force and torque. They are used to calculate proper leg force references, that are then realized in the actuators of the leg.

Force based control of walking can be estimated to be more robust on difficult i.e. soft terrain due to rapid response to plasticity and other non-linear characteristics of the terrain, control and mechanics of the vehicle. The main benefit of using force control in actuators is, that the legs will support, with the commanded forces, even in the case of a leg penetration into the terrain.

One of the main goals of the work is to present methods to control locomotion using force control of the body in combination with evolving suitable nonperiodic (often called "free") foot-hold selection algorithms, that decide continuously the next leg to be lifted and the next one to be used to support. The development, although interesting, of the proper free gait is beyond the scope of this work. Free gaits are, however, being studied actively by the research group (Halme et al. 1993).

Framework of study

The framework of the study presented is shown in Fig. 1. It also shows the problem definition and the developed blocks. The blocks beyond the scope of this work are dashed in Fig. 1. An external system or operator gives a body reference in position, velocity, acceleration or force format, or a combination of several formats. If the reference is in the position oriented formats, the developed methods transform the position reference to body force references, that would move the body as desired. All existing forces in the body have to be taken into account. They are also included in the cases where the operator gives application oriented body force references, called utility forces.

Leg force decomposition takes care of distributing the body forces evenly to all supporting legs. Legs may also receive position oriented references from locomotion control, for example commands to lift a leg and place it to a new support position. Note, that locomotion and gaits are not considered in this work to a larger extent than necessary. Locomotion control decides, which legs support and which legs are moved to new support positions. Force control of the body requires only as input data the positions of the supporting legs and that the desired support can be realized with the legs in question. However, advice to change to currently active leg configuration (the set of supporting legs) may be given by the leg force decomposition.

The result of leg force control to the body are measured and estimated based on several sensors and the legs themselves. The position estimation methods developed by the research group (Hartikainen et al. 1992c) are used in this work.

Four different force control methods for the body of a walking machine are presented. Three of them are based on force control of all actuators of supporting legs.

The first method can be applied in cases, where the reference body force is close to vertical. This is the case, when the weight of the vehicle is relatively large compared to the horizontal traction forces and the vehicle moves on relatively flat horizontal terrain. The burden of calculations necessary in this case is linearly dependent on the number of supporting legs and can be realized in a real-time control system with a few tens of milliseconds calculation interval.

An improved version of the above mentioned method uses an inclined optimization coordinate system. The inclination is done according the total body force reference. The first phase of optimization is done in the XY plane of the new coordinate system. The previous solution is included in the next phase calculating

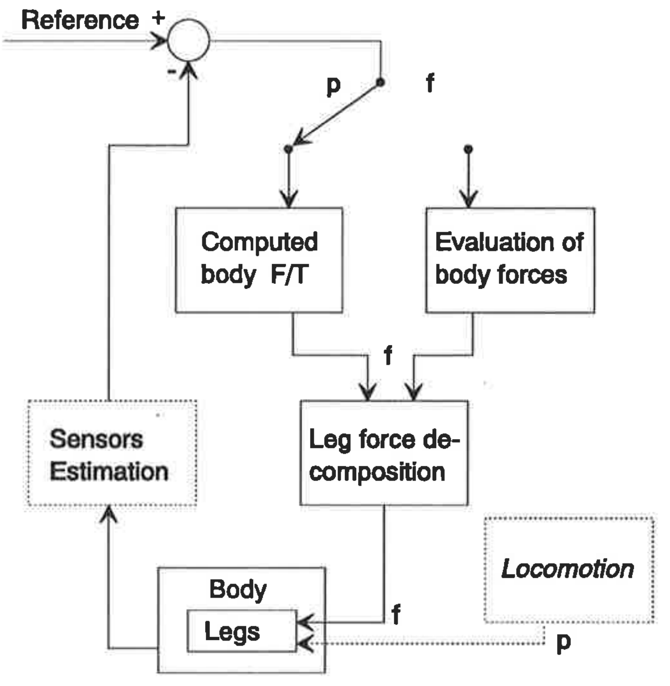

Fig. 1. Overwiev of force related control of walking machines.

the forces parallel to the Z direction. The superiority of this method was noticed even when keeping the possibility of slippage small. This method is suggested for future development of the walking machines for soft and uneven terrain with a proper free gait algorithm. The operator guides the velocity or position of the body with these two methods. The control method in question is described in more detail in Fig. 2. The control loop of the position and orientation of the body is closed in the cascade manner by closed force control loops in the legs.

If a leg under force control slips, it moves rapidly either to the opposing object or the limits of its working area. Moving to the limit of the working area causes the need to lift the leg.

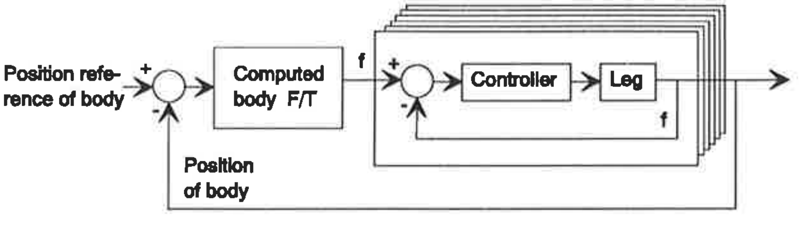

Fig. 2. Main priciple of body force control: position control of the body closed by force control of legs. The main benefit is support on soft soil.

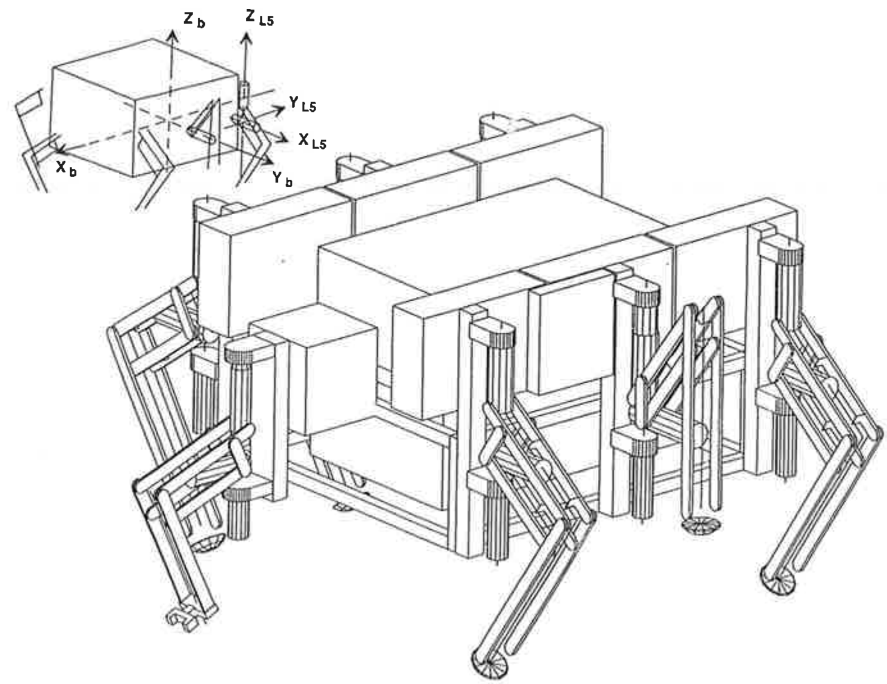

Fig. 3. The self-contained walking machine MECANT I (by Markku Paakkunainen (HUT) 1993 with GRASP).

It is often desired that a walking machine participate in specialized tasks. Examples of such cases are pulling a boat ashore, pulling logs closer to roads and removing debris covering dangerous barrels in a case of an accident. The need to provide forces between zero and the maximum available is the common factor of these cases. Leg force distribution is calculated in a similar manner in all three methods above.

The fourth force control method is used to control body attitude and altitude by force control, but the direction angle and horizontal traction movements by position controlled locomotion. The method is a necessary addition for walking on uneven and soft terrain with the traditional locomotion methods.

The MECANT I of Helsinki University of Technology (Hartikainen et al. 1992b) has been used as a test bed for the developed force control methods. A CAD made, three dimensional drawing of the MECANT I, can be seen in Fig. 3. The main coordinate systems of the vehicle can also be seen in the small inset in Fig. 3. The body coordinate system is located in the middle of the body with the XY plane on the same plane as the horizontal actuators. The leg coordinate system of leg 5 is also drawn as an example. The YZ plane of it is parallel to a side of the MECANT I. More of the vehicle can be found in section 1.2.

The methods developed are very applicable to other previously developed walking machines. Some of them have been actuated by electrical motors through gears. Torque control of electrical motors is quite simple, but can not be done through gears.

A method for force control of a hydraulic actuator is presented. Due to its simplicity it is quite robust. The high noise content of signals measured in the process of hydraulics caused some difficulties. There seem to be a lot of new and open fields in the theory and methods of force control of hydraulic actuators. The method presented here is sufficient to be used with hydraulic equipment mentioned for the position control. The method presented for force control of actuators is a more practical than scientific contribution. It is, however, sufficient for force control of walking, since the large mass of the body of any walking machine filters the main effects of the inaccuracy.

The contents of this thesis can be outlined as follows. The numerous force control methods are presented in the beginning. The MECANT I walking machine and other application areas, where the methods presented could be used are in the next sections. Forces of walking and some possible user interfaces are analyzed in chapters 2 and 3 respectively. The evaluation of leg forces is presented in two phases in chapter 4. The body forces, that are needed according to the desires of the operator, are calculated first. The second phase distributes the forces to the legs.

Chapter 5 concentrates on the force control of hydraulic actuators. In addition to the presentation of some alternative controllers, the force process in actuators is modelled and simulated and friction compensation considered. Chapter 6 outlines the methods to integrate force control with locomotion control. These methods are also the basis for recommended future research in chapter 7. Results are presented in chapter 7.

The main contributions of the work presented are as follows:

- presented a control method for walking, that would enable walking on plastic terrain and maintain body attitude regardless of leg penetration into the soil

- the body force reference can be realized with a leg force distribution, that minimizes the horizontal forces in order to keep the possibility of slippage small

- attitude and altitude control of a walking vehicle have been designed and realized with the MECANT I: attitude errors were corrected within 1 second

- force control of asymmetric hydraulic piston and symmetrical valves has been realized in practice

- hydraulic force process has been modelled using differential equations.

1.1 RELATED WORK

The force control of a walking machine is a fruitful subject to study. Quite a lot has been written about the subject, but it still offers plenty of theoretical difficulties to be solved. Walking machines have great potential in the future (within the next 10 years); they are energy efficient on soft and uneven soil compared to track or wheeled vehicles. Extensive surveys of the advantages (and technological basis of walking machines) have been written by Todd (1985) and Järvinen (1988) in English and Finnish languages correspondingly. The need to resist the compaction resistance only in specific locations and the use of compaction resistance to create thrust forces are the main reasons for energy economy in walking.

Very little has been written concerning force control of hydraulic actuators, although force control research on walking machines has usually been done with hydraulic systems. Also the body force control i.e. resolving the body force reference is seldom considered. The research of force control of walking machines has been concentrated on the leg force distribution.

The Adaptive Suspension Vehicle (ASV) (Pugh et al. 1990) set of projects has been an encouraging example. Since it was successfully constructed and operated, as seen in several video tapes showing walking on grass and sand fields, it has been easier to start development of another walking machine. However, it is quite difficult to resolve, based on publications, how body force control was actually utilized and what the main benefits of it were in the ASV. The effectiveness or status of the force control used can not be commented on based on the video films, although the ASV pulls a heavy sledge in one of the video tapes.

Despite the technical success of the ASV, the manufacturing or copying of it for research purposes has not started. It was designed mostly for transportation duties. One of the difficulties of the ASV is the complex and therefore quite expensive mechanical design (Waldron et al. 1984).

1.1.1 Force control in robotics

Force control is usually used in robotics to guarantee that the end-effector forces caused by the manipulator arm to the object are as desired. Manipulating objects with fingers is somewhat similar to the contrary case of walking, where the body is moved by causing forces to the terrain with the legs.

Force control is actually one of the main subjects studied in robotics. The number of studies is, however, not reflected completely in the quality of results and general usability in practical applications. The large number of different possible methods and wide variation in the needs of applications are the main reasons for the small number of related applications. The number of, even elementarily, force controlled industrial robot applications in continuous industrial operation is still very small. There is one industrial robot manufacturer that has integrated 3 d.o.f force sensor to the wrist of an industrial robot. Functions to maintain surface force or reduce path speed according to force measurements can be called during program execution. Control bandwidth is a few Hz.

However, force control is coming into practical use in such areas, where economy of the technology is not the main concern, like undersea duties. Yoerger et al. (1991) have developed for a Remotely Operated Vehicle (ROV) a three d.o.f. arm, that is torque controlled and has a special reducer (1:30) utilizing cables and pulleys. The arm is backdriveable due to the compliance in the reducer. The motor torques are measured by utilizing only the compliance and angle measurement with a resolver integrated into the stator of the brushless DC motors. No more than three joints are necessary in the arm, since the vehicle itself can be moved in order to move the tool to the correct position and orientation.

The use of gears is one of the main difficulties of force control in robotics, because actuator inertia seen at the end-effector is increased by the square of the gear ratio. This problem is overcome with walking machines by the use of hydraulics. Direct drive motors without gears have been used in robotics in order to overcome the force control problem through gears. The dynamic effects of the links are more important in robotics than the dynamic effects of legs in walking.

Theoretical aspects of force control have been studied widely in robotics during the latest 20 years. The methods can be divided into a few main classes. Among them are:

- end effector force control
- robot dynamics
- simultaneous position and force control of an n-link manipulator.

Six axis force and torque (F/T) sensors attached to wrists of robots have been used for force monitoring and decisions on the actions of industrial robots in manufacturing tasks. The main problem of these experiments has been the low level of sensor interfaces in industrial robots. In addition to guarded motions (move until a sensor exceeds a limit) robots have been able to correct the position and orientation of the tool with a bandwidth of a few Hz. End effector speed control based on force sensors can also be accomplished with commercial industrial robots. Lédeczi et al. (1990) have presented several practical and simple force control methods with industrial robots in detail and described an intelligent sensor, that processes the detected F/T values and sends the results or action orders to the robot via binary channels.

The task in the end effector force control is to calculate actuator force (and speed) references, when the force and torque of the end effector is specified by experience concerning the interaction of the tool and the work piece. When the forces caused by the movements, acceleration, inertia, weights, etc. of the links of the manipulator arm are also considered, the problem is called dynamical robot control.

The numerous algorithms presented in literature for end effector force control ((explicit force, accomodation (position or velocity loop), impedance and stiffness based force control methods)) have a lot in common and are versions of the impedance based force control according to Goldenberg (1992). All the methods are equivalent to a complete set of state variable feedback laws.

The recent topics of force control research seem to be robust force control and replacement of sensors with observers (for example (Komada et al. 1992)). Although many of the force control papers presented these days deal with co-operative control of several co-operative arms, they seem to give quite little to this case of a walking machine, where the opposing load force or the carried mass of each leg are not known in advance (or vary a lot) and the force process (of hydraulics) is very non-linear. The non-linearity of the soil and rolling related to stepping mean, that individual paths for each legs are not known in advance.

Stiffness, accomodation, hybrid and impedance based force control

A short survey of the basic force control methods studied in robotics is presented here. The well known spring equation is the basis of the stiffness control. Let us assume a robot arm has been given a (six d.o.f.) position reference $\boldsymbol{p}_{ref}$. If it can not reach the position reference, but is left $\boldsymbol{dr}$ distance from it, the arm will try to reach the reference position by exerting a force $\boldsymbol{f}$ to the environment.

$$\boldsymbol{f} = \boldsymbol{K}\,\boldsymbol{dr} \tag{1}$$

$\boldsymbol{K}$ is the so called stiffness matrix. It can usually be chosen to be diagonal. The diagonal variables are set large in those directions, where high environmental stiffness is desired (i.e. position control) and small in compliant directions. The desired actuator torques can be calculated with the help of the Jacobian matrix as presented in Appendix A.

A new speed reference is calculated in the accomodation based force control. If we assume, that movements according to the nominal trajectory causes the tool (the six d.o.f.) velocity vector $\boldsymbol{v}_n$ and the F/T sensor attached to the wrist then detects the F/T vector $\boldsymbol{f}$. Then the new velocity reference $\boldsymbol{v}_{ref}$ is given by:

$$\boldsymbol{v}_{ref} = \boldsymbol{v}_n - \boldsymbol{K}_a \boldsymbol{f} \tag{2}$$

The velocity reference can be transformed to the actuator space by the transposed Jacobian matrix.

Some degrees of freedom of the tool or the robot arm are position controlled and the other force controlled (in actuator, cartesian or configuration space) in the so called hybrid control of manipulator arms. The selection and also the stiffness may vary during different stages of the application process. The control method is usually performed in the Cartesian application coordinates, where orthogonal coordinates are either position or force controlled. Force control is made along directions in which the robot arm is constrained by the environment and position control along directions in which the arm is unconstrained and free to move. The robot may be of the revolute type. This leads to the "hybrid" control of the actuators; the commanded actuator torque is based partially on the position and torque errors. One might assume a high possibility of instability, when the same actuator is controlled based on both position and force. However, Fisher & Mujtaba (1992) have shown, that a stable hybrid control can be developed for all mechanics.

Impedance control of robot mechanics has been widely studied in recent years. The basic idea is, that the end-effector of a robot manipulator reacts to external forces with a programmable compliance. In other words the end-effector tries to reach the nominal path, but accepts error due to external forces. The mechanical impedance relates speed and force in an analogous manner to voltage and current in electrical networks. The mechanical sources of impedance are mass, damper and spring. Due to the analogy to electronics, mechanical impedance networks can be simplified similar to electrical networks.

There have been several different impedance control algorithms since its development in the '70s. It is basically a "computed-torque" method. Its main benefit is the stability even after collisions with a rigid environment. The actuator torques are computed using Eq. (3) based on the path reference (time sequence of position, speed and acceleration), measured path and the desired impedance parameters (the diagonal matrices K_p, K_v and M). Note that the "virtual" mass M is also a parameter, that is tuned during the application development.

$$\tau = J^T\{(K_p(x_d - x) + K_v(\dot{x}_d - \dot{x}) + M(\ddot{x}_d - \ddot{x})\} \qquad (3)$$

Lee & Lee (1991) have extended the basic equation (Eq. (3)) by including the contact and environmental forces and their time derivatives.

The impedance control methods have been extended by Schneider & Cannon (1992) to control two co-operative robot arms in moving a relatively heavy mass. They use a weighted pseudoinverse[1] to calculate the optimum actuator forces and a predefined "internal force", that load internally (i.e. squeezes the object). The internal force does not move the object. It is quite obvious, that the method could be extended to move a walking machine at least in relatively rigid terrain where the predicted paths for each leg could be defined.

Numerous extended methods

Grabbe et al. (1993) have reviewed several simultaneous force and position decoupling methods of a single n-link constrained robot manipulator. The methods are well described according to Grabbe et al. (1993) in the following references: McClamroch & Wang (1988), Cai & Goldenberg (1989), Kankaanranta & Koivo (1988) and Cole (1989). Constrained means in this case, that the robot has contact with the (stiff) environment and can not therefore move in all directions. They

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1 Pseudoinverse is a common method to calculate a solution for vector equations of type $y = A\ x$, where the number of elements in x is larger than that of y. The given particular solution is the least-squares solution, that minimizes the norm $\| y - A\ x \|_2$. The size of A does not have to be square or A may be singular.

have considered the specification of the position i.e. the path in the "free" directions and the specification of the forces (and torques) to be exerted by the end effector on the environment. It is assumed, that the manipulator is always in contact with the constraint surface and the surface is rigid and frictionless. Note, that these assumptions are not true in the case of mechanical walking.

Grabbe et al. (1993) noticed similarities in the methods developed by the above mentioned scientists and have developed such a general transformation, which includes all the methods as different special cases.

Liu et al. (1988) have also developed a universal force controller, from which the original forms of the hybrid position/force, impedance and stiffness controllers can be derived. They recommend the use of feedforward dynamic compensation as long as the exact values of the dynamic parameters, including the stiffness of the environment, are known. They have also briefly described an adaptive force controller, that recursively identifies the unknown dynamic parameters in case they can not be specified in advance.

Ohishi et al. (1992) have force controlled a direct-drive robot arm without a force sensor using observers instead. They used acceleration control based on the H^{∞} method. Friction was identified recursively during the operation. They compared the operation with a force sensor instead of the observers and gained similar results with or without the force sensor.

Volpe & Khosla (1992) have compared several force control strategies with the same hardware. The best results are given by "integral gain explicit force control". Its basic equation is as follows (Volpe & Khosla 1992):

$$\tau = J^T\{K_{fi}\int(f_e - f)dt - K_v\dot{x}\} + g\,u_g \tag{4}$$

In other words the feedforward joint torques are calculated (quite heuristically) based on an integral of the force error, viscous friction compensation and (obviously) torque vector caused by gravity and the mass of the robot arm. Volpe & Khosla (1992) tested the method with a direct drive arm. The torque control of a direct drive motor is quite easy: the torque depends linearly on the current. The gears found in industrial robots make this kind of "torque-computed" method more difficult.

Dynamics included

The goal of the inverse dynamical control solution of a robot is to calculate the actuator torque or force references so that the end effector moves as desired and the end effector exerts the desired forces and torques to the environment. The problem has been widely considered in the robot control theory and several solutions have been created. The solution is typically based on the recursive Newton-Euler equations for each link. Inertial forces caused to the masses of the links and actuators, centrifugal and Coriolian acceleration, payload and the utility task are typically considered.

Since the current velocity of each link is known, the dynamic forces and torques caused by the inertia and movements of each link are calculated from the base to the end effector. The force reference to act on the environment is finally included in the dynamic force at the end effector and the effects of that end effector force are added to the dynamic forces in order to derive the desired actuator forces link by link from the end effector to the base. Thus two successive chains of calculations are needed. The calculation using these algorithms and parallel calculation hardware takes at least (2*N + 6) floating point calculation intervals, where N is the number of d.o.f. of these serial manipulators.

Hashimoto & Kimura (1989) have developed a faster parallel algorithm for the inverse dynamic solution. It can be calculated within (N + 5) intervals and the number of needed floating point operations is (60*N + 19).

The number of calculations of the algorithm presented by Hashimoto & Kimura (1989) is within the possibilities of the controller hardware of the modern industrial robots or evolving numerical processors, but robots utilizing dynamic control have not been presented to the markets. Among the reasons are the difficulties to motivate the customers to pay even a limited extra cost caused by the related hardware and software and the limited power of the motors that anyway prevent the robots from moving unrealistically fast based on too rapid commands.

1.1.2 Force control of multi-limb mechanisms

Force control of the redundant mechanism with several limbs is a logical extension to the studies of force control with so called serial manipulators, like industrial robots. Related problems can be found in many applications in addition to walking machines. Among these applications are co-ordinated control of two or more co-operating manipulator arms moving a common object and universal multi-fingered grippers. The main differences to the gripping problems is, that positions of gripping fingertips can be chosen more freely and gravity has a tendency to keep the foot force references of the properly positioned feet in general in a downward direction since the body is above the terrain.

Thrusters of a free swimming vehicle can also be considered as sort of limbs, since they provide the commanded forces for the body. Similarities and differences to force control of walking can be found in the work done by Silvestre et al. (1991). Forces and torques caused by buoyancy, water currents and hydrodynamic drag have to be considered in addition to gravity. Predictive control based on an extensive model of the vehicle dynamics is used to calculate steering references for all thrusters. Future states were estimated with the model and the quadratic cost functional to penalize control efforts were used.

Force control of the Adaptive Suspension Vehicle

Redundant force control evolved to large extent in the theory of walking machines via the ASV project and its predecessors, like OSU Hexapod (Klein et al. 1983), at the Ohio State University, where Orin & Oh (1981) had considered the concept earlier. R.B. McGhee and Orin presented a paper concerning a mathematical programming approach to control joint positions and torques in legged locomotion systems in 1976 (Gao & Song 1992). Professor Waldron has recently conducted and to a great extent published the force related ASV work.

The body control philosophy of the ASV belongs to the class of "computed torque control" methods. The basic equation used for commanded acceleration (Gardner et al. 1990) is according to Eq. (5). The index d denotes the commanded vectors and $\boldsymbol{x}$ to the position of the body.

$$\boldsymbol{a}_c = \ddot{\boldsymbol{x}}_d + \boldsymbol{K}_v(\dot{\boldsymbol{x}}_d - \dot{\boldsymbol{x}}) + \boldsymbol{K}_p(\boldsymbol{x}_d - \boldsymbol{x}) \tag{5}$$

The force control of the ASV is obviously not completely published. The vehicle has been marketed by a spin-off company (as seen on the title page of (Pugh et al. 1990)). Therefore detailed documentation is not likely to be published in the near future. By using several hints from different sources, however, something about the algorithms used can be outlined. Note, that the force control development of the ASV has been continued for several years and several algorithms have been tested.

The algorithm to calculate the necessary leg tip forces to move and carry the ASV was divided to horizontal and vertical portions in corresponding order (Pugh et al. 1990, p. 36). Song & Waldron (1989, p. 163) consider an algorithm tested on the ASV and based on the Moore-Penrose pseudoinverses very effective in practice. They did not describe the algorithm, but refered to the dissertation of Vijaykumar (1987) instead. However, Vijaykumar (1987) did not describe any "pseudoinverse" algorithms completely and, in addition preferred other methods (Vijaykumar 1987, p. 305, 307).

Clarifications for the "pseudoinverse methods" have been presented by Kumar & Waldron (1987) within the concept of multi-fingered gripping. The methods are based on several assumptions and are therefore called "sub-optimal" by Kumar & Waldron (1987). According to the main assumption, the normals at the point of contact pass through the centroid of the contact points (Kumar & Waldron 1987, p. 252).

Kumar & Waldron (1987) chose quite a surprising coordinate system: z axis parallel to the "wrench axis". All forces and torques exerted on an object can be replaced by a force and a torque exerted along and about the wrench axis. In the case of walking, this may be a difficult coordinate system, since the orientation of the body and the position and the orientation of the line of action of the wrench change continuously as the body of the walking machine accelerates or changes orientation.

The "*zero interaction force*" concept was described by Waldron (1986) to be tested as one of several formulations in the ASV. The basic assumption (and obviously a goal) was, that the foot interaction forces in the horizontal plane are zero. Such a force is defined as "*the component of the difference between two foot forces directed along the line between them*" (Waldron 1986, p. 214).

The complete version of the "zero interaction force" method was presented by Kumar & Waldron (1988). They prove theoretically, that the pseudoinverse solution fulfills the "zero interaction force" requirement when all the force and torque references are calculated together. However, they present a faster algorithm (Kumar & Waldron 1988) to calculate the solution. It is based on a "*helicoidal vector field*". This solution fulfills the original equilibrium equations of the commanded body forces and also the zero interaction requirement. When the number of supporting legs was 3, 4, 5 and 6 correspondingly, 317, 357, 397 and 440 floating point operations were needed in the algorithm in a MATLAB simulation. The inversion of a 3 x 3 matrix was calculated using Gaussian elimination by the MATLAB system in this simulation.

A great deal of effort has been put on keeping the lateral force components relatively small compared to the vertical forces by the ASV project groups during the late 80's. This is done in order to prevent slipping of the foot. The problem was already formulated by Kumar & Waldron (1987).

Gardner outlined three algorithms to "*minimize the maximum ratio of tangential foot reaction force to foot normal force*", when the surface at the points of foot contact do not align with the body z-axis (Gardner 1992). These miss-alignments, i.e. shape of the supporting surface of the terrain, are supposed to be known in advance.

Gardner (1992) formulated the equilibrium equations in the local support coordinate systems oriented according to the local foothold orientation (of each leg) and solved them with pseudoinverse, numerical IMSL software and an approximate solution (Gardner 1992). Gardner compared the solutions with three 0.3*g forward acceleration and tripod gaiting cases, that had different simulated surface orientations. The walking machine simulated had dimensions similar to the ASV and was almost becoming unstable by exceeding the support polygon at the end of all cases. Interaction forces are needed in some walking cases, like walking on the top of a small crest, according to Gardner (1992). The zero interaction concept would not be a proper choice there according to him.

Gardner obtained very large maximum ratios for the pseudoinverse method and acceptable for the others. He does not mention the magnitudes of the forces in the critical legs in the critical phases; they are obviously quite small.

Although iterating, the "approximative optimal solution" of Gardner (1992) is quite attractive; it is well documented and converged usually within 15 iterations. Gardner noticed also that the pseudoinverse solution, however, is better in energy consumption (about 7 per cent reduction).

The problem definition of Gardner (1992) is inspiring. It is better to minimize the force parallel to the ground surface in order to reduce the risk of slipping than to minimize the forces in the local coordinate system of the vehicle. Since a supporting leg penetrates to a varying extent into the soft soil in a forest, there is a rather good coefficient of friction in the (usually horizontal) directions of ground level. Taking into account the often existing angle between the body coordinate system and the estimated slope (ground surface) is therefore desirable. The problem definition of Gardner is somewhat impractical, since the exact shape of ground is usually not known in advance or even if known, the shape and "supportability" of the soil beneath the foot do not correlate a lot. For example, the shape of long grass or other forest vegetation does not correlate with the best support force direction.

Very little is written in the literature concerning the force control of hydraulic actuators. Noisy data sequences presenting pressure histories similar to those presented in this thesis can be seen in one of the ASV documents (Nair et al. 1992, Fig. 11). The ASV figures were measured under position control.

The methods of obtaining the six-dimensional position and the velocity of the vehicle and adding position and velocity error based accelerations to feedforward accelerations are considered successful and important in the control of the ASV by Pugh et al. (1990). Some excellent body position control results are documented in (Pugh et al. 1990).

Force decomposition

The interesting problem of force decomposition has also been considered by many research teams in other applications than walking. Control of multi-fingered or multi-arm gripping and object handling with the fingers or the arms is a dual problem in a sense.

Force control of a walking machine with electrical actuators, force sensors at each leg tip and on soft soil has been studied by Gorinevsky & Shneider (1990). The upper levels of control take care of locomotion and provide the lower levels of control with leg position commands. Factors based on force errors between the calculated and measured values and noticed "sinkages" are added to the nominal positions.

It was interesting to notice several matters in the paper of Gorinevsky & Shneider (1990). They also used pseudoinverse to optimize the leg force references. According to them it provides a solution for minimum energy consumption and is more attractive in computational simplicity. The optimal forces are linearly dependent on the leg positions according to them. They calculated the optimum force distribution in all leg positions when any one of the legs noticed a contact or was to be lifted and interpolated the force commands linearly between the two such instants. Periodic gait was used in their experiments.

Huang & Waldron (1990) also noticed that the support force references change linearly between the time instants, when any one of the legs is lifted or placed. A maximum desired force is needed, when a rear leg is lifted or placed.

Linear optimization (usually called Linear Programming i.e. LP) methods were considered too time consuming in the early evolution of the force distribution problem (Orin & Oh 1981). In the most recent research, however, such methods have been used. The equations of equilibrium would be so-called equality constraints of linear programming and all limitations like non-negativity of the support forces, maximum friction coefficient of soil, and maximum joint forces or torques would be inequalities. As processing capabilities have increased and improved versions of LP have evolved, such methods could also be used in practice.

Cheng & Orin (1990) have developed for force distribution a linear programming method called "the compact-dual LP method". They simplify joint constraints, the friction and equilibrium related equations in several steps and finally rely on linear programming packages; the Simplex method is used in their case. The main difficulty in LP methods is the high possibility of non-continuous solutions; small changes in the situation may cause large changes in the successive solutions.

Nahon & Angeles (1992) consider "linear-quadratic programming" superior to linear programming schemes in terms of speed and quality. The method provides continuous solutions and an initial guess is not needed. Compared to the "compact-dual LP method" the execution times are reduced to half and are in the range of 100 ms with four fingers and a Sun 3/80 computer.

Gao & Song (1992) have developed a method to calculate the leg force distribution by modelling the stiffnessies in the legs and their net effect on the position of the body. They disregarded the deformations in actuators and the terrain. Gao & Song (1992) modelled the bending pantograph legs as energy storage according to structural mechanics while they carry the vehicle. A quadruped walking chair for the disabled was their simulated application.

Maekawa et al. (1991) have combined stiffness and position control of fingers of a three-fingered hand. An object is grasped by stiffness control of each fingertip and moved by controlling finger tip trajectories according to the commanded trajectory of the object. Therefore all actuators are position controlled with variable stiffness. The stiffness chosen is based on jacobians.

Cheng et al. (1993) have considered multi-fingered gripping of planar and solid objects. They have combined the search for finger positions with finger force calculation in a single method. The user can specify the squeezing force in advance. The algorithm based on superposition of normal and tangential finger forces at the "normal force focus" calculates the finger forces, that are also within the desired friction zones.

Tao & Luh (1992) have suggested robust position and force control for a system of multiple redundant robots. The computed-torque based method has something in common with the impedance methods, since the actuator torques are calculated based on nominal acceleration, speed and position error in addition to Coriolis, centrifugal and gravity forces, commanded internal force and terms of redundancy. Tao & Luh (1992) presented a robust control method applicable in situations, when the model of the system is not accurate. They proved the robust method asymptotically stable and showed the stability with simulations using false parameters being one-half of the accurate ones.

1.1.3 Force control of hydraulic actuators

Force control has been considered quite little in hydraulics. Less has been written concerning special equipment that is continuously switched from position control to force control and vice versa. In addition the matter of force control of asymmetric cylinder actuator with a symmetric valve has not been considered in the literature of hydraulics. As a matter of fact such cases are considered unsuitable (Viersma 1980). The reason is the stepwise changes in the pressures during the changes in the direction of the movement of the piston of the actuator. Viersma (1980) definitely recommends the usage of asymmetric valves with asymmetric actuators. The installation used in MECANT I, where the smaller area of the piston usually carries the weight of the vehicle is not considered desirable in literature like (Pyrhönen 1984, p. 41) due to cavitation.

When a asymmetric piston is controlled by a symmetric piston, pressure shocks are noticed, when the direction of the movement is changed (Kauranne 1987). The only method of removing these shocks is to use a special asymmetric valve, the asymmetry of which is the same as that of the effective areas of the piston.

Accurate motion and force control is desired in the paper industry in the finishing of paper reels. This topic has been studied by the VTT Electronics Laboratory in Oulu by Nevala (1991). They have used directional proportional valves for position and velocity control of asymmetrical cylinders and two pressure servo valves for each actuator for the so called nip load control. The nip load is the radial force between the paper roll and the backing reel drum.

The position/velocity control was made digitally, but the pressure control was made with an analog PI-controller according to the set-value calculated by a VME-controller (Nevala 1991). The nip load was measured by shearing force detectors in addition to pressure sensors. A position measurement system with a resolution of 0.001 mm was integrated into the cylinders in order to synchronize two parallel cylinders properly. A maximum of 0.3 kN deviation for settings ranging from 0.5 to 10 kN was also achieved when the load was moving (Nevala 1991).

Nevala (1993) has recently published a paper describing the application of a paper center winder and several analog pressure controllers and a differential form of a digital PI force controller using a force sensor in details. Nevala also studied friction compensated pressure control of the piston side, when constant pressure was kept by pressure servo valves at the side of the piston rod. Force errors were typically less than 0.4 kN as reference force varied from 0.0 to 10.0 kN.

The state equation based force control with different observers and feed-forward methods has been simulated by Conrad & Jensen (1986). Their test case was a symmetrical cylinder with a constant load force. The steady state was disturbed by changes in the position of the piston i.e. the opposing edge of the environment. The changes were sinusoidal with a 1 Hz oscillation. It was assumed, that the environment always generates a constant opposing force. They could maintain the commanded force towards the environment by using state estimate and "unity output" feedback.

Position control of a symmetric actuator has been considered by Köckemann et al. (1990). They consider usage of non-linear methods essential in the control of hydraulics. They present the related state equations and a model for the friction.

Force control of hydraulic cylinders has also been studied by using pulse-width-modulation of a two state four-way valve (Kondo & Yamaguchi 1993).

1.1.4 Gaits of walking machines

There are lot of different subjects to be studied in the locomotion control of walking. The gait used determines the number of supporting legs, decides when a leg is lifted, where an "air-borne" leg is moved to support, outlines the path for a supporting leg and decides the time instant a leg is lifted.

The main subjects of locomotion control are vehicle stability, maneuverability, free gaits and gait selection. Legs have to be in phase so that the weight of the machine is continuously supported and the legs do not collide during continuous transportation of the body.

Slow walking (typical to hydraulically powered walking machines) has to be made so that the body is continuously stable. This means, that the projection of the center of gravity is always within the polygon formed by the outermost of the supporting legs.

The group of periodic gaits is large. It is said to be as many as 40 000 different gaits, since a gait can be characterized by a few real variables. The reader is referred to the extensive gait analysis of Song & Waldron (1989), where follow-the-leader gaits are also presented. The readers of Finnish language are referenced to (Hartikainen 1990). Periodic gaits are characterized by the following matters relevant to the integration of body force control.

- similar states of the same leg during successive strokes occur at the same interval for all legs, that interval being the cycle time (Song & Waldron 1989, p. 28)

- each leg has to wait its turn even if their calculated movements based on the body movement commands may be short and irrelevant.

Gaits that does not follow a fixed sequence of lifting and placing of legs, are called free gaits. The decision of the lifted leg can be continuously based on measured and estimated quantities in a free gait. In addition the number of supporting legs may vary. The most useful quantities for leg lifting decision are its current position, speed and distance to the limits of its mechanical working area as in (Halme et al. 1993). The quality of terrain has also been used to step over bad patches on the ground.

A free gait is a natural choice for force control of body movements, because the future position of an explicitly force controlled leg are not known in advance and the positions depend on local structure and plasticity of the terrain. Therefore free gait algorithms are presented in this survey.

Pal & Jayarajan (1991) considered each leg of a quadruped vehicle as a finite state machine. They considered a simplified case of linear forward gait only. Four different states were associated with the position of each leg. A machine state was designated in terms of the states of the legs. Rows of a state transition table were labeled by a machine state and contained a list of connecting states. The lists were ordered in the order of their promise according to the estimated cost of reaching the goal. A graph search algorithm was used to search for the optimal gait to the goal. In order to create continuous movement, the goal receded as the machine approached the previous goal.

Halme et al. (1993) describe a gait state based free gait algorithm. The definition for states is simpler and the number of possible states is much smaller than that of Pal & Jayarajan (1991). The states (Halme et al. 1993) are actually possible combinations of three to six supporting legs, 33 different ones. The gait control is based on repeated calculation of a triggering variable for each supporting leg. The variable is the "maximum predicted duty time" that is the time the leg has until it would collide with the walls of its (artificial) working volume. The one closing zero is lifted. A new gait state is chosen according to stability and other criterium among the set of currently possible gait states.

1.2 DESCRIPTION OF TEST ENVIRONMENT: MECANT I

The MECANT I is a six legged, self contained, combustion engine driven hydraulic walking machine. The weight is slightly above 1000 kg. It has a computer network for coordinated control; each leg is equipped with a leg controller, that takes care of the elementary servo control (Pitkänen 1991). The machine is remote controlled via a radio link and an operator information system (Hartikainen et al. 1992a).

The number of the legs (six) is chosen for the static stability; the body can be continuously supported by at least three legs during all phases of walking. Eight would be even better in this sense, but would mean a more complex mechanical system.

The hydraulic, mechanical and electrical design is documented more in detail by Leppänen (1993). The maximum forces available at the actuators with different supply pressures are given in Table 1. The maximum supply pressure when the system is powered by the combustion engine is 295 bar. Most of the tests presented in this paper are done with an external pressure supply, the maximum pressure of which is 265 bar. Since the linear actuators are asymmetric, there are different maximum pressures for retracting and extending directions. Only retracting (upward) forces of the vertical actuator are needed, because positive (upward) forces of the leg are not needed. Note, that the ankle moves downward, when the vertical actuator moves upwards, due to the pantograph mechanism.

Table 1. Maximum forces and torques available with different supply pressures

actuator	260 bar	295 bar	test leg 120 bar
Hor+	16000 N	18200 N	7400 N
Hor-	10800 N	12250 N	3600 N
Ver+	22800 N	25900 N	3600 N
Rot	421 Nm	478 Nm	144 Nm

The hydraulic diagrams of the MECANT I and one leg of it are presented in Figs. 4 and 5 correspondingly. The pressure is kept constant by the internal hydraulic control circuit of the pump, the pressure limiter circuit and the pressure accumulator.

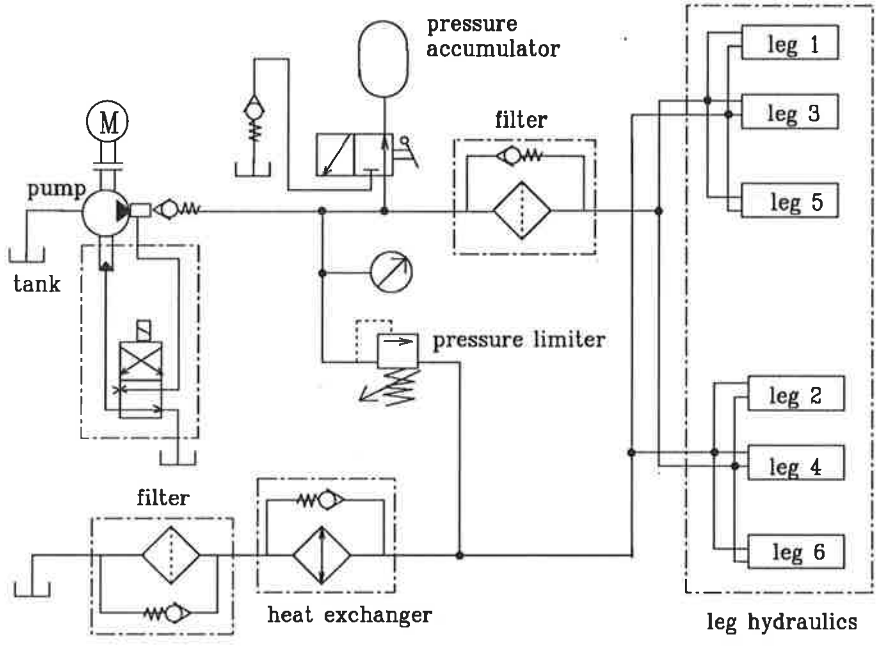

Fig. 4. Hydraulic diagram of MECANT I (Leppänen 1993).

A base for a forest going utility machine capable for walking in all directions was the underlying goal in the design of the MECANT I. Speed of the vehicle was not so relevant in this miniaturized model of a walking machine. In order to be utilized as easily as possible in the markets, cheap off-the-shelf and proven hydraulics were used. The mechanical design of the ASV can be characterized as follows:

- the feet are close to the center point of their working area during normal forward walking (transportation); thus the feet are able to move in any direction

- symmetrical linear actuators are used

- all actuators are driven by individual variable displacement pumps; this minimizes heat dissipation during fast movements of the actuators (Waldron et al. 1984).

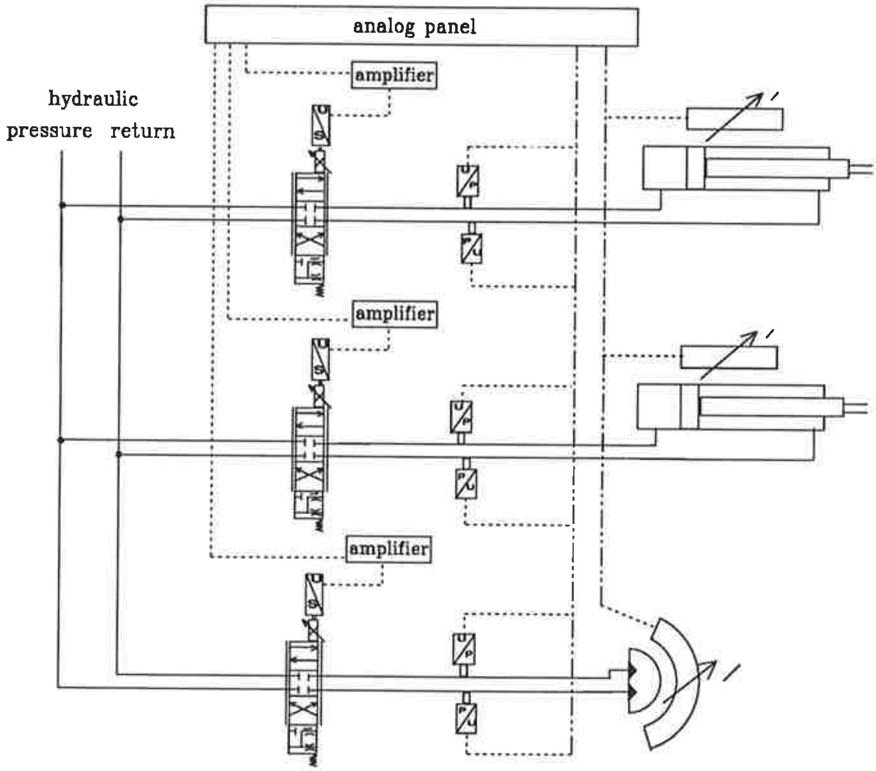

Fig. 5. Hydraulic diagram of one leg of the MECANT I (Leppänen 1993).

1.2.1 Pantograph leg

The pantograph mechanism of the test leg can be seen in Fig. 6. The main advantage of the pantograph leg is the decoupling of horizontal and vertical movements and forces; i.e. if the ankle is commanded to be moved horizontally, only the horizontal actuator has to be moved. Bending lateral forces are the disadvantage of pantograph design; the horizontal actuator also carries the weight of the body frame.

Pantograph mechanisms are considered more closely by Song (1984). Decoupling is actually a conclusion of the Theorems 1 and 2 on pages 303-308 of (Song 1984) and has been proved by Song. The same concept of decoupling is effective for both position and force.

The hardware components participating in the force control are presented in Fig. 7. The pistons of the linear actuators are under cover. The pistons are attached to the cover. The linear actuators were designed during the project, since proper ones were not available on the market.

The vertical actuator (and also piston) moves upwards and retracts, when the ankle is lowered. The upward directed forces of the piston carry the weight of the

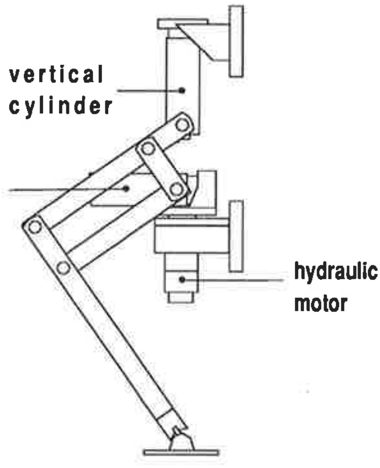

Fig. 6. Pantograph mechanism of test leg (by Pitkänen 1991).

body. Note, that the upward force generated at the ankle of the leg could be larger than the downward forces, that normally carry the body of the vehicle, since the effective surface area at the extending side of the piston is larger. The relation between these maximum forces is the same as the relation between the areas of the piston and the piston rod.

The horizontal piston is also asymmetric. It can push with larger forces than pull. The rotating actuator (motor) is symmetrical and it may rotate less than a full circle.

Potentiometres are used to measure the position of all actuators. Pressure sensors are used to estimate the forces, that the actuators causes to the ankles of the legs.

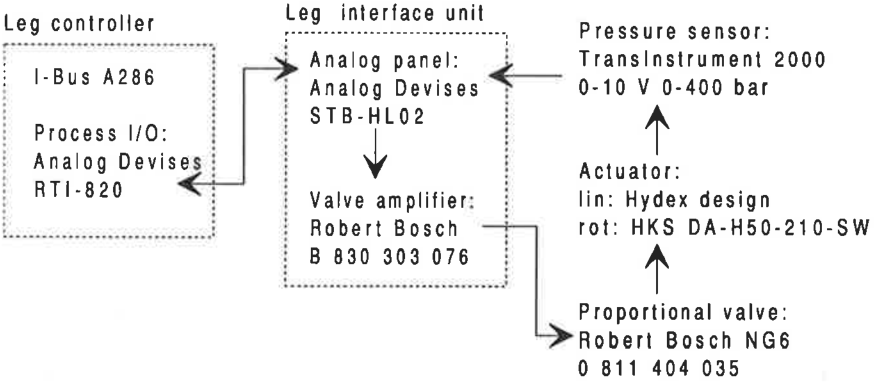

Fig. 7. Hardware related to the force control.

The leg mechanism is described more in detail by Pitkänen (1991). The test leg was utilized in the force control development described in this paper, and it will be installed as a test manipulator of three d.o.f. in front of the MECANT I.

Hydraulic proportional flow control valves with dedicated position servo boards are used to control the hydraulic flow and pressure.

The basic construction of the legs of the MECANT I is similar to the test leg. The size and the maximum forces were increased during the design of the body. The working pressure was also increased from 120 bar to 300 bar. The test leg had similar vertical and horizontal actuators, but the areas on the piston rod sides of the vertical actuators of MECANT I are larger areas than those of its horizontal actuators. The limb lengths were also increased, but not the relations; thus the mechanical gain in position and the relative reduction in force remained the same (4 for vertical and 5 for horizontal). The ankle was simplified to one free rotational axis parallel to the last bar and a spherical "shoe".

1.2.2 Equipment used for force control

Force control of hydraulic actuators is done by regulating the control voltage of the valve from -5 to +5 Volts. The voltage input was originally meant for the control of oil flow through the valve in a relative manner; no flow with zero voltage and valve totally open with +5 V or -5 V. The actual flow is a function of the pressure used, supply and chamber pressures, oil characteristics and temperature.

The force generated by the actuators depends heavily on factors other than the valve and actuator themselves. The movements of the actuator change the force output greatly, since hydraulic oil does not get compressed a lot, when the pressure is increased. The compression of all fluids is small.

The compliance of the leg mechanisms allow the actuator to move, when the opposing force is changed. This movement, even a small one, changes the oil volume and therefore rapidly the pressure. The oil volume in the hoses and pipes is also compressed when the pressure is increased. The flexibility of the hoses usually causes more oil flow than the compressibility of oil.

The source pressure is generated by a rotating pump. The pump creates a lot of high frequency fluctuations in the supply pressure. The force control is based on pressure measurements. If the supply pressure fluctuations do not arrive at the actuator chambers simultaneously, the fluctuations can be seen as noise in the force estimation.

The output resolution of the analog output boards is 2.44 mV. If the actuator does not move at all, the output pressure varies from zero to the supply pressure within three per cent of the control voltage (150 mV). Thus 122 different voltage values can be used with the theoretical force control area, where oil does not flow at all. The discretation may cause some noise in the output pressures and forces.

The analog boards have a timing problem compared to an ideal D/A converter. Since the analog output values are transmitted to the board via an eight bit byte location in the shared memory, three such bytes are needed and the board needs time to refresh itself. One DA-conversion lasts about 3 ms. The vertical control voltage is written to the DA-converter immediately after calculations, but due to the time needed for refreshing, the horizontal and rotational voltages are written after 10 ms delays. This is repeated after every 40 ms, which is the servo interval.

Force control hardware is presented in Fig. 7. For sensors are not used in the ankles, because they would easily be broken in natural terrain, that may contain rocks, or cause reliability problems below freezing point. There is often water in the soil under the snow in Finland. Force estimation using the pressures is performed instead of using force sensors.

1.3 OTHER POSSIBLE APPLICATIONS FOR FORCE CONTROL

The main subjects studied in this work are:

- the force control of hydraulic equipment mentioned for position control and

- the optimization of actuator forces of a redundant mechanism, that produces the force commands to an object by using all actuators.

Applications where the developed methods could be used are quite numerous. Redundancy is, however, quite rare in practical machinery due to the cost of the extra actuators needed. An automatic changeover from position control to force control could be a desirable safety improvement in many hydraulic machines. If collision is detected during position controlled movements, a change over to maintain a certain force could reduce the damage of the collisions. The following examples of evolving systems, that could use the developed methods, can be mentioned:

- the co-operation of several robot manipulators (for example fingers) to move (or carry) an object

- force operated excavator arms; new operator interface or teleoperation

- the optimization of the steering jets of a close maneuvering satellite and similarly the steering jets of a floating underwater vehicle

- active shock absorbers with return of constant duration to the start position commanded

- stabilizing force based attitude and altitude control of road vehicles during changing load and road conditions

- the steering of floating oil production platforms

- stabilization of a large mass on moving platforms or in the presence of external disturbances.

- usage of a manipulator or boom arm of a work machine vehicle to stabilize the vehicle in case of emergency

One of the examples is considered more closely in the following section.

1.3.1 Force controlled excavator

Let us consider a typical excavator with a bucket. The boom itself has two degrees of freedom and the bucket one, to change the angle between the bucket and the last joint. The boom (and the chair of the operator) is installed on a rotating base. The operator moves the bucket traditionally in a cylindrical joint axis based coordinate system.

A cylinder coordinate system would be better for the steering of an excavator arm. Thus the operator should also be provided with a possibility to move the cutting tip of the bucket edge in a cylinder coordinate system and simultaneously to be able to control the orientation of the bucket. The directions concerned by the operator should be up-down, right-left and extend-retract. They could also be the intermediate degrees of freedom of the control system. Adding more degrees of freedom to the "wrist" of the bucket would enable more flexibility to the motions of the bucket.

The force control of an excavator and feedback from the detected forces in the bucket using so-called telepresence would mean better feasibility in several duties like digging soil close to piping in muddy waters. The operator would feel the pipes without breaking them. The load of the bucket is lighter than the force caused by collisions with rigid objects in the environment. Telepresence could also help in loading large stones into the bucket.

In the suggested concept of teleoperation of an excavator, the operator is provided with a pendant equipped with a tip (master), the movements or forces of which are enlarged to the bucket (slave). When considerable opposing forces caused by the ground are detected, the arm switches over to the force control mode and the detected forces are informed to the operator by the master arm in a so-called bilateral manner. The operator provides a four axis force reference with the master arm to the tip of the bucket. The control system calculates the optimum set of actuator forces that generate the tip force reference by using the optimization methods presented in this work. Similarly the load adaptive PI force controller presented later is quite usable with typical hydraulic systems of excavators.

The force feed-back of telepresence is traditionally provided by reflecting process forces (felt by operator via the slave arm) to an actively controlled master arm. Small air tight plastic bags under the finger tips of the operator and pressure (reduction) control of the bags could be a cheaper method.

A future vision of an excavator operated by telepresence and bilateral control is presented in Fig. 8. The operator feels the opposing objects in the soil

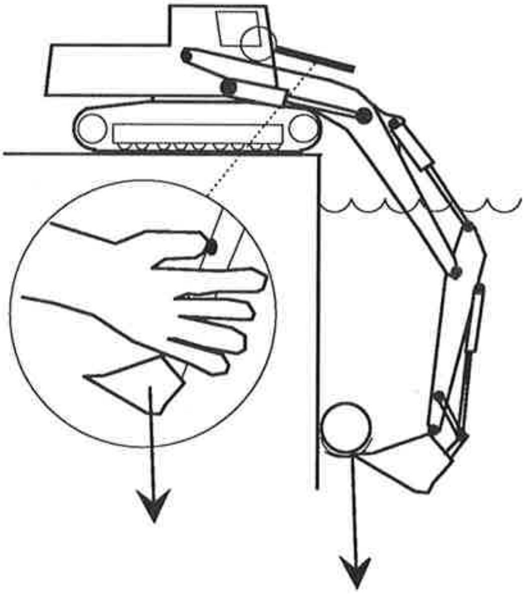

Fig. 8. Force controlled excavator.

via the control pendant instead of seeing them or estimating them by using the engine sound and vehicle vibration. The economic aspects of the technology could be motivated by the smaller risk of damaging objects buried in the terrain, like cables and pipes.

Another simpler and more practical force control method of an excavator is suggested. The operator could have a potentiometer knob to adjust a "force level" between 10 and 100 percent. If the full 100 percent is chosen, the excavator arm would act as previously with full actuator forces or according to the flow orders adjusted by the control pendants. If a value less than 100 is chosen, the force output of actuators would be only a proportional share of the maximum force of the actuators, when opposing forces have been detected. The operator could reduce, with the method suggested, the risk of damaging forces when the cavity gets close to the objects aimed at. The surface of the cavity could also be more even than when dug with the full forces.

2 FORCES OF STATIC WALKING

The forces of static walking are considered in this chapter. Static walking is the short form of "statically stable walking". It means in practice, that the body is continuously supported by at least three points i.e. feet in this case. If a statically stable walking machine is stopped, it would remain in the same orientation and position. Statically stable walking means, in other words, slow speeds and small accelerations and decelerations.

Gravity forces are more significant and larger than inertial forces due to relatively small angular and translational acceleration in statically stable walking. The opposite is true with dynamic walking, where inertial forces of the body are used actively to balance the body. For example trotting four-legged machines have been developed (Yoneda & Hirose 1992). Two leg pairs on the opposite sides support the body one pair after another. The vehicle could not balance on the two legs even if it could stop. Dynamically stable walking machines are usually addressed as running machines. Among them are the well demonstrated one-legged hopping machines (Raibert 1986).

Considering only static walking, also decreases the complexity of force related calculations. Force control of a walking machine can be considered basically as force control of a free mass or body, because the body of the machine is typically much heavier than the moving legs. The complete basic motion equations for a free object are the well known equations of Newton (6) and Euler (7):

$$\boldsymbol{R} = m\ddot{\boldsymbol{x}} \tag{6}$$

$$\boldsymbol{T} = \boldsymbol{I}_t\ddot{\boldsymbol{\theta}} + \dot{\boldsymbol{\theta}} \times (\boldsymbol{I}_t\dot{\boldsymbol{\theta}}) \tag{7}$$

$\boldsymbol{R}$ and $\boldsymbol{T}$ are the resultant force and torque applied to the body. $\boldsymbol{I}_t$ is the so called inertial tensor (3 x 3 matrix) of the object. It depends on the position and the orientation of the coordinate system. It is wise to define the coordinate system origin at the center of gravity and orient it according to the main axes of inertia in order to keep non-diagonal (mass products of inertia) values small. This has actually been done with the MECANT I. The diagonal values (mass moments of inertia) are the sums of the masses of each component multiplied by the square of the distance to the corresponding axis. The non-diagonal values of the MECANT I are less than one percent of the diagonal values and therefore value 0.0 is used for the non-diagonal values in the torque control of the body. It is assumed, that the error caused by this simplification can not be seen in the movements of the body. This error is in the same magnitude as caused by the legs accelerating during the movements in the air. The latter part of the Euler Eq. (7) deals with gyroscopic forces related to rotation and is typically neglected with statically walking machines. The friction in the supporting legs and the non-idealities of the hydraulic system are assumed to cause definitely more disturbing force components than the simplification of the inertial tensor.

The following forces of walking are considered in the described analysis of walking:

- gravity

- inertial forces caused by the translational and angular acceleration references

- viscous i.e. speed dependent friction forces

- utility forces i.e. the forces the vehicle should provide to the external world

- leg forces to be provided by an individual leg

- actuator force and friction forces in actuators.

The forces caused by reference acceleration are essential in this work, because many of the methods presented belong to the class of "computed torque" methods, where the force references are derived from the acceleration references.

Chung (1985) has extensively considered and simulated force interactions between legs. The two-dimensional imaginary model had three linear one degree of freedom legs. The hybrid control signal for an actuator was based on the position, velocity and force error of it. Actual forces were estimations of the contact forces.

The case of continuous control was found stable by Chung (1985, p. 216), but discrete control was stable only with shorter control intervals. The instability was indicated by oscillating force interactions between the legs, but the body or the support force of it were not affected. Chung (1985, p. 225) assumes, that the insufficient control frequency and extensive stiffness of the simulated system are the reasons for the instability.

It is assumed, that the large mass and inertia of the body of the MECANT I reduce the possibility of oscillatory leg interactions. The relatively slow tuning of the leg force controllers is also assumed to disable leg interactions. Note, that position feedback is not used in the force control of actuators of the MECANT I, but was used in the analysis of Chung (1985). Position feedback will easily cause stiffness, that in turn will easily cause oscillations as will be seen later in Fig. 48.

Oscillatory leg interactions have not been noticed in the numerous tests made with the MECANT I although the leg force controllers are not exactly stable, when the actuators do not move, as will be seen later in chapter 5. An analysis of the leg interactions have not been done due the reasons presented above. However, several of the sheet-iron plates in MECANT I started to oscillate in their resonant frequency of about 20 Hz during a few tests, where the legs did not move.

The tip forces can be used in most aspects of analysis of force control of a walking machine due the well known "force-couple" system of mechanics

(Meriam & Kraige 1987, p. 40). The tip forces are not relevant for example in the analysis of energy consumption. Energy is consumed of course by the actuators. If we know the instantaneous force (F) and velocity (v) of each actuator, the power of energy consumption of one actuator is given by:

$$p = F v \tag{8}$$

Adding the power of all actuators together according to Eq. (8) gives only an approximative result in practice, since there are plenty of fluctuations in speed and force estimates. When the force estimates are based on the measured pressures, the power consumption also includes the power needed to overcome the friction forces. Powers of some actuators may become negative indicating that the actuator moves in the opposite direction to the force it generates. In the hydraulic power system of MECANT I, the backward flow of one actuator will be used by the other actuators. Large amounts of backward flows will return to the tank via relief valves and the corresponding energy can not be reused.

Energy consumption of walking is actually quite a complex matter, as shown in the analysis of Lapshin (1993). Two intuitive means to keep the energy consumption as small as possible have been used in this work. They are to keep all forces as small as possible and to remove the force peaks, that often exist with position controlled actuators, that can load each other.

2.1 PROBLEM DEFINITION

The purpose of the thesis is to define all force related matters of walking with a walking machine. The result should be usable and well documented, when force controlled walking machines for soft and uneven terrain are to be developed or the characteristics of position controlled walking are to be improved.

Solutions to the following matters were to be developed at the beginning of these studies:

- even load distribution for the legs of a walking machine with a minimal number of calculations
- energy efficient locomotion control in uneven, varying and soft environment
- minimization of the possibility of a leg to slip
- necessary user interface to force controlled walking
- stabilization of the body despite rolling due to steps taken
- force based motion control of a walking machine despite leg penetration in to the soil during a support phase

- ankle force estimation without force sensors

- evaluation of the necessity of force controlled walking modes

- force control of hydraulic actuators using pressure sensors only; especially force control of the hydraulic system installed in the MECANT I

- realize force control despite different types of non-linear friction

- integration of force control and position controlled locomotion in order to improve soft and uneven terrain adaptability.

2.2 EXPERIMENTAL FORCE ANALYSIS OF BODY

Experiments were done in order to analyze the behavior of the body supported by legs. Impulse tests were made at first. One of them is shown in Fig. 9. The body is lying on the floor in the beginning, but supports itself with six legs. The supporting force is increased by 3000 N in an instant as shown in the lower part of Fig. 9. The sum of the estimated vertical leg forces is also shown by the dashed line. The upper part shows the vertical speed of the body. As seen, there is a delay of one second, until the body starts to move. The force reference

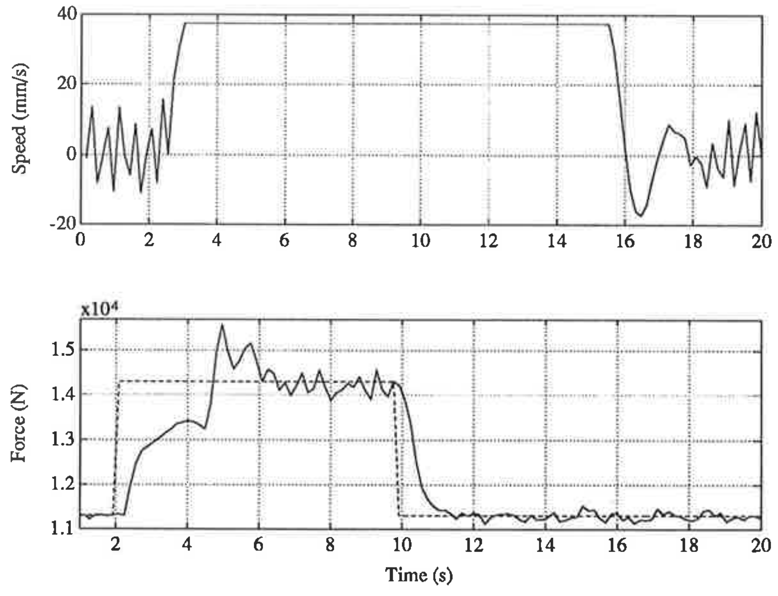

Fig. 9. Impulse test: body lifted by a constant force for a certain duration.

is not met in the beginning. Note, that the speed of the body soon reaches its maximum value and is constant for about 5.5 seconds after the lifting force reference has been stopped. Limitation of the speed is obviously due to the maximum yield of the hydraulic pump. The energy stored in the compliance of the leg joints during the acceleration phase and the comparatively small share of viscous friction are other reasons for this kind of movement. The acceleration is immediate due to the large amount of static friction. An ideal freely floating mass would increase speed with constant acceleration during the pulse of extra force and maintain the achieved speed after the pulse.

Orientation has not been controlled in the case of Fig. 9. It varied other-wise slowly between -2 and +2 degrees, but there were some oscillations (from 11 deg to -5 deg) after 5 s but earlier than 6.5 s from the start. Based on Fig. 9 one can only come to the conclusion, that the vertical speed should be actively damped i.e. braked.

Braking was tested in another test shown in Fig. 10. By properly choosing the magnitude and the duration of the braking force, the body was neatly stopped. Braking also has an effect after a certain delay. In this case it is about 1.7 s.

An interesting observation can be made concerning the natural frequency of the vehicle according to Figs. 9 and 10. The body can be seen to oscillate vertically with an angular velocity of approx. 0.5 1/s. The legs and the actuators are compliant mechanical structures. The well analyzed spring-mass-damper model of a second order (Dorf 1974) can be applied to support of the body. The damping ratio and the natural frequency of the system can be estimated experimentally.

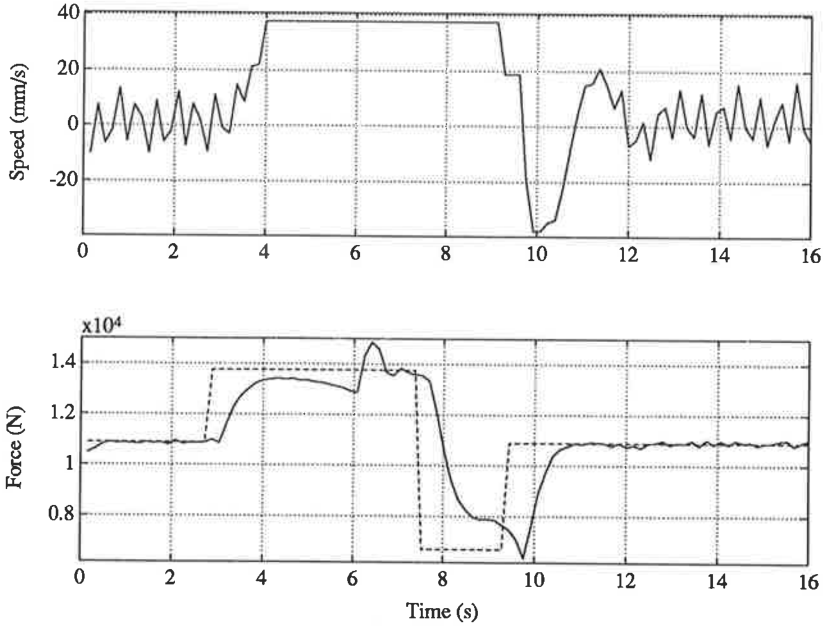

Fig. 10. Upward impulse (2850 N) test with downward brake (-4200 N).

Energy is stored as strain energy to the deformations of the compliant mechanism. Pugh et al. (1990, page 35) claim that this energy could be utilized in the control of the ASV, but further information is not given. This could be an interesting subject for future studies.

2.3 FORCE CONTROL VERSUS POSITION CONTROL OF LEGS

The main advantage of the force control of a body is its ability to adapt to the elastic and plastic soil material typical in the forest environment. Plasticity means here, that the displacement does not disappear, when the load is removed. The characteristics of the soil vary a lot in a typical forest. Under the surface there may be hard rock or wet soil, that at first allows penetration as a damper with a greatly variable damping factor, that usually increases. Some objects, like branches, may act as springs under the foot.

Load-displacement curves of forest soil in Finland are presented for example by Lammasniemi (1983). The curves display the vertical resisting force as a function of displacement, when a circular plate penetrates into the soil. The curves show the wide variation of soil characteristics in a forests. The in forest soil is typically plastic. A force controlled leg would carry the body as desired even if the leg penetrates into the soil during the step.

Let us assume a case, where four legs are used to support the vehicle and there is a hole in the terrain under one of the legs. It is certain, that the leg will float in the air with position control, but contrarily move rapidly to the bottom of the hole with force control. If the leg above the hole is critical, the machine will fall over with position controlled legs, if the bottom of the hole is not met earlier due to the tilting of the body.

Force control will soften the movements of the body due to the elasticity of the force control compared to the more rigid position control. If a stone got stuck between two legs, they would press it between them relatively hard under position control. How hard, depends on the compliancy of the position control and the legs. This is not the case under force control, where the pressing force would be the commanded one and is typically very small between two legs.

Inaccuracies in the leg coordinate system i.e. inverse kinematics of legs are the main reasons for large forces between a pair of position controlled legs. Because position control will maintain the largest possible forces in the case of such inaccuracies, the energy losses are also significant in such cases. Force control will prevent such excessive forces and therefore reduce energy consumption.

2.4 EXPERIMENTAL ANALYSIS OF FORCES DURING WALKING

The use of force estimation during position controlled walking offered a possibility to analyze forces during walking. A series of tests were made to define the coefficients of friction. The MECANT I was lifted into the air and slow walking under position control was activated. Actuator forces were estimated during the movements of the legs, transformed to the leg coordinate system and stored at 40 ms intervals. The YZ path and the friction forces of the test are presented in Fig. 11. A clockwise movement has been made. The position units are in mm and the forces in Newtons, but divided by 5. Note, that the weight of the leg is combined with the friction along the Z axis. The friction parallel to the Y axis of the leg coordinate system seemed to be rather small. It varied between 50 and 100 N during the faster movements in the air and was about 50 N during the support phase. This means, that during walking with four legs supporting on level terrain the friction is compensated for by an extra force of about 200 N.

The situation is different, when the body is carried. The body was standing still in the beginning of the test, but supported by the legs. Leg 1 is supported by a force of about 2000 N in the beginning. The body accelerated forward during the first second. The Y component of the leg force increased to 1000 N during the first second. Oscillations were noticed in the Y component later on during the support phase. They are an indication that the other legs start to drag, but also an indication of the compliance of the legs in the horizontal plane.

The YZ path and the estimated forces of leg 1 and the test where the weight of the body was carried are presented in Fig. 12. A counter-clockwise leg movement was made. The starting position and the direction of movement is presented by an arrow. The position units are in mm and the forces in Newtons, but divided

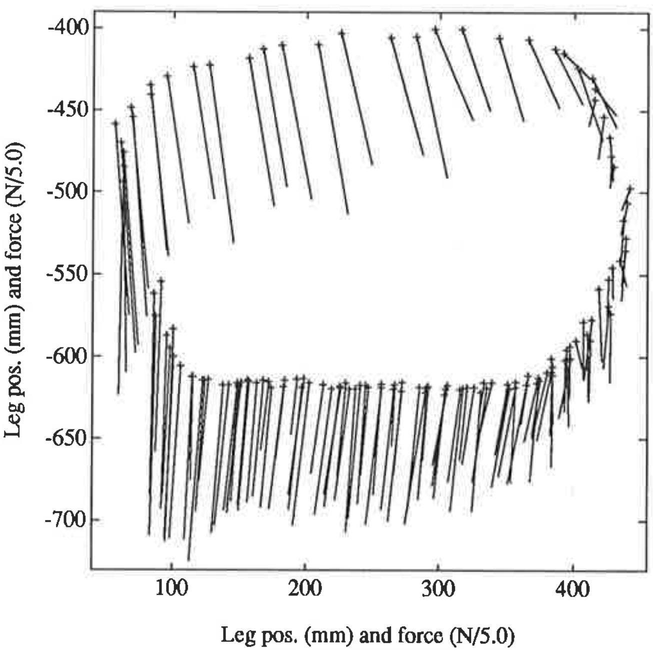

Fig. 11. YZ path and forces due to leg weight and friction shown during a clockwise step.

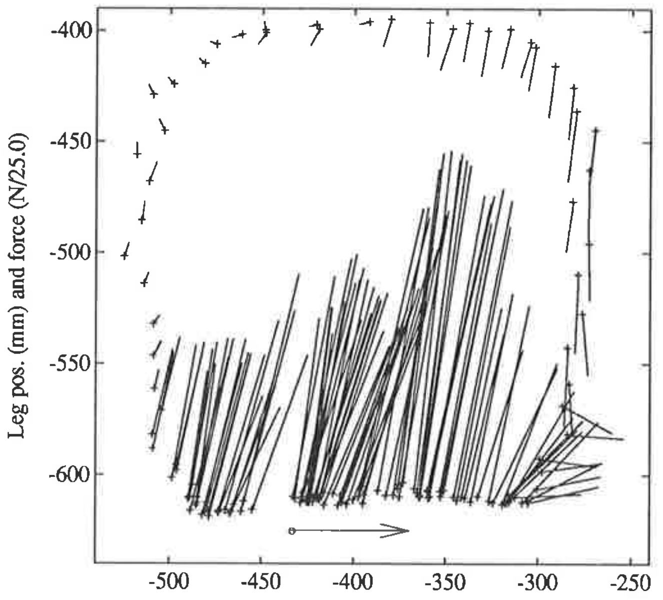

Fig. 12. YZ path and forces of leg 1 with the body carried and accelerated forward on a flat surface; a counter-clockwise step taken.

by 25. The horizontal force components during acceleration can be clearly seen. One may also note, that the horizontal forces are first increased and then the movement is started. The increase of dragging forces after ground contact has been reached can also be seen. Note, that these figures are based on tests, where position control of legs is used. The forces are presented as vectors starting from the position of the leg tip indicated by a '+' character. The forces are caused by the supporting ground to the leg.

All thrusting forces of the supporting legs are added together in Fig. 13. It shows, that a force in excess of 1000 N is used to move the body forward. There is, however, severe oscillation with a rather constant period in the forward thrusting force. The reason for the oscillations is the horizontal compliance and back-clash of the legs. This oscillation does not cause a lot of movements, but causes notable forces due to the large mass of the body. An indication of the oscillations can also be seen in Fig. 12. There are clusters of leg positions during the support phase, that contain more positions than other segments of the support phase.

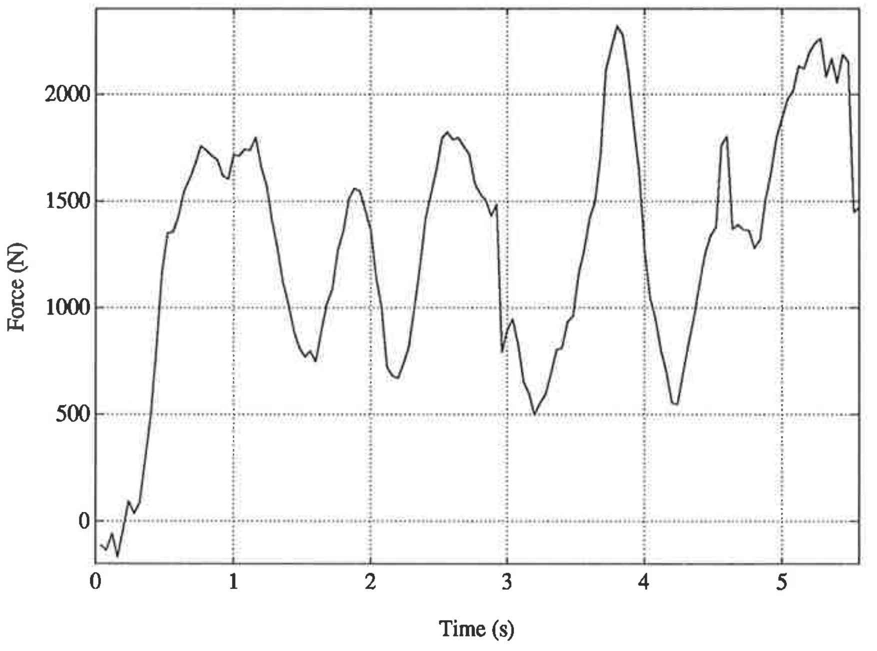

Fig. 13. Sum of forward thrusting forces of all supporting legs while MECANT I is accelerating forward from rest on a flat surface.

3 DESIRED FORCE CONTROL MODES OF A WALKING MACHINE

There are two main motivations for force control of a walking machine. The first one is improved ability to negotiate uneven, soft and plastic terrain. On the other hand an application of a walking machine may desire the body to provide certain forces. The body would provide, strictly speaking, either maximal force or no force at all under pure position control in case the positions can not be followed exactly due to external objects or loads.

Despite the fact that excavators are in a mechanical sense, position controlled, the operator may skillfully control the valve handles (actuator specific potentiometres) so that crude force control in actuator space is made. Also the compliances in the mechanisms and terrain support help in keeping the forces smaller than the maximal ones in the case desired. The force control methods presented in this work provide a means to establish commanded forces with more variety and smaller resolution and oriented to the task space of the application.

The main task of a walking machine is to move in all six degrees of freedom of the body. It may move the body either due to transport itself and the payload or participate actively in the task the vehicle and its equipment are performing. Such modes where the vehicle participates in the task of the vehicle are called in this work utility modes. The vehicle may be desired to provide a force or simultaneously a force and a path for the body during utility modes. Thus the force control modes can be divided into utility and transportation i.e. motion modes.

The operator interfaces described here refer to the radio-linked remote operation system of the MECANT I. However, the tele-operation interfaces presented are of such high functional i.e. supervisory level of the vehicle, that they could also be used with more automatic or even autonomous piloting of the vehicle. As matter of fact, reading the command vectors from a human being via control sticks is more difficult, than from another computer as seen from the point of view of a walking machine.

The coordinate systems used in the MECANT I are presented in Fig. 14. The numbering of the legs can be seen in the left top view. The subscript b denotes the body coordinate system, Li the leg coordinate systems, p the path coordinate system and t the terrain coordinate system. The origin of the path coordinate system (Hartikainen et al. 1992b) is located in the origin of the body coordinate system, but the XY plane of the path coordinate system is in the horizontal level. The support plane is estimated by the positions of the supporting legs. A dashed line describing the estimated support plane is shown in the right sub-figure of Fig. 14. The intersection of the Z axis of the body coordinate system and the support plane is the origin of the terrain coordinate system. The X axes

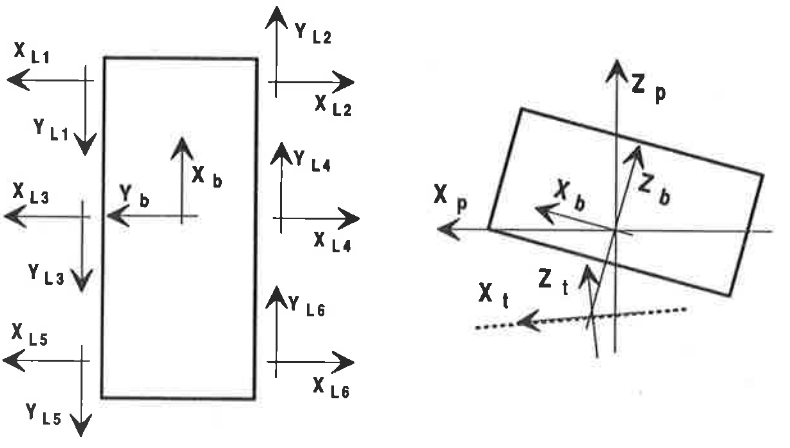

Fig. 14. Body (b), leg (Li), path (p) and terrain (t) coordinate systems. Top view on the left and side view on the right.

of both the path and the terrain coordinate systems are in the plane defined by the X and the Z axes of the body coordinate systems.

3.1 FORCE CONTROLLED MOTIONS OF BODY

The established methods of user interface for locomotion (Leppänen 1993, Hartikainen et al. 1992c) are also proper for force controlled motions of the body. The underlying idea is to derive the command accelerations and forces based on the gravitational forces and changes in the operator given body velocity references. A new operator interface is not needed, but an accurate model of the vehicle is needed in order to define all forces that are present during the operator desired movements.

The mode assumes, that the body is not subject to external disturbing forces but is free to move. Therefore the inertia based model can be used to derive the body force references.

Entering the resultant of the body force or components of it could be an alternative to operator interface. It is, however, considered a less useful method. The operator should then change the force reference according to the attitudes or the body or the attitude of the terrain walked on. The resultant or the body forces reference never points in the same direction as the body should be moved. Therefore the usage of velocity based operator interface is purposeful.

3.2 UTILITY MODE

The main principle of the utility modes is simple. The operator continuously defines a force that the body provides for the utility task. The system then calculates all the other needed forces to support, stabilize and reorient the vehicle. The idea is to let the operator concentrate only on the utility force needed in the application, so that he or she does not have to concentrate on the body movements.

The velocities of the body are supposed to be small in the utility modes. Movements are, in addition, not always necessary. The utility equipment could also desire that different time series of forces be provided to the environment without moving.

Pulling and pushing objects with the body or mechanical pushers or hooks attached to it are examples of the utility modes. The vehicle could also tap or even (smoothen) the terrain with special tools attached to it. With a proper gait or environmental measurements in order to prevent the feet from stepping into the furrows, a walking machine could participate in agricultural tasks such as plowing. Planting trees is a utility task, where force estimation can be used to select a proper planting location. Bulldozing in such locations as accident areas where a human being can not enter do to poisonous substances involved, may be a proper task for a force controlled walking machine.

An example of utility tasks is presented in Fig. 15. It concerns pulling a boat ashore. As we all know, pulling a boat with a sharply raising force may break the rope or attachments to the boat. Pulling the boat with a tractor typically causes sharply increasing forces. The magnitude and the direction of the utility force ($\boldsymbol{F}_u$ in Fig. 15) can be defined by the existing operator interface, but the point of attachment has to be defined for the system in advance. This is not usually a problem in practice, since new tooling or attachment points are not frequently installed.

Note one practical advantage of pulling. When the directions of the utility force and the rope differ, the body reacts to the force component perpendicular to the rope by reorientating itself to an orientation and a position where the force and the rope are parallel again. Thus the utility forces help to stabilize the body.

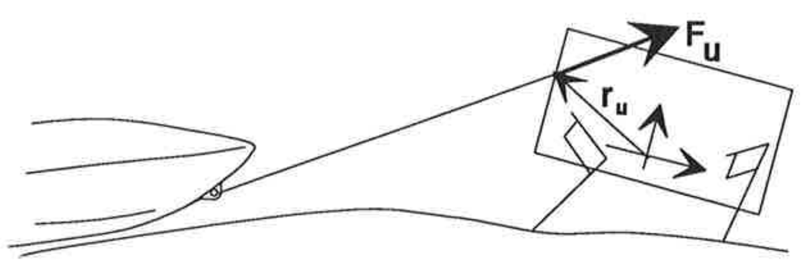

Fig. 15. Utility mode: pulling. Operator concentrates only on the pulling force $\boldsymbol{F}_u$, but has to predefine attachment position $\boldsymbol{r}_u$.

3.2.1 Operator interface of utility force mode

Handling one of the control sticks can be done without losing concentration on the utility task according to personal experience. In other words, the operator should be able to define the utility force continuously by one control stick.

The direction of a utility task force is usually attached to the horizontal level outside of the vehicle. An attitude change of the body should not demand any steering reactions by the operator. Therefore the utility force demand is defined in the path coordinate system (see Fig. 14). The path coordinate system also has an important role in the stability control (Kärkkäinen 1992).

The utility force command is entered with the three d.o.f. control stick. Continuously entering three dimensional vectors with the three d.o.f. control stick and concentrating on the utility task simultaneously may be difficult and cause oscillations. Therefore in some modes of utility force operation one of the force components is defined in advance and the two other continuously adjusted by the two axis control stick. The operator decides, by the selection of the mode, which of the force components in the path coordinate system is constant, and may select the maximum absolute force in the plane defined by that constant force and may continuously adjust the other two force components with the control stick. The third d.o.f. of the control stick can be used to select the constant value in advance.

If the constant force component is along the Z axis or is zero, the utility force is in the horizontal level. Then the utility force vectors are within a circle. If the constant component is not zero, the force vectors start from the top of a cone and end at the bottom plane of the cone. For example in the case of Fig. 15 it is wise to lift the bow of the boat to lighten it for easier movements. This lifting force would be the constant component.

When the X axis of the control stick unit is oriented according to the horizontal projection (seen from above) of the X axis of the vehicle, pushing the "force" control stick forwards causes a forward utility force. In other words the utility force points to the direction where the control stick is pushed when the vehicle and the operator control stick unit are similarly oriented.

Let us assume, that the force control stick for the utility force gives two values u_x and u_y between -1.0 and 1.0, the vertical component (Z axis of the path coordinate system) of the utility force is F_c and the maximum absolute force in the plane parallel to XY plane defined by the F_c is F_{pmax}. The components of the utility force in the path coordinate system are given by:

$$F_u^x = F_{pmax} u_x \tag{9}$$

$$F_u^y = F_{pmax} u_y \tag{10}$$

$$F_u^z = F_c \tag{11}$$

The definition of utility force is visualized in Fig. 16. The operator may desire similar constant forces in other main directions, too. These cases can be handled similarly. Another more general alternative would be to allow the opera-

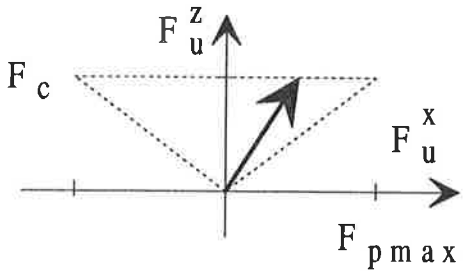

Fig. 16. Definition of utility force by one constant and two continuous variables entered by the operator.

tor to define a three d.o.f. vector, that should always be present in the utility force, and allow the operator to define the forces in the perpendicular plane by the control stick. Usage of a coordinate system attached to a tool and related camera system can be useful with teleoperated applications, when the walking machine is equipped with a manipulator arm. Then the operator could command forces to be provided by the legs to the environment via the body and the manipulator. The operator could easily define the forces in the plane of visual screen and the direction perpendicular to it.

Special user interfaces may quite easily be developed for special applications based on entering three dimensional vectors for the control system. Entering torques may be similarly important in some applications. Further description of extensive operator interface alternatives is skipped for future research work.

The utility force vector given by the above equations has to be transformed to the body coordinate system. Such transformations are already used in locomotion (Hartikainen et al. 1992c). The result is the utility force reference in the body coordinate system $\boldsymbol{F}_{ub}$.

Usage of a "dead-man-handle" would be highly desirable here in order to prevent rapid movements when the opposing force to the utility force vanishes from the environment. This would be the case, when the rope is cut in the case of Fig. 15.

4 OPTIMIZATION OF LEG FORCES

The main duties of legs is to support and move a walking machine. These duties can be combined and transformed to a force control problem. "Computed torque method" is a common name for these methods. In the case of a walking machine such a six element force vector is calculated for the body, that would move, rotate and carry the body as desired. The three first elements are forces along the directions of a rectangular coordinate system and the three last elements are torques about the same axes. The body coordinate system attached to the frame of the body is usually used.

The supporting legs should, of course, provide the reference forces to the body of the walking machine together. The number of degrees of freedom (d.o.f.) of the body is six and there are always at least three legs supporting a statically stable walking machine. The number of d.o.f. in a leg is three. The number of leg force solutions, that could generate the body force reference is indefinite. The optimization of the leg force solution i.e. choosing the best solution is called "the leg force distribution problem".

The analysis is based on the following assumptions. Some of them are especially relevant for walking on natural terrain.

- The force analysis can be based on the tip forces at the ankles of a walking machine.

- Leg mechanisms can be assumed to be solid. The energy stored to the compliance of the legs and the supporting terrain is not utilized, because the amount of the energy stored depends on the quality of the soil in the terrain and attitude changes of the body. These factors can not be modelled. The forces caused by this energy are considered as noise in the control of walking.

- Motion of a walking machine is co-operation of numerous actuators, that are subject to different forms of friction during the motion. It is assumed, that the compensation of the frictional effects can be done on a larger body scale instead of actuator level friction compensation.

- Several such leg mechanisms are attached to the body, that can provide three dimensional pushing forces in any direction to the environment.

- The weight of the body is comparatively large compared to the horizontal thrusting forces available.

- Stable force servos can be realized at the actuator level.

- Dynamic forces dealing with acceleration or deceleration are considered similar to static forces in order to simplify further integration of dynamic control.

The multivariable control alternative of body motion control, for example Eq. (5), was not tested in practice. The methods presented are supposed to be more applicable to soft terrain, because motion estimation of the body is not needed to the same extent as in multivariable control.

4.1 BODY FRAME FORCE REFERENCE FOR MOTION CONTROL

One method of solving the force distribution problem and its extension to minimize the risk of leg slippage on slopes or with an inclined body is presented in this chapter. The optimization is based on pseudoinverse minimization in two successive phases: the lateral forces are first optimized separately and then the vertical forces including the previous solution in the leading equations.

The possible angles between the body and terrain are quite limited in practice. The probability of slippage is minimized by choosing the first optimization plane perpendicular to the supporting force reference.

The main idea of the force based control of a vehicle body is to combine all requirements to move and support the body to a single six d.o.f. force vector. The changes in the desired movements are seen as accelerations. The mass and inertia of the body are known, so the changes in the velocity references of the body can be changed to body force requests.

The following factors are used to contribute to the body force request:

- weight of the body
- operator given velocity and position references
- friction of locomotion caused by soil compaction and leg mechanisms
- altitude and attitude control

Let us consider an object with a coordinate system attached to it. If several concurrent forces $\boldsymbol{F}_i$ (the sum of which is the resultant $\boldsymbol{R}$) act on the object at locations $\boldsymbol{r}_i$, the total torque $\boldsymbol{T}$ is:

$$\boldsymbol{T} = \sum_{i=1}^{N} \boldsymbol{F}_i \times \boldsymbol{r}_i \tag{12}$$

Note that the inverse of the principle is used in the force control of the body. The body torque, that would move the body as desired, is calculated first. The optimum set of leg forces, that generate this body torque reference, is calculated based on the body torque reference and the measured leg positions. There is an indefinite number of solutions that also fulfill the requirement of summing up to the resultant $\boldsymbol{R}$.

In the equilibrium, the sums of all forces and torques acting on a rigid free body are zero. Equilibrium means that the body is stationary or continues the previous movement with constant linear and angular velocity.

In the case of walking machines, the pure equilibrium concept has to be extended with gravity compensation and acceleration force references derived based on the actions of the operator. The legs together have to generate such a force, that carry the vehicle and compensate for the general friction forces of walking. A small force reference to the desired direction of translational movement is required to overcome the stochastic frictional forces of walking.

The most significant forces of the force evaluation are shown in Fig. 17. The thick supporting leg forces together provide the resultant body force and torque commands, that are drawn by using thick dashed vectors. Note that all the forces in Fig. 17 are along the body coordinate system.

There is an example of the main forces of such walking, where orientation changes of the body are not desired, in Fig. 18 in three phases. The first phase shows, that gravity force (G) is one of the main factors in force control of walking. The next phase shows the components of the body force reference $\boldsymbol{R}$. They are $\boldsymbol{F}_{oper}$ (derived from operator given velocity reference), $\boldsymbol{F}_{alt}$ (to lift or lower the altitude of the body according to the needs of gait control, environment detection and reference set by the operator) and $\boldsymbol{F}_w$ to compensate for the weight of the vehicle (mass M_v). The resultant force $\boldsymbol{R}$ is distributed to the supporting legs in the last phase. The leg forces are drawn to start from the support i.e. ground contact positions of legs marked with an asterisk (*). The supporting ground causes the displayed force vectors to the leg and further to the body.

The different components of the body force reference are evaluated in the following sections. The components are combined to body force and torque refe-

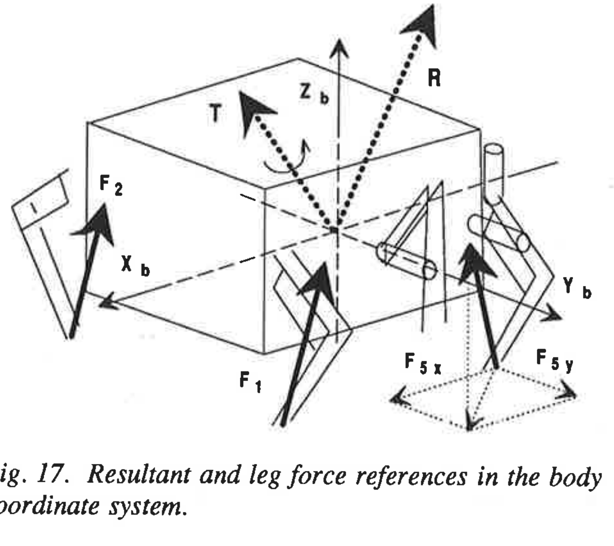

Fig. 17. Resultant and leg force references in the body coordinate system.

rence by addition, often called superposition, as described after the presentation of the components in the sections that follow.

4.1.1 Gravity

The forces needed to move a walking machine are usually relatively small compared to the forces that carry the body. The center of gravity is usually not in the origin of the body coordinate system, where several of the calculations are made. The weight also causes the vehicle to tilt unless not actively compensated for.

It is assumed for simplicity (as in the case of MECANT I), that the weight of the moving legs are small compared to the weight of the body and the legs are usually evenly distributed over the mass of the vehicle. Similarly torques caused by acceleration of moving joints are considered neglible, because they will stochastically balance themselves. The real effect of these factors is seen as the shaking of the vehicle during movements, especially when legs are lifted from the ground.

The direction of gravity (body coordinate system vector $\boldsymbol{u}_g$) can be measured with sufficient accuracy using inertial navigation systems for vehicle use, that are usually a combination of inclinometers, rate gyros and acceleration sensors. Examples and analysis of such systems can be found in (Rintanen & Kauppi 1993), (Tani & Shirai 1989) or (Barshan & Durrant-Whyte 1993). The attitude angles of the vehicle can be calculated based on the gravity vector and vice versa. The weight of the body is compensated for with the body coordinate system force reference:

$$\boldsymbol{F}_w = -M_v \boldsymbol{u}_g \tag{13}$$

The offset of the center of gravity from the origin of the coordinate system causes a torque, that has to be compensated for. If the position of the center of gravity of the vehicle is $\boldsymbol{p}_{cg}$, then the compensating torque is:

$$\boldsymbol{T}_w = -M_v(\boldsymbol{p}_{cg} \times \boldsymbol{u}_g) \tag{14}$$

4.1.2 Operator commands to force reference

Body force control offers an effective way to move the body of a walking machine, because only a limited number of data have to be transferred to the body control. All data is included in the six component resultant body reference force vector. Integration of the needs into one vector is needed. The operator may have plenty of different needs to move the body. The operator may want to move the body linearly forward or rotate the body to another orientation or attitude. Or these needs may be randomly combined.

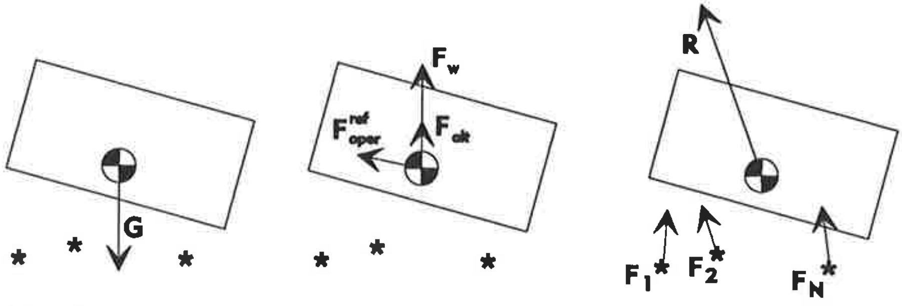

Fig. 18. Forces desired to move body with constant orientation.

The control system itself (especially locomotion control) may cause movements i.e. velocity references in the two additional degrees of freedom. The possibility to simultaneously control all the six degrees of freedom of the body of a walking machine is necessary, although the human operator usually can master only two or three of them at a time.

For example, the translational force reference of the case in Fig. 18, that continuously changes its direction, is calculated with the concept of normal (or centripetal) acceleration of a circular motion model. If the forward speed of the vehicle is v_x and it is desired to move on a circular path with radius r, then the centripetal force F_n causing the centripetal acceleration reference is:

$$F_n = M_v \frac{v_x^2}{r} \tag{15}$$

Note that the direction of the centripetal force (always towards the center of the radius) will change continuously causing a change in the orientation of the vehicle. In this case the operator originated translational body force reference is given by Eq. (16).

$$F_{oper}^{ref} = \begin{bmatrix} M_v a_{oper}^{xref} \\ F_n \\ 0 \end{bmatrix} \tag{16}$$

The acceleration reference along the path is calculated as below according to the changes in the operator given speed reference.

The changes in the translational speed reference cause accelerations, that are easily derived. The time derivative of the speed reference i.e. the acceleration reference should be in addition low-pass filtered in order to smooth the response. For example so called exponential filter of first order is sufficient for the purpose. The acceleration reference for all indices x, y and z is given in Eq. (17).

$$a_{oper}^{ref} = \frac{\Delta v^{ref}}{T_{cntl}} \tag{17}$$

Then the velocity reference given by the operator causes the following component to the body force reference:

$$F_{oper}^{ref} = M_v \begin{bmatrix} a_{oper}^{xref} \\ a_{oper}^{yref} \\ a_{oper}^{zref} \end{bmatrix} \tag{18}$$

If a free body rotates with an angular speed and angular acceleration, the torque necessary to produce this rotation is given by Euler's equation (7).

Changes in the angular speed references of the body are filtered similarly as the changes in velocity reference in order to get the three angular acceleration references. The desired body torques are then calculated using Euler's equation (7).

$$\alpha_{oper}^{ref} = \frac{\Delta \omega^{ref}}{T_{cntl}} \tag{19}$$

$$T_{oper}^{ref} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \begin{bmatrix} \alpha_{oper}^{xref} \\ \alpha_{oper}^{yref} \\ \alpha_{oper}^{zref} \end{bmatrix} + \begin{bmatrix} \omega_y \omega_z (I_{zz} - I_{yy}) \\ \omega_x \omega_z (I_{xx} - I_{zz}) \\ \omega_x \omega_y (I_{yy} - I_{xx}) \end{bmatrix} \tag{20}$$

As seen in Eq. (20), the actual angular velocities of the body are also needed in the definition of the body torques. They can be either estimated based on the previous acceleration commands or measured by a gyro system.

4.1.3 Rule based altitude and attitude control

It is desirable, that the operator has to consider only, how to move the body, but does not have to concentrate on the legs. Some degrees of freedom of the body are, in addition, being controlled autonomously, without operator assistance in several modes of locomotion. The modes are called test-init, manual, omni-directional, locomotion and work machine and are described in more detail by Hartikainen et al. (1992c). The control system will take care of the terrain following by estimating the support plane and calculating the references for the altitude and the attitude angles.

The autonomy decreases the number of matters the operator needs to concentrate on. The altitude of the body and the attitude about X and Y axes of the body are controlled autonomously by the system in many of the modes used. The altitude could be controlled according to the estimated ground clearance and attitudes based on the attitude of the ground. The machine could attain maximum capability to move to all directions, when the attitudes controlled are based on the estimated support plane and real attitudes.

The need to provide reference values for the body force control regarding vehicle altitude and attitude angles is one of the many supervising control problems of a walking machine. Corresponding estimates of the current altitude and attitude values are needed. They are provided by altitude estimation based on the positions of the supporting feet and inclination sensors or more general inertial navigation systems.

The attitude and altitude control of a walking machine can be considered similar to the control of a free object, because the mass of the legs is relatively small. The control problem is similar to the "stabilization of a large mass", where inertia plays an important role. One of the characteristics of the attitude and altitude control of a walking machine is, that the reference paths or orientations are not known in advance. Therefore a continuous form of control is needed, that maintains, as well as possible, the altitude and attitude references as long as the power of actuators allow. Large inertia has also advantageous filtering effects, that can be used with nonlinear controllers. In other words non-linear control methods do not easily cause instability of the system.

Several different controllers were tested in the control of altitude and attitude. The traditional P and PI controllers were tested at first and soon found to be unusable. A discrete linear-quadratic (LQ) controller was also inefficient, although the form of it quite well matched expectations. The states were for example in attitude control, the attitude error and the time difference of attitude. The resulting LQ controller calculated correction torques so that the attitude error would be steered to zero and angular speeds rapidly damped i.e. negative feed-back from both angular error and speed. However, the LQ controller was unable to stabilize the body with numerically estimated parameters based on (Little & Laub 1986) or other tested parameters. The failure of the linear LQ controller caused the writer to suspect, that the function between altitudes, attitudes and forces of the body is mainly characterized by non-linear factors. The tests confirming this have already been documented in section 2.2.

Control tests were made with a model-based, but heuristic, non-linear controller (Lehtinen 1993). The first usable period of stable attitudes and altitude were gained with the heuristic method. The process was analyzed further with several test force references without closing the control loop. It was soon noticed that attitudes can be controlled faster and there are severe delays in the altitude process caused by the delays and the saturation of the hydraulic system. The attitudes and altitude seemed to also have cross-effects. This is actually obvious due to the usage of the inclination sensors, that are also sensitive to the accelerations caused by the shaking of the body. Lifting the body from the ground seemed to also cause instability in attitudes in the beginning.

The altitude control is made similar to Fig. 10. If the absolute value of altitude error exceeds a limit, an upward or downward force reference is added to the weight compensating force reference of the body. The magnitude of this force reference depends on the direction (upwards or downwards) and slightly on the current altitude. The magnitudes were chosen to be the minimum force to cause rapidly constant upward or downward speed of the body. The constant speed seems to be a function of the pump used and the power available. The constant speed is also seen in Figs. 9 and 10.

The altitude correcting force reference is kept active until the altitude reaches a braking distance to the altitude reference. If the vertical speed of the body is then larger than a certain limit, a reverse braking force is added to the supporting force reference. The duration of the braking force depends slightly on the altitude and is typically significantly shorter, than that of the accelerating force reference. This also shows the non-linearity of the process between the body force reference and the altitude. Tuning the parameters of the braking force are quite difficult, since the delays in the altitude process are typically longer than the braking period. In other words the speed is not usually changed during the braking period, but the speed is reduced and may easily change its sign after the period of the braking force reference. The braking is of course interrupted, if the speed is reduced close to zero or to the opposite direction during the braking period.

The hysteresis caused by the dead-zone (accepted altitude zone) may cause repeated switching from altitude correction to zero altitude correction force close to a limit of the dead-zone. This is prevented by keeping the correcting force active for an extra control interval if such oscillations occur. The attitude control is more liable to oscillations, because the altitude estimation based on the support plane estimation has low-pass filtering characteristics.

The process is continuously monitored and some of the actions depend on the present status of the process with the rule-based control method presented. The usage of correcting and reverse force references can be considered as model based, where a "friction model" is included in the different magnitudes and duration of the correcting and reverse force references. To gain a response as fast as possible to the changes that typically happen during walking was one of the main design goals. The duration of the control interval may be relatively long due to the mechanical inertia in the system. An interval of 160 ms has been used with the MECANT I hardware.

The attitudes were controlled quite similarly. The method assumes, that the attitude and the angular velocity measurements are accurate. The attitude angles derived from the inclinometers were originally severely filtered (Kärkkäinen 1992) (discrete Butterworth of the third order), because the inclinometers were designed to be used to control the long term attitudes of the body, not to prevent shaking caused by changes in support states of the legs. The scope of the attitude control presented here is extended to minimize the short term shaking caused by leg penetration into the terrain or stepping i.e. lifting and placing of legs.

The estimation of angular velocity based on the differentiation of the attitude estimates can be replaced by a more expensive rate gyro system (Rintanen & Kauppi 1993) in the case of oscillations caused by the inclinometer based attitude control. The usage of inclinometers only was desired, because they are quite inexpensive and simple and accurately give the often needed steady state attitude. Inclinometers are damped, but can not differentiate acceleration from attitude. The original coefficients of the Butterworth filter were designed for a 0.5 Hz cut-off

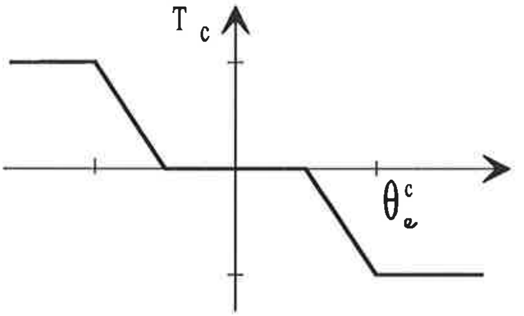

Fig. 19. Partly linear function between correcting torque and attitude error.

frequency (Kärkkäinen 1992). A "hybrid median filter" (Heinonen & Neuvo 1987) was found to be suitable for attitude control. The nine latest measurements were used in the filter. The attitude given by the filter used was the median of three values: the one measured four intervals ago, averages of four measurements before or after the measurement four intervals ago.

When an attitude correction torque is needed, it is calculated based on attitude error according to the function in Fig. 19. It contains a dead-zone and also limits the maximum value of the compensating torque. Very large angular speeds were braked by increased braking force references.

The attitude and altitude control is executed as a state machine and in a loop repeated three times with arrays of variables. The differences in altitude and attitude control are taken care of by selecting some special tests according to the loop index. The executed code can be characterized with the following pseudocode. Note that tabulation is used to indicate program sequences.

```
if (attitude/altitude control not active)
   check the need by calculating attitude/altitude error;
   if (error larger than limit)
      activate positive or negative attitude/altitude
      acceleration by force or torque;
      if (high altitude and vertical force needed)
         extra increase of vertical force;
else

   according to attitude/altitude control status

      case acceleration:
         if (distance to reference < braking distance)
            if (speed is small and oscillations noticed)
               deactivate force reference for
               attitude/altitude correction;
               return to error checking;
            else
```

activate braking;
if (body in high altitude and vertical
force needed)
decreased maximum duration of braking;
if (large angular speed)
increase braking torque and maximize
its duration;
if (angular speed small or to wrong direction)
stop braking and return to error checking;
if (downward movement is to be braked)
decrease maximum duration of braking;
else
correction torques are calculated based on
saturation function outside braking angle;

case braking:
decrement brake time counter;
if (speed reduced to zero or speed to wrong direction
or end of maximum brake time)
stop braking;
reactivate error checking;

The first tests described later in section 6.2 were made with six legs supporting. The control was also tested with the same parameters using four legs only. The results were not as good as with all six legs, that were used in the original tuning of the parameters. The differences are obviously caused by the reduced sum of the total friction, when the number of supporting legs is decreased.

The number of parameters of the attitude and altitude control presented to be tuned is 14. Most of them are quite easy to tune based on simple tests or to define in advance. Most probably three sets are needed in the case of MECANT I according to the number of supporting legs.

Note that friction compensation of the movements of the body related to the attitude and altitude control are integrated to the rule based force and torque commands and no actuator level friction compensation is to be activated in this case. The tests, that were the basis for the rule based controller were also done without actuator level friction compensation. It was also noted, that braking forces need to be much smaller than accelerating forces. This also indicates the existence of large friction. In addition, delays and the incapability to answer flow demands in the hydraulics system are dominant factors for the results.

4.1.4 General friction compensation

When the body is moving, some energy is lost due to friction in the mechanisms of the legs and actuators. Since several legs contribute to the translational movements simultaneously in different joint angles, it can be assumed, that the friction forces can be compensated for with an artificial (and relatively small) force reference aligned with the velocity reference v_d. The force reference is according to Eq. (21).

$$F^{v}_{fric} = k_{fric}\, v_d \tag{21}$$

The coefficient of friction compensation k_{fric} is, of course, relatively small as presented in section 2.4.

4.1.5 Integration to one body force reference

It is a common practice with forces to add several components to form one resultant force. Since a free body has three translational and three rotational degrees of freedom, a six component force and torque vector is calculated as body force reference. It is the sum of all the factors described in the sections above as well as forces caused by general viscous friction of the leg mechanisms and soil compaction.

The body force reference is given in the body coordinate system of the vehicle. It is designated as follows:

$$W^{ref}_{b} = \begin{bmatrix} F^{ref}_{b} \\ T^{ref}_{b} \end{bmatrix} = \begin{bmatrix} F^{xref}_{b} \\ F^{yref}_{b} \\ F^{zref}_{b} \\ T^{xref}_{b} \\ T^{yref}_{b} \\ T^{zref}_{b} \end{bmatrix} \tag{22}$$

The force components of the body force reference are given in Eq. (23).

$$F^{ref}_{b} = F_{alt} + F^{ref}_{oper} + F_{w} + F^{v}_{fric} \tag{23}$$

Similarly the torque components of the body force reference are:

$$T^{ref}_{b} = T^{xy}_{att} + T^{ref}_{oper} + T_{w} \tag{24}$$

Usage of three d.o.f. acceleration sensors attached to the body could offer a possibility to establish a body force controller at this level. Acceleration errors could be used to add a new force reference component to the body force reference. This aspect of body control has not been tested, because the noise due to leg placements and lift-offs seen by the acceleration sensors is assumed to be rather large during walking.

4.2 BODY FORCE REFERENCES IN UTILITY MODE

The main duty of the body is to provide the utility force reference in the utility mode. At this point it is not important whether the body moves or not. The body may move, if the external opposing force decreases and the vehicle tries to increase the force it is providing by moving to the direction of the force provided. As a matter of fact the movements can also be opposite to the direction of the utility force reference. Imagine the case of Fig. 15, when the boat is moved backwards from a land storage to the sea by pulling it with a smaller force.

The torque component to be provided by the body in the body coordinate system due to the utility force reference is calculated as follows:

$$\boldsymbol{T}_{ub} = \boldsymbol{F}_{ub} \times \boldsymbol{r}_{u} \tag{25}$$

The body force and torque references should, of course, compensate for the other force factors caused by the body itself. They are the attitude and altitude control, weight and torque caused by the weight of the body. The attitude and altitude control are needed, since the vehicle may move and proper altitude and attitude are needed in the locomotion. The dynamical effects of the rotation and acceleration are skipped here on purpose, since the velocities and accelerations are supposed to be relatively small in the utility modes.

Weight and utility forces provided by the body are given as examples in Fig. 20. Note that the XY plane of the body coordinate system is rotated to the hori-

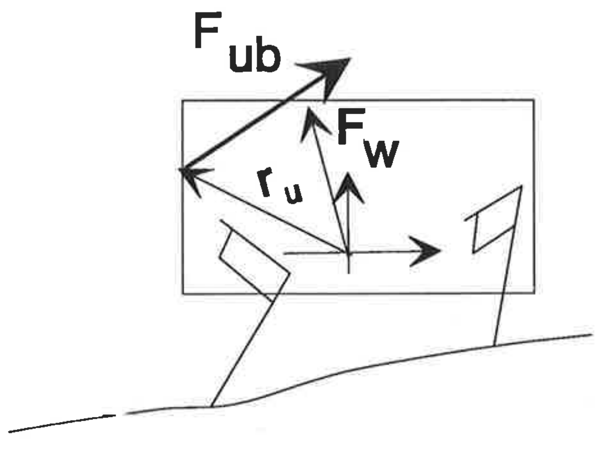

Fig. 20. Forces and torques to be provided by the body in utility modes.

zontal level in Fig. 20. The factors caused by gravity are described in section 4.1.1 and altitude and attitude control in section 4.1.3. The body force references caused by them can be included in a similar manner as in the force based motion control of a walking machine.

The force components of the total body force reference in the utility mode are given in Eq. (26).

$$\boldsymbol{F}_b^{ref} = \boldsymbol{F}_{alt} + \boldsymbol{F}_w + \boldsymbol{F}_{ub} \tag{26}$$

Similarly the torque components of the total body force reference in the utility mode are:

$$\boldsymbol{T}_b^{ref} = \boldsymbol{T}_{att}^{xy} + \boldsymbol{T}_w + \boldsymbol{T}_{ub} \tag{27}$$

4.3 OPTIMUM LEG FORCE SOLUTION

Leg forces, that together produce the force reference to move and support the body, can be used to control the movements of a walking machine in force or acceleration based control. The rectangular force references in the body coordinate system must be solved first. They are then transferred to the actuator space, where the actual force control is made. The legs should continuously produce, within a certain accuracy, the force reference vector regardless of the movement of the leg.

There is an indefinite number of solutions to produce the six degrees of freedom body force reference, because at least three legs are always used to support the body in the case of static walking and there are at least nine actuators in the supporting legs. Choosing the best suitable solution is an optimization task called "leg force distribution" and is the subject of this section.

What is the optimum leg force solution? Is it a local or the global optimum? What solution should be given, when the set of positions of legs makes it impossible to prevent tilting? Is the optimum solution somewhere singular?

Optimality depends on the point of view, because walking and especially forces in walking is a very complex process, where all variables affect all other variables. An optimal solution would benefit control of walking as much as possible. Any optimal solution in that sense can be suboptimal, when its behaviour is analyzed according to partial goals. A generally optimum leg force solution can be characterized with the following aspects:

- the sum of the absolute leg forces is as small as possible in order to keep the energy consumption small

- the possibility of the existence of upward leg force references is as small as possible or the existence of such upward force references always indicates an improper set of leg positions and body force reference

- vertical force references are as evenly distributed as possible in order to keep the vehicle well in balance and the load evenly distributed over the legs

- leg force distribution does not change a lot, when leg positions are slightly changed

- the components of the solved leg forces are as equal as possible in order to distribute the load evenly to all actuators.

A lot of effort has been put into removing such leg force solutions, which include upward force references for legs. Such a reference indicates, that the leg should grip the terrain instead of pushing it. Removing such references means, that force references of other legs have to be increased. Walking machines can anyway be steered to such leg configurations, that completely downward pushing leg force orders are impossible. Therefore the existence of an improper solution should be used to activate changing to a better leg configuration, but not to be activated as a leg force solution.

The solution given in the following sections fulfills all the above requirements and can be realized with a practical calculation capacity at least five times a second. In addition it indicates by the existence of upward force references, that leg positions are not feasible with the body force and torque reference in question.

The mathematical formulation of the leg force decomposition problem is quite straightforward. Let us assume, that there are mechanisms (N units) in a free object or body, that can produce three dimensional forces to the environment. The forces should together produce a six dimensional body force. The equations are actually the force and torque equations of equilibrium. They use the notation of Eq. (22):

$$F_b^{xref} = \sum_{i=1}^{N} F_{ix} \tag{28}$$

$$F_b^{yref} = \sum_{i=1}^{N} F_{iy} \tag{29}$$

$$F_b^{zref} = \sum_{i=1}^{N} F_{iz} \tag{30}$$

$$T_b^{xref} = \sum_{i=1}^{N} r_{iy} F_{iz} - \sum_{i=1}^{N} r_{iz} F_{iy} \tag{31}$$

$$T_b^{yref} = \sum_{i=1}^{N} r_{iz} F_{ix} - \sum_{i=1}^{N} r_{ix} F_{iz} \tag{32}$$

$$T_b^{zref} = \sum_{i=1}^{N} r_{ix} F_{iy} - \sum_{i=1}^{N} r_{iy} F_{ix} \tag{33}$$

Note that the index i refers to the supporting legs. N is the number of supporting legs. N varies from 3 to 6. Only the supporting legs are considered in the following equations. For example r_{2y} is the y component of the second supporting leg in the body coordinate system. The six equilibrium equations above can also be presented in a matrix format as follows. The body force reference vector $\boldsymbol{W}_b^{ref}$ is described in Eq. (22). A column vector $\boldsymbol{F}$ represents ankle forces of all the supporting legs:

$$\boldsymbol{W}_b^{ref} = \boldsymbol{A} \begin{bmatrix} F_{1x} \\ F_{2x} \\ \vdots \\ F_{Nx} \\ F_{1y} \\ \vdots \\ F_{Nz} \end{bmatrix} = \boldsymbol{A}\,\boldsymbol{F} \tag{34}$$

The size of the components in Eq. (34) are 6 x 1, 6 x 3*N and 3*N x 1. Matrix $\boldsymbol{A}$ is as follows:

$$\boldsymbol{A} = \begin{bmatrix} 1 & 1 & \dots & 1 & 0 & \dots & 0 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 & 1 & \dots & 1 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 & 0 & \dots & 0 & 1 & \dots & 1 \\ 0 & 0 & \dots & 0 & -r_{1z} & \dots & -r_{Nz} & r_{1y} & \dots & r_{Ny} \\ r_{1z} & r_{2z} & \dots & r_{Nz} & 0 & \dots & 0 & -r_{1x} & \dots & r_{Nx} \\ -r_{1y} & -r_{2y} & \dots & -r_{Ny} & r_{1x} & \dots & r_{Nx} & 0 & \dots & 0 \end{bmatrix} \tag{35}$$

The underspecified set of linear equations in Eq. (34) can be solved with so called pseudoinverse (often also called Moore-Penrose inverse). In this case it minimizes the following vector norm.

$$\|\boldsymbol{F}\|_2 = \sqrt{\sum_{i=1}^{N} |\boldsymbol{F}_i|^2} \tag{36}$$

The general pseudoinverse solution for Eq. (34) is given by:

$$\boldsymbol{F} = \boldsymbol{A}^{+}\boldsymbol{W}_b^{ref} + (\boldsymbol{I} - \boldsymbol{A}^{+}\boldsymbol{A})\boldsymbol{V}_n \tag{37}$$

The pseudoinverse matrix A^+ is:

$$A^+ = A^T(A\,A^T)^{-1} \tag{38}$$

V_n can be an arbitrary vector. The first part of the general solution, that uses the pseudoinverse matrix, is called the particular solution and the latter part the homogenous solution. The homogenous part corresponds, in our case of the leg force distribution, to the internal forces of the system. They are forces that the legs produce on each other i.e. pulling or pushing forces between the two tips of different legs.

This particular solution gives the minimum solution in the sense of a common square norm. This means, that the smallest possible sum of leg force references is given by the particular solution. Therefore the particular solution should be utilized as much as possible. Note, that if a general solution is used, it has a larger square norm than the particular solution where V_n is a zero vector. The general solution would physically mean, that forces are added to the particular solution, but the legs also generate extra forces, that compensate for each other and are not shown in the movements of the body. Some leg pairs could squeeze the terrain between them or some legs could push the terrain with extra forces and the other legs should compensate for this by gripping the terrain simultaneously. However, a leg can not grip the terrain. Thus leg force references upwards are practically impossible.

Doty et al. (1993) have described and considered extensively the usability of the generalized inverse. They have noticed, that it can not be used as a general solution to all matrix equations. The conditions are, that the equation system is linear and the vectors in question have physically consistent i.e. meaningful Euclidean norms. This requires, that the elements of a vector have the same physical units. This is a proper place to state only, that the presentation in the following sections is not in conflict with the non-invariancy problem stressed by Doty et al. (1993). This subject is considered in detail in the section dealing with different norms or weights of the pseudoinverse solution (section 4.3.2).

An upward leg force reference could also happen theoretically with the particular solution. This would mean, that the center of gravity leaves or is outside of the so called support polygon and one or a few of the legs should grip the terrain to prevent tilting. The possibility for such a positive force reference is very small, since the motion planning algorithms keep the center of gravity within the support polygon and the working areas of the legs are limited for maximum a priori stability.

The particular solution of the pseudoinverse gives the solution that has the smallest square sum of all components in the leg force vectors (Eq. (36)). This means for example, that if we have to calculate the solution in the case of symmetrically distributed legs and a straightforward force reference, the resulting leg forces are not only directed forward. Since the norm is a square norm of all the force vectors, the lengths of all components tend to be equal or as equal as possible but they also fulfill the other constraints. If one of the components were longer than the others, its square would contribute extensively to the norm.

Eq. (38) and the numerical matrix multiplication and inversion can be used to calculate the leg force reference solution, that have the smallest square norm. The main difficulty of the method is the inversion of the 6 x 6 matrix ($\boldsymbol{B}\,\boldsymbol{B}^T$). Althogether 2458 floating point operations were needed in a MATLAB simulation of the method with 4 legs supporting. Such a large number of calculations is not considered practical. Another aspect is the typically large difference in the magnitudes of horizontal and vertical forces due to the weight. If the leg force solution is made in the matrix format, the vertical forces are minimized at the expense of the horizontal forces in order to minimize the square norm of all forces. Therefore the horizontal forces have a tendency to increase and this may cause larger possibilities of slipping.

"Horizontal" forces should be kept as small as possible. There are two reasons for this:

- the relation between the horizontal and vertical leg forces is kept as small as possible in order to minimize the risk of slippage upon ground contact

- horizontal forces usually cause unnecessary energy dissipation with legs opposing each other with forces.

The wish to keep "horizontal" forces as small as possible offers a possibility to decrease the complexity of the solution. This can be done by considering at first only the horizontal part of the equilibrium equations. The equations in question are (28), (29) and (33). The simplified matrix equation is:

$$\boldsymbol{W}_{hor}^{ref} = \begin{bmatrix} F_b^{xref} \\ F_b^{yref} \\ T_b^{zref} \end{bmatrix} = \boldsymbol{B} \begin{bmatrix} F_{1x} \\ F_{2x} \\ \vdots \\ F_{Nx} \\ F_{1y} \\ \vdots \\ F_{Ny} \end{bmatrix} = \boldsymbol{B}\,\boldsymbol{F}_{hor} \tag{39}$$

Matrix $\boldsymbol{B}$ is a submatrix of matrix $\boldsymbol{A}$ (Eq. (35)):

$$\boldsymbol{B} = \begin{bmatrix} 1 & 1 & \dots & 1 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 & 1 & \dots & 1 \\ -r_{1y} & -r_{2y} & \dots & -r_{Ny} & r_{1x} & \dots & r_{Nx} \end{bmatrix} \tag{40}$$

The pseudoinverse of matrix $\boldsymbol{B}$ is calculated according to Eq. (38). Since many of the its elements are 0 or 1, a symbolic solution is considered. It was soon noticed that different sums are necessary for a symbolic solution. The sums are the following:

$$sc = \sum_{i=1}^{N} r_{ic} \,, \; c = x, y, z \tag{41}$$

$$s^2c = \sum_{i=1}^{N} (r_{ic})^2 \,, \; c = x, y, z \tag{42}$$

$$scd = \sum_{i=1}^{N} r_{ic} r_{id} \,, \; (c,d) = (x,y), (x,z), (y,z) \tag{43}$$

Then the matrix of Eq. (38) to be inverted is:

$$\boldsymbol{B}\,\boldsymbol{B}^T = \begin{bmatrix} N & 0 & -sy \\ 0 & N & sx \\ -sy & sx & s^2x+s^2y \end{bmatrix} \tag{44}$$

A square matrix can be inverted if and only if the determinant of the matrix is not equal to zero (see for example Kreyszig (1988)). This implies, that all rows and colums has to be linearly independent. The determinant is:

$$detBBt = N(ns2xy - sx^2 - sy^2), \quad ns2xy = N(s^2x + s^2y) \tag{45}$$

The possibility to a zero determinant is very small in practice, because the positions of the legs are always within the working areas and it in not possible to place all supporting legs in one common position or along a common line. In addition, small change in any position of any leg will change immediately the determinant in Eq. (45).

The symbolic deduction of $\boldsymbol{B}^+$ (evaluated with the help of the MACSYMA program package) is given in detail in Appendix B. The intermediate results given above are used.

The numerical values of X and Y components of the leg force references can be calculated based on the equations in Appendix B. These values are applied to the remaining vertical set of the six equations of equilibrium i.e. Eq. (30), (31) and (32). By regrouping the known and unknown factors to different sides a new set of torque equations to be inverted by pseudoinverse can be written. When the torque references and the torques caused by horizontal leg forces (both known) are combined, the new references caused by vertical (Z) leg components are according to Eq. (46) and (47).

$$\acute{T}_x = T_b^{xref} + \sum_{i=1}^{N} r_{iz} F_{iy} \tag{46}$$

$$\acute{T}_y = T_b^{yref} - \sum_{i=1}^{N} r_{iz} F_{ix} \tag{47}$$

New equations for the vertical forces are in matrix format:

$$W_{vert}^{ref} = \begin{bmatrix} F_b^{zref} \\ \acute{T}_x \\ \acute{T}_y \end{bmatrix} = \begin{bmatrix} 1 & \dots & 1 \\ r_{1y} & \dots & r_{Ny} \\ -r_{1x} & \dots & -r_{Nx} \end{bmatrix} \begin{bmatrix} F_{1z} \\ F_{2z} \\ \vdots \\ F_{Nz} \end{bmatrix} = C F_z \tag{48}$$

When the C matrix is multiplied with its transpose the result is:

$$C\,C^T = \begin{bmatrix} N & sy & -sx \\ sy & s^2y & -sxy \\ -sx & -sxy & s^2x \end{bmatrix} \tag{49}$$

The matrix of Eq. (49) can be inverted analogously to the previus case in Eq. (44), if non-zero determinant exists. The determinant of the matrix in Eq. (49) is:

$$detCCt = Ns^2x\,s^2y + 2sxsysxy - s^2xsy^2 - Nsxy^2 - s^2ysx^2 \tag{50}$$

The symbolic deduction of C^+ is given in detail in Appendix C. The force references calculated from the body force reference are at the end of Appendix B and C given by Eq. (51), (52) and (53). The intermediate variables calculated earlier and in Appendix B and C are also used.

$$F_{ix} = detBBt^{-1} \begin{Bmatrix} (xpx - nsy\,r_{iy})F_b^{xref} + \\ (nsx\,r_{iy} - sxsy)F_b^{yref} + \\ (nsy - np2\,r_{iy})T_b^{zref} \end{Bmatrix} \tag{51}$$

$$F_{iy} = detBBt^{-1} \begin{Bmatrix} (sxsy - nsy\,r_{ix})F_b^{xref} + \\ (ypy - nsx\,r_{ix})F_b^{yref} + \\ (np2\,r_{ix} - nsx)T_b^{zref} \end{Bmatrix} \tag{52}$$

$$F_{iz} = detCCt^{-1} \begin{Bmatrix} (k_1 r_{ix} + k_2 r_{iy} + k_3)F_b^{zref} + \\ (k_4 r_{ix} + k_5 r_{iy} + k_2)\acute{T}_x - \\ (k_6 r_{ix} + k_4 r_{iy} + k_1)\acute{T}_y \end{Bmatrix} \tag{53}$$

It is obvious that the leg force references are linearly dependent on leg positions. Therefore this kind of distribution is often called "planar". The number of calculations is reduced to (30*N + 21) multiplications and (29*N + 13) additions, because a large amount of intermediate variables are used. N is the number of the supporting legs. This is a reduction of a magnitude compared with a case of straightforward matrix calculations.

A force distribution case calculated by a MATLAB simulation program using the equations above is listed in List 1. There are only two components in the body force reference: a 12 kN support force due to the weight and an inertial

pos. of foot tips [m] =

0.7150	0.0	-0.7150
1.2115	-1.2115	1.2115
-0.6100	-0.6100	-0.6100

des. body forces [N] =

-1800 0 12000

des. body torque [Nm] =

0 0 0

foot forces [kN] =

-0.4811	-0.8379	-0.4811
-0.1053	0.0	0.1053
3.7678	6.0000	2.2322

List 1. A force distribution case.

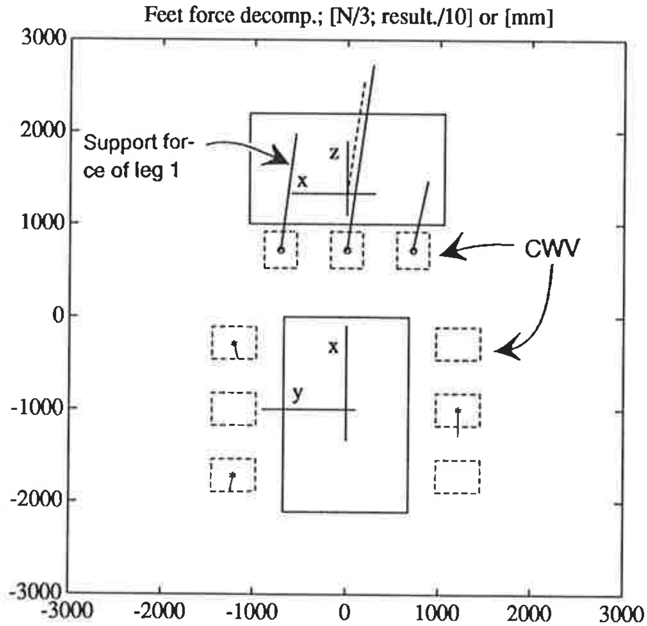

*Fig. 21. Graphical description of a force distribution. The resultant body force and rectangles of "constrained walking volumes" are dashed. Support forces of legs start from * and o.*

force caused by 0.15*g acceleration backwards (along -X). This acceleration could also mean, that the body is standing still and inclined on a slope of 8.6 degrees. Note that the leg forces also have components in the Y direction, but the sum of the Y components of the leg force references is zero as it also should be in this case. The leg positions are in the middle of the most usable "constrained walking volume (CWV)" specified by Hartikainen (1990). The use of a CWV is necessary, since the legs can not be allowed to reach such configuration (state) and tip positions, where the body might tilt. That could be quite easily done even with four supporting legs for example by lifting the rear legs and moving the supporting four to the same side of the center of gravity.

The force distribution of List 1 is also described in Fig. 21. It has side and top views. The units are in Newtons or in mm's. The leg forces and the resultant force are differently scaled. The leg forces should be multiplied by 3 and the resultant body force by 10 in order to estimate the numerical values. The relative positions of the legs are in mm's according to the units of the axes. The supporting (or ground contact) positions of legs are represented by 'o' in the side view and by '*' in the top view. The CWV volumes are represented by dashed rectangles. The resultant body force reference is described as a dashed line. The leg forces are displayed as forces that the supporting ground should produce at the

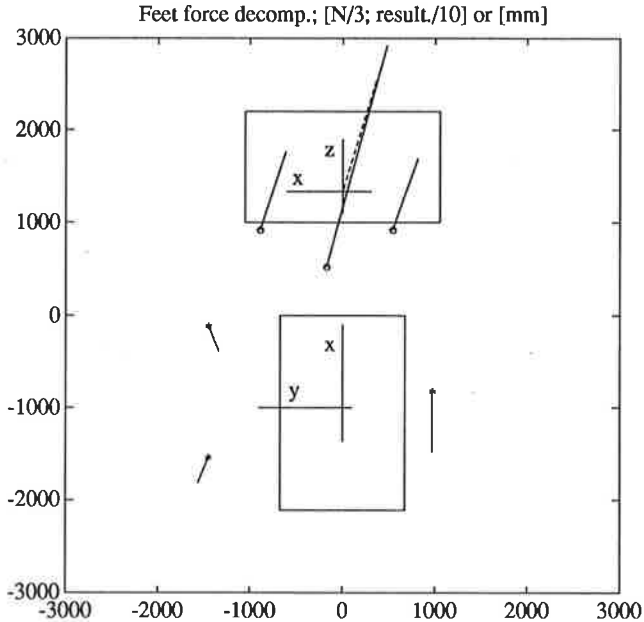

*Fig. 22. Three supporting legs at the worst corners of CWVs; 0.3*g horizontal acceleration. Upper figure is side view and lower seen from above.*

tip of a foot. It is quite obvious that the sum of the leg forces is the resultant body force reference.

A leg force reference can be considered unusable, when there is one or more upward leg force references i.e. a leg or many legs should grip the soil beneath or the force limits of the actuators are exceeded. Gripping can not be done in practice. The most extreme cases of force distribution will happen at the edges of the CWVs, because the CWVs are defined to maximize the a priori stability of the vehicle. In the worst case all the leg positions are located at the corners of the corresponding CWV so that the center of gravity gets close to the edge of the support polygon. The body force and torque references may also increase the possibility of improper leg force references. They are in practice quite rare, since the horizontal force references are quite small compared to the weight of the body.

When the previous force distribution case of List 1 and Fig. 21 is modified by increasing the backward acceleration to 0.3*g and by moving the legs into the worst corners of the CWVs, the force distribution can be seen in Fig. 22. The 0.3*g acceleration causes a similar horizontal force at a slope of 16.7 degrees of inclination. Leg 4 should support with a quite large force, because it is alone on the other side. It has to compensate for the torque caused by the other more extended legs. The vertical support force of leg 4 has, as a matter of fact, exceeded the practical limit of the actuator.

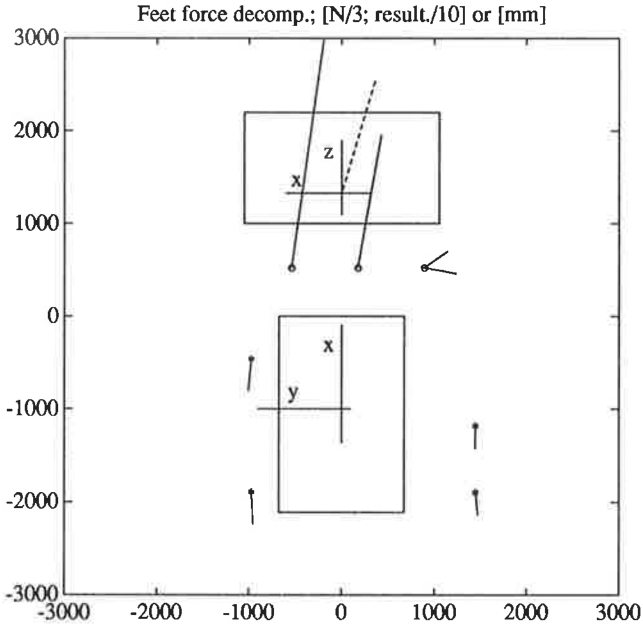

*Fig. 23. Four supporting legs at the worst corners of CWVs; 0.3*g horizontal acceleration. Note, that legs 5 and 6 seem to be in the same position in the side view.*

Four legs are usually supporting during walking with the MECANT I, because the force capability of the vertical actuator is a limiting factor. This will also minimize soil penetration on soft terrain, where five supporting legs may be necessary. The worst case with four legs, where all the legs are in the out most corner of the corresponding CWV and the horizontal acceleration is 0.3*g, is presented in Fig. 23. Note, that legs 5 and 6 become critical in the case of Fig. 23. Their force references are almost horizontal indicating high risk for slippage. The force reference of leg 6 is in addition upwards, which is impossible. However, this worst case is quite unlikely to happen. The legs are usually lifted one by one with a free gait locomotion algorithm, that could be suitable for controlling the gait (configuration) states of force controlled walking. This means, that the legs will hardly ever be positioned as in the worst case. If the legs can not be lifted, the body should be moved with the position control loop closed around the force control loop to a position, where force references are feasible. The case of Fig. 23 can be improved easily. For example reducing the horizontal acceleration to 0.15*g causes all the leg force references to point downwards with a larger angle than 45 degrees from the vertical direction. The lower the body is positioned, the more feasible the leg forces become. Thus the altitude of the vehicle should be kept as low as possible during force controlled movements.

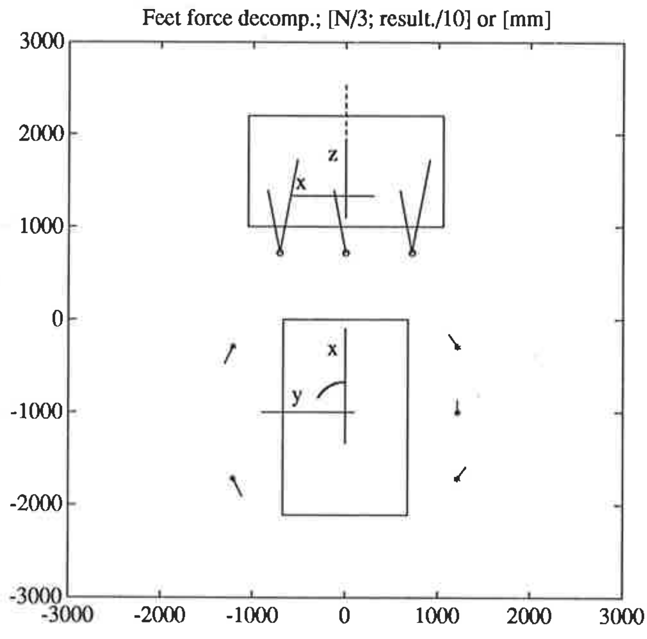

Fig. 24. Rotating 3600 Nm torque desired about the Z axis.

The body torque references were zero in the previous figures. The legs may quite easily produce large vertical torques to the body. For example, a case where the weight of the body is carried and the body is rotated about the Z axis with a torque of 3600 Nm, is presented in Fig. 24. The torque reference is presented as an arc about the Z axis. Note that the legs clearly cause the body to rotate accordingly. This can be seen in the vertical downward view of Fig. 24.

The actual positions of the legs when five or six are supporting is not critical for the leg force references, because the CWVs of five or more legs are always evenly distributed and the center of gravity is well within the support polygon.

Because the leg force distribution presented above is sensitive to the unstable leg configuration and positions and the distribution is a linear function of the leg positions, the calculations could be used as a (non-linear) measure of stability. It is also a consistent method of including all desires to move the walking machine in the stability analysis via the body force reference. A leg should be lifted and another placed to support, when any of the legs produce upward forces i.e. grip the terrain. Thus the vertical leg force reference can be a triggering factor for leg lifting.

The leg force references are transferred further to each leg coordinate system. This is done by translation and renaming some coordinate axes in the simple mechanical case of the MECANT I. The leg provides the force vector reference evaluated by the body force control. The rectangular leg force reference

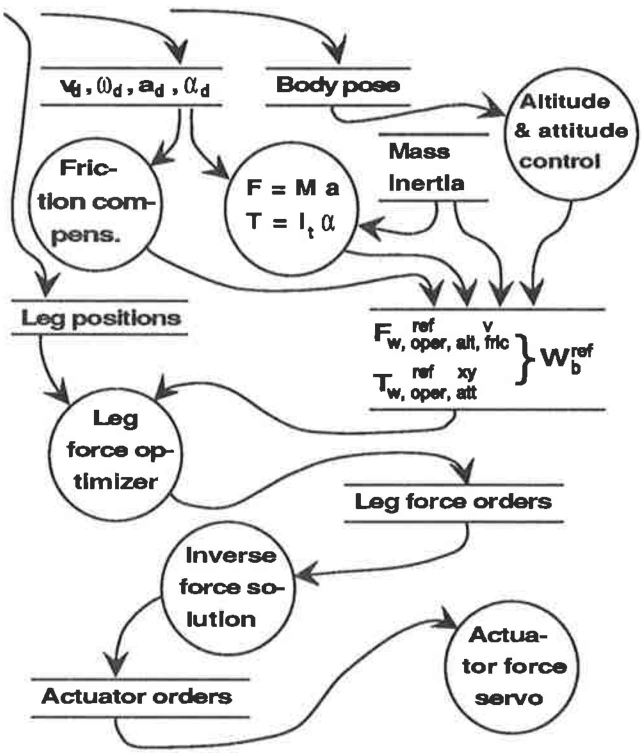

Fig. 25. Calculation of leg actuator force orders from desired body movements and weight.

is transferred further to joint force references (i.e. references) according to the inverse force equations derived in Appendix A. The positions of the joints are used as input for the calculations made by the leg controllers.

The method presented in this chapter is concluded in Fig. 25. The "body pose" is a short form of the position and orientation of the body. All desires concerning torques and forces to be created by the body are transformed to the body coordinate force reference.

Several alternatives can be chosen to keep the force references within acceptable limits. The actuator force references may not exceed the capabilities of the actuators and the vertical force references may not be upward.

If too large actuator force references are desired, the operator references are reduced and a new set of actuator force references are calculated. The operator is, of course, warned for example by a visual signal or an audible alarm about these exceptional cases when the body control surpasses the references given by the operator. If the reduction of the operator given references does not help (for example when the center of gravity is close to the borders of the support polygon), a stabilizing force reference may be added to the body force reference. The direction of the stabilizing force reference is from the center of gravity to the center point of the support polygon in the horizontal XY plane of the body.

Two methods to minimize the possibility of slipping when the body is greatly inclined are presented in the following section.

4.3.1 Minimization of the possibility of ground level slippage

When there is a large angle between the body and the ground level, the force distribution calculation presented above may lead rather easily to such leg force references, that are proper in the body coordinate system, but improper at the ground level i.e. parallel to the ground level that is usually horizontal. Such a force reference may easily cause the slippage of a foot.

Gardner (1992) minimized the risk of slippage by taking into account the micro structure of the ground surface below the foot by maximizing the force perpendicular to the local ground plane and minimizing the force in the plane. This causes substantial difficulties! The load carrying properties of the terrain and the best loading direction are not necessarily related to the shape of the ground surface. As a contradiction it may be stated that a foot which has penetrated into the ground has a good grip sideways, but a lose (or no) grip in the direction perpendicular to the surface of the terrain (usually vertical direction). In other words the grip is good in the horizontal direction, since mechanical walking machines intended for forest use are quite heavy. A good horizontal grip is visualized in Fig. 26.

Minimizing the forces in the ground plane directions instead of the body coordinate system XY plane offers a possibility to stochastically reduce the possibility of slippage of a leg on the ground. The method presented above is done in two phases: horizontal and vertical optimization. The first phase can be changed to corresponding optimization at the estimated ground level. After the two phases, the force references are changed back to the body coordinate system.

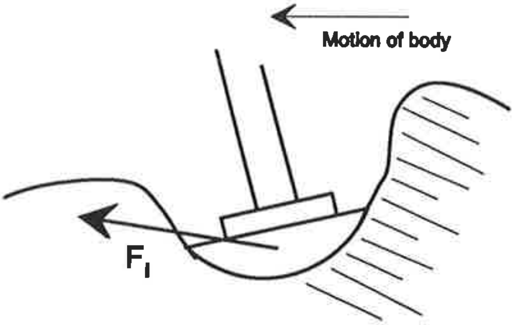

Fig. 26. Typical penetration of a leg into the soil of forest terrain. Ground support force and direction of body movement shown.

Let us define another coordinate system parallel to the ground in the origin of the body coordinate system. As a matter of fact such a ground orientation estimation plane is maintained in the gait control software of MECANT I. It is based on the current footprints (positions of ankles) of the machine and the least squares estimation of a plane, that is most common for all the foot positions. Let us assume, that the body coordinate system should be rotated by angle θ about the Y axis and angle α about the X axis in order to rotate the XY plane parallel to the ground plane. Then the following 3 x 3 transformation matrix would transform any column vector $\boldsymbol{v}$ from the body coordinate system into the path coordinate system. The path coordinate system is defined in Fig. 14. The transformation assigned $\boldsymbol{P}$ is:

$$\boldsymbol{P} = \begin{bmatrix} \cos\theta & \sin\alpha\sin\theta & \cos\alpha\sin\theta \\ 0 & \cos\alpha & -\sin\alpha \\ -\sin\theta & \sin\alpha\cos\theta & \cos\alpha\cos\theta \end{bmatrix} \tag{54}$$

The inverse transformation is $\boldsymbol{P}^{-1}$. It is also the transpose, since the positions of both origins of coordinate systems are the same. Its symbolical presentation is:

$$\boldsymbol{P}^{-1} = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ \sin\alpha\sin\theta & \cos\alpha & \sin\alpha\cos\theta \\ \cos\alpha\sin\theta & -\sin\alpha & \cos\alpha\cos\theta \end{bmatrix} \tag{55}$$

The positions of the supporting legs, the body force and torque references are transformed to the new optimization coordinate system parallel to the path coordinate system by multiplying them as three element column vectors by $\boldsymbol{P}$. The resulting new vectors are the input to the same calculations concluded in Eq. (51), (52) and (53).

The result is a set of optimum leg forces in the path coordinate system. They are transformed back to the body coordinate system by multiplying them by the inverse transformation $\boldsymbol{P}^{-1}$.

The leg force optimization case of Fig. 23 (weight and backward acceleration of -0.3*g) is compared with the two different optimization planes in Fig. 27. The views are sideways. The orientation of the terrain is presented by dotted lines in the body coordinate system. The resultant force is perpendicular to the terrain in this case. The leg positions are also the worst possible, in the outermost corners of the CWVs. The minimization of the horizontal forces is done at the terrain level perpendicular to the resultant in the upper part of the figure. The horizontal optimization of the lower and the worse of these two cases is done in the XY plane of the body coordinate system.

The change of the horizontal minimization plane does not change the absolute sum of all leg force vectors more than 4 percent. This means that the change of the horizontal minimization plane does not waste energy.

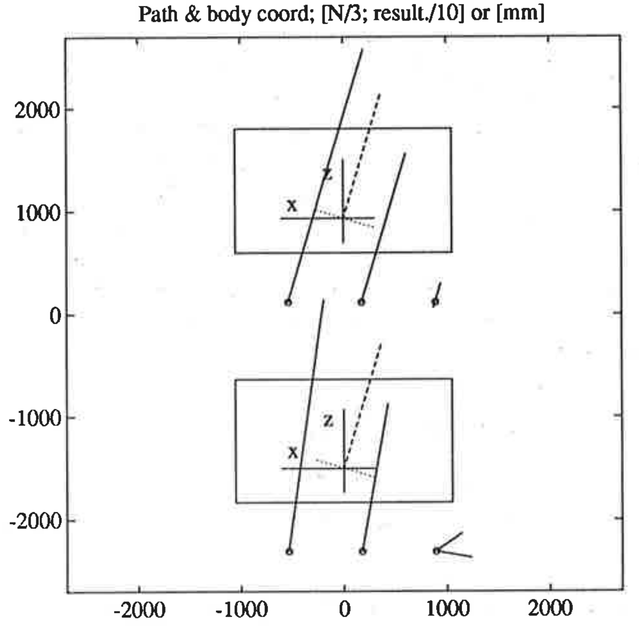

Fig. 27. Comparision of force optimization according to ground level and plane parallel to XY plane of the body coordinate system.

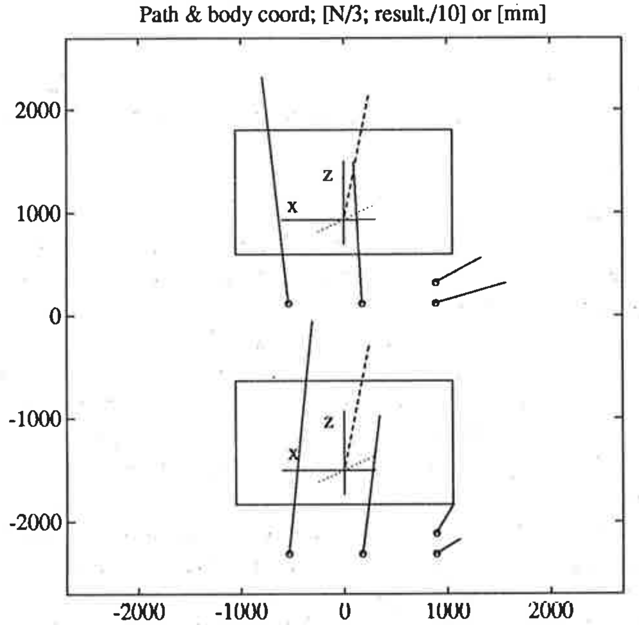

Fig. 28. Comparision of optimization plane parallel to terrain estimation plane or the XY plane of the body coordinate system.

The force reference need not be aligned with the normal of the terrain estimation plane. This is tested in the case of Fig. 28. The terrain and the force reference are in different inclinations; the backward acceleration is -0.2*g and the terrain inclination is 25 degrees in the opposite direction. Horizontal optimization in the plane of terrain (upper subfigure) and the XY plane of the body (lower subfigure) are compared. Quite surprisingly the body coordinate optimization gives to legs 5 and 6 force references that are more vertical i.e. less probable to slip. The reason for this is quite obvious. The body coordinate XY plane is closer to the normal of the force reference. If the horizontal forces were optimized in the plane normal to the force reference, then the large forces of legs 1 and 4 would be parallel to the resultant and legs 5 and 6 do not need to compensate for the horizontal components of legs 1 and 4 with "opposite" horizontal components.

The concept of optimization of the horizontal force in the plane perpendicular to the force reference (-0.2*g and weight) is tested in the previous case of Fig. 28, but is optimized in the plane perpendicular to the force reference. The transformation **P** (Eq. (54)) and its inverse can be used as previously, but with different angles. The new set of inclination angles is calculated according to Eq. (56) and Eq. (57).

$$\breve{\theta} = \tan^{-1}\left(\frac{F_b^{xref}}{F_b^{zref}}\right) \tag{56}$$

$$\breve{\alpha} = -\tan^{-1}\left(\frac{F_b^{yref}}{F_b^{zref}}\right) \tag{57}$$

The optimization in the plane perpendicular to the force reference (upper subfigure) and in the body coordinate system plane (lower subfigure) are compared in Fig. 29. The terrain estimation plane orientation is also marked in the subfigures, although the information about terrain inclination is not used in this case. It can be seen, that the leg forces of the less supporting legs 5 and 6 form a larger angle (thus smaller possibility to slip) when optimized in the plane perpendicular to the force reference. It is even better with this unrealistic large angle (about 40 degrees in Fig. 29) between the force reference and the terrain. The maximum angle about the Y axis is approx. 20 degrees and in the perpendicular direction 25 degrees (about X) with the mechanics of MECANT I.

The change of the optimization plane presented in this section requires calculation of 6 trigonometric functions, (18*N + 24) multiplications and (24*N + 4) additions.

Linearity of the leg force distribution can be seen in the example of Figs. 30 and 31. The positions of the legs are calculated in a gait simulator (evolved from the one described by Hartikainen (1990)). Two successive positions and 0.3*g forward acceleration are used in both figures. Legs 2, 3, 4 and 5 carry the weight in Fig. 30. Leg 4 gets close to the rear limit of the CWV used in this gait case. The rear supporting legs have large loads, since the line between them belongs to the support polygon and gets close to the center of gravity. It is close to the

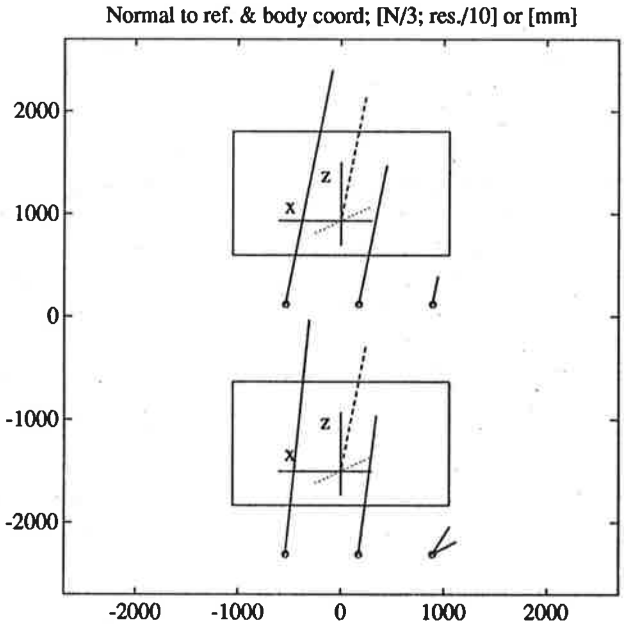

Fig. 29. Comparision of optimization in the plane normal to the force reference and the XY plane.

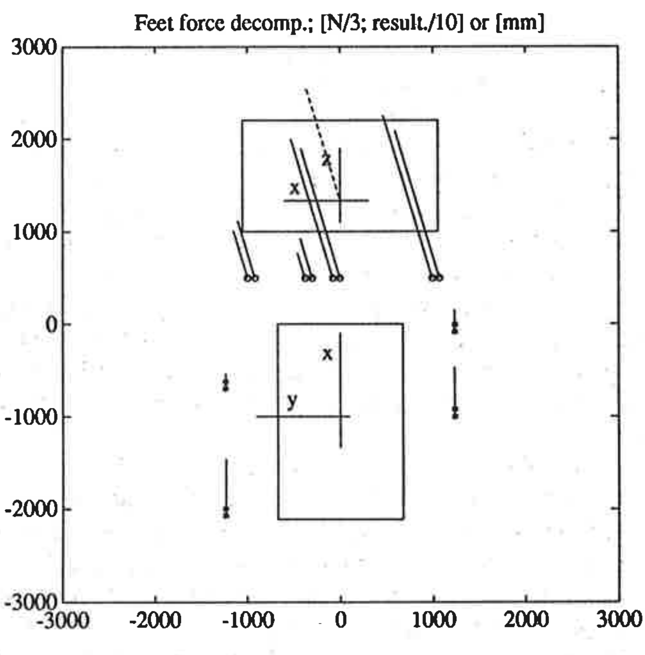

Fig. 30. A step sequence and leg force orders before leg 4 is lifted.

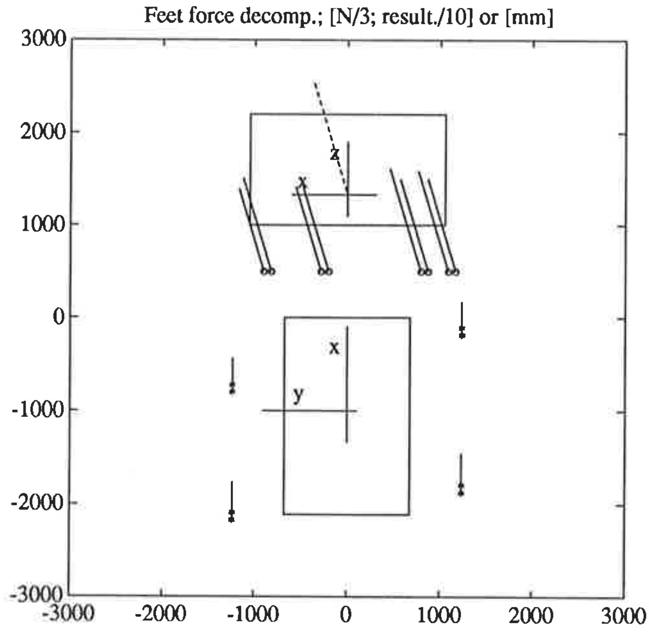

Fig. 31. A step sequence and leg force orders after leg 4 is lifted and leg 6 starts to support.

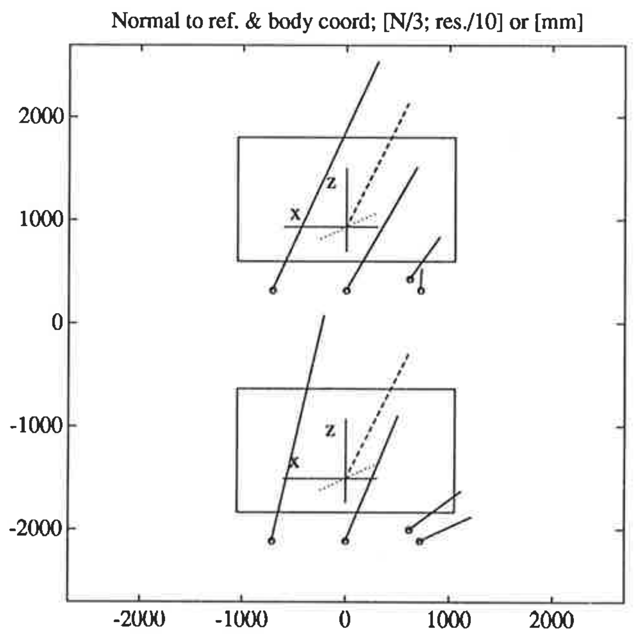

Fig. 32. Optimization plane compared with large forward desired body force due to utility force and compensating torque.

origin of the body coordinate system. The horizontal forces are optimized in this case in the plane perpendicular to the force reference.

Since periodic gait was used in the simulation, that generated the positions of the legs, as leg 4 is lifted leg 6 replaces it. Two successive sets of leg positions and corresponding leg force references after the changeover from leg 4 to leg 6 are visualized in Fig. 31. The load is distributed more evenly, since the edges of the support polygon are more distant from the center of gravity.

Large lateral force references may be desired with the utility modes of the vehicle. It is especially wise that the optimization plane be chosen to be perpendicular to the force reference. This is visualized in Fig. 32, where the forward force reference is 6000 N and the utility force is compensated for partly by a torque reference of 3000 Nm about the X axis.

4.3.2 Benefits of different weights of pseudoinverse

Doty et al. (1993) noticed, that a generalized inverse often provides different solutions based on the formulation of the problem. They require, in order to solve these problems, that the vectors in the basic equation subject to the procedure of pseudoinverse have physically consistent norms. In other words, all elements in the inner product of the vectors have to have the same physical unit. This is required for the successful usage of pseudoinverse. Doty et al. (1993) have also expanded the problem and solved it in more general cases, too.

The leg force vectors in the case of this work have the same unit Newton (1 N) all the time i.e. their norms are physically consistent. The body force reference vectors have both a force and torque component with units Newton (1 N) and Newton-meter (1 Nm) respectively. Thus body force vectors do not have physically consistent norms.

The possibility to use different norms often called weights in the generalized inverse, offers a possibility to modify the norms into a proper format. Diagonal weight matrices are considered most suitable for the task by Doty et al. (1993), Schneider & Cannon (1992) and Huang & Lu (1993).

If we assign the elements of a diagonal weight matrix $\boldsymbol{Q}$ as q_{ii}, the weighted square norm of the body force vector of for example Eq. (39) is in Eq. (58).

$$\|\cdot\|_2 = q_{11}(F_b^{xref})^2 + q_{22}(F_b^{yref})^2 + q_{33}(T_b^{zref})^2 \tag{58}$$

In order to unify the units of all components of Eq. (58), the diagonal components of $\boldsymbol{Q}$ dealing with forces have to have units in square meters (1 m^2) and the components dealing with torques should be unitless. Doty et al. (1993) recommend redefining the weight matrix in square root form. Then the particular solution of Eq. (37) would be given according to:

$$\boldsymbol{F} = [\boldsymbol{Q}^{\frac{1}{2}}\boldsymbol{B}]^{+}\,\boldsymbol{Q}^{\frac{1}{2}}\boldsymbol{W}_b^{ref} \tag{59}$$

The calculation procedure presented in the previous sections is physically correct, if the body and the leg force vectors are assumed to have been multiplied with a weight matrix of the form presented in Eq. (60). Two elements in the diagonal of the matrix in Eq. (60) have meter (1 m) as unit, but the lowest element of the diagonal is unitless.

$$Q^{\frac{1}{2}} = \begin{bmatrix} 1m & 0 & 0 \\ 0 & 1m & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{60}$$

Several different numerical values were inserted into the weight matrix of Eq. (60) in order to test the effect of weighting according to Eq. (59). However, the same original result was always gained. An explanation is given by Golub & Van Loan (1983, p. 180). The weighting method above is called "row weighting" of the "weighted least squares problem". The solution of the original unweighted equation is also the solution for the weighted equation, when the original vector i.e. the body force vector belongs to the range of the matrix. That is actually the case according to the original Eq. (37).

The "column weighting" method presented by Golub & Van Loan (1983, p. 179) changes the norm and therefore also the result. The column weighting method assumes a non-singular weighting matrix $\boldsymbol{G}$. It also minimizes a least squares norm:

$$\|z\|_G = \|\boldsymbol{G}^{-1}z\|_2 \tag{61}$$

If the rank of the matrix is the number of columns, column weighting does not give any new solutions. This may happen only with matrix $\boldsymbol{C}$ and Eq. (48), when there are only three legs supporting.

Several different candidates for a weight matrix were tested. No relevant weighting methods, that could provide something usable for walking, were found during the analysis and weights have not been used in the leg force distribution of MECANT I.

An example of weighting is shown in Fig. 33. The rotating leg force distribution case in Fig. 24 is calculated with a weighting matrix, that is otherwise a unity matrix, but the element at position (8, 12) is 2.0. All elements in the main diagonal are 1.0 and other non-diagonal elements are zero. One can clearly see the significant effect to the result and the larger nature of the solution as the total sum of the solved leg forces is concerned. Leg 4 would have rather large possibility to slip.

If we imagine, that leg 4 is situated beside a rectangular barrier, the wall of which is along the X axis of the body coordinate system, the forward pointing force reference of leg 4 in Fig. 24 is not useful. The force distribution in Fig. 33 would clearly utilize the barrier by gripping the barrier between the legs. Thus weighting could be useful, if the shape of terrain was known in advance. This leads to an interesting research subject, where some of the leg forces are attached

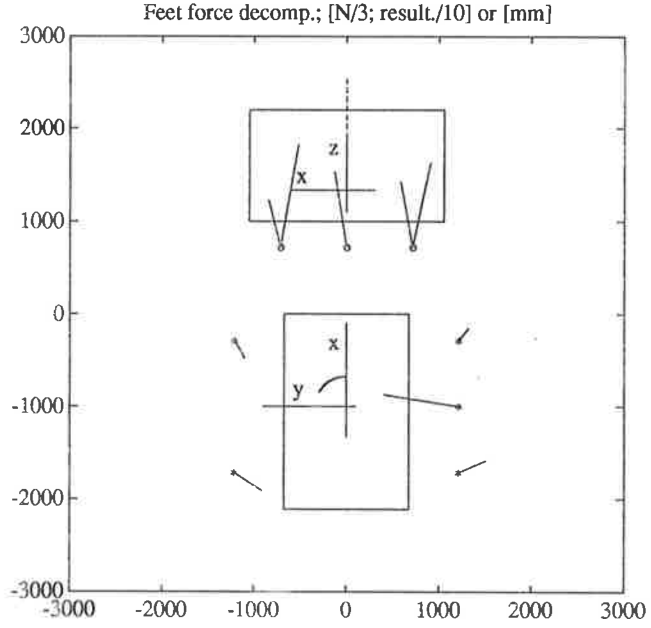

Fig. 33. Rotation forces calculated with a column weighting matrix close to unity matrix except one non-zero non-diagonal element.

at first as desired and the rest optimized according to the methods presented in this work.

4.3.3 Comparisions to methods presented in literature

The optimization of leg force distribution presented in the above sections can be compared to a few methods presented earlier. The calculation burdens of the method presented are compared to those of the "zero interaction" method presented by Kumar & Waldron (1988) (see section 1.1.2) in Table 2. The number of floating point operations of both methods (optimization in the body coordinate system and optimization in the plane perpendicular to the body force reference) are listed in Table 2. Optimization of the body coordinate system can often be chosen, because the angle between the force reference and the terrain is often small.

The requirement of zero interaction force is not fulfilled in the methods presented in this paper. However, the horizontal forces between the legs are relatively small. For example in the case of Fig. 29 the maximum component of horizontal interaction forces is 1290 N, where the weight is 12 000 N. The maximum angle between the difference of leg tip forces and the line between two leg

Table 2. Number of floating point operations compared to the zero interaction method by Kumar & Waldron (1988).

legs	Kumar-Waldron	body coord.	normal to force ref.
3	317	223	379
4	357	284	476
5	397	345	573
6	440	406	670

tips is 101 degrees. It happens with legs 1 and 3. An angle of 90 degrees would mean "zero interaction".

The leg force distribution calculated by matrix form pseudoinverse managed rather badly in the comparison by Gardner (1992). The same test (tripod gait with 0.3*g acceleration) and MECANT I dimensions with the calculations presented in

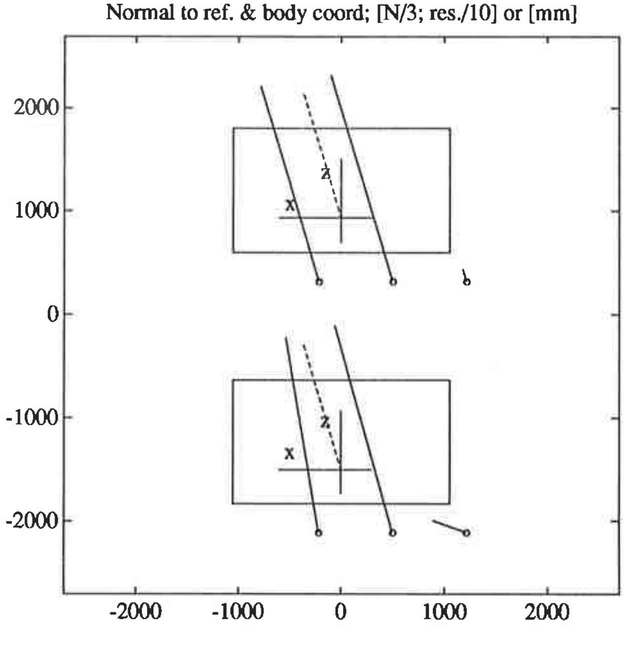

*Fig. 34. Tripod gait and 0.3*g forward acceleration.*

this work gave notable results (all leg forces parallel to the resultant of the body force reference). When the stroke was expanded to 1 m, some undesired results could be noticed. The 1 m stroke was clearly out of the CWV and close to the mechanical limits of MECANT I (depends on the foot distance from the body). The test of Gardner is visualized at the end of such a stroke with the developed methods in Fig. 34. The upper subfigure is based on optimization in the plane normal to the force reference and the lower in the body coordinate XY plane. The result presented in the lower subfigure is also the same given by the zero interaction solution of Kumar & Waldron (1988). The forces in the upper case of Fig. 34 are very parallel to the force reference as also desired by Gardner.

4.4 REAL-TIME ASPECTS OF FORCE CONTROL FOR WALKING

Control systems of walking machines could either be centralized or distributed. Centralizing is possible, because the distances between the units are in the class of a few meters. The main advantage of centralized control under one control computer is speed of information flow from one logical unit to another. The complexity of such a controller and the large number of analog input and output to and from processes (I/O) are the drawbacks of a decentralized control.

The future of vehicle control is in distributed control integrated into the mechanical system. These control systems are often called embedded control systems. The main component of embedded control systems are node controllers, that contain fast serial transmission lines, analog I/O in various formats and sufficient amounts of calculation capacity. Micro controllers are micro chips, that contain in addition to a CPU and mathematical capacity, the data transmission capacity and the analog I/O mentioned above. Only the control signal for the actuators usually has to be amplified outside the node controllers. The size and power consumption of node controllers are small and reliability high, due to the use of micro controllers.

The type of control of walking machines is naturally decentralized, because the control can be divided to frequently activated leg control including actuator control and the less frequent supervisory body control that coordinates the actions of all legs. The wiring is kept minimal with distributed control allowing for maximum reliability. Distributed wiring and data transmission instead of centralized analog signals are advantageous also in noise suppression, that is often a problem in vehicle control systems.

Real-time multi-tasking and network oriented operative systems with flexible development tools are equally important to the evolution of embedded systems as the evolving node controller hardware. There are several serial communication (de facto) standards that are also IC chip oriented with inexpensive hardware and sufficiently fast in data transmission.

Communication capabilities are a larger bottle neck in the control of walking than the calculation capabilities. Calculation capacity can be locally expanded to meet the needs. Control algorithms of walking should be developed so that the data transmission needs are in the class of the leading edge of the general hardware and software developed for the vehicle control systems. Then the cheap hardware produced for automotive markets can be used for control of walking. The demands for economy, in order to be comparable with existing wheeled vehicles, can then be met.

For example CAN (Controller Area Network) (Kytölä 1992) designed for vehicle controllers has a maximum transmission speed of 1 Mbit/s and is becoming more and more common. CAN is subject to standardization by ISO. Obviously the MECANT I communication hardware could be replaced by cheaper CAN hardware. Installing the leg nodes in a star format around a supervisory node, would certainly enable walking, using CAN networks, but would not utilize the network as well as possible.

The chosen controller system for MECANT I meets most of the desired specifications except in complexity, size, weight and reliability. It is, however, flexible as it consists of mass produced PC hardware. The operative system contains the necessary development tools and is network oriented. The communication capacity is estimated to be up to 200 kbytes/s of application oriented data; the error-free token-passing overhead uses the rest of the 2.5 Mbit/s communication capacity. Micro controllers have already surpassed these rates and such rates will evolve to vehicle control system hardware obviously within a year or two. If communication speed becomes a problem with a microcontroller, the are plenty of IC chips for communication up to 10 Mbit/s transmission speeds, that could be installed in addition to the microcontroller with shared memory access.

How the capacity of the network is utilized, is essential for control of walking. The main idea is to send, as seldom as possible, as much data as possible, in order to keep the response times of fast action messages low. The data may not, of course, be buffered too long period before sending the data. For example "ground contact detected at leg 1 in position ..." is such a fast message. This means that the algorithms are to be developed using local autonomy, that can perform all necessary activities based on the relatively infrequent incoming messages.

The force control methods based on actuator force control of all actuators has a practical disadvantage: the force decomposition is based on the leg positions. Because all leg positions are needed for the calculations, the proper place for the calculations is in the main computer. Therefore there is a delay between the time the leg positions are measured and corresponding force references are activated.

The force control was tested with six supporting legs and as often as possible in the network of the MECANT I. Steps were not taken i.e. locomotion messages were not sent. The loop containing

- body force reference calculation for six legs based on last leg positions and body position and orientation,

- force reference transmission to all six legs and

- leg position transmission from all legs to the main computer.

was performed with an interval of 33 ms, which is estimated to be sufficient for force control of the body. Only one message has to be sent to and from each leg, because the position of the legs is returned by the reply necessary with the operative system used.

Note, that the force control interval of 33 ms is faster than necessary and locomotion oriented information (a few bytes actually) could be attached to the force messages and the reply without an increase in the interval. In addition the leg moving in the air does not need any frequent message. The locomotion oriented calculations (for example according to Halme et al. (1993)) in the main computer can be performed while the messages are transferred between the main and the leg computers.

The exact value of the Z coordinate of the positions of the legs is needed only in the estimation of thrust forces of the position/force control method presented in section 6.2. The future estimates of the lateral (X, Y) position at certain instants of support states can be used to calculate the future vertical leg force distribution. Such instances are defined by any change in the leg support state i.e. placement to the support or lift-off of any leg. The leg force distribution at these instances is usable, because, the leg force distribution changes linearly during changes in leg positions as long as the supporting leg configuration remains the same. This method has been presented and tested by Gorinevsky & Shneider (1990) with good results. The mechanism to change support force reference linearly along with position interpolation in horizontal directions is easily implemented in the leg controller. Attitude and altitude control would be taken care of separately, as described in section 6.2.

5 FORCE CONTROL OF HYDRAULIC ACTUATORS

Establishing stable and reliable force control of the hydraulic actuators is one of the difficult matters in the control of the legs of MECANT I. The control has to be very robust due to the following problems:

- the (external) load of a leg varies greatly and rapidly during walking
- movements of the other legs cause pressure drops in the hydraulic actuators
- all the valves are symmetric, but the vertical and horizontal actuators are asymmetric
- the closed loop proportional hydraulic valve and its control board are designed for position control
- the force reference should be maintained despite of the movement of the leg.

Hydraulic pressure in an actuator, and thus the output force of the actuator, depends heavily on the external forces (load) that oppose the force generated by the actuator. When these two reach an equilibrium state, the piston of the actuator does not move or moves at a constant speed. The load varies greatly, when the other legs start or finish their support phases. The load of another supporting leg may become three times higher at that instant.

The compliance of the leg mechanism allows the piston of the actuator to move, when the opposing force is changed. This movement, even a small one, changes the oil volume and therefore rapidly changes the pressure due to the compressibility of oil. The oil volume in the hoses and pipes is also compressed when the pressure is increased. The flexibility of the hoses usually causes more oil flow than the compressibility of the oil.

It was planned that the force control of the hydraulic system originally designed for position control would be taken care of by control algorithms and the pressure sensors to the extent proven to be necessary and worthwhile. Difficulties in force control were foreseen for example in the pressure vs. control voltage characteristics of the valves used (copied from the data sheet to Fig. 35). The valve gives the source pressure to the pressure output when three percent or more of the control voltage is used. Note, that the gain was measured with closed pipes; thus oil flow was not possible.

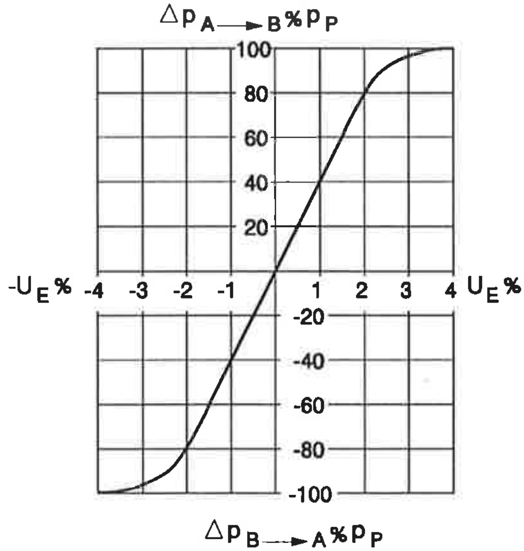

Fig. 35. Pressure gain of the hydraulic valve (as described by the manufacturer).

5.1 MODELLING AND SIMULATION

The purpose of the force process modelling and simulation of an hydraulic actuator was to generate a model-based force controller. It was obvious from the start, that the process model would not be a linear one, because many non-linear factors are involved. Typical non-linear factors are friction, hysteresis, valve flow curve and pressure gain of valve. The valve flow curve is, as well known, relative to the square of the pressure difference.

It was noticed during the evaluation of the model, that the opposing load of the actuator has a very important role in the force process. The load can not be modelled in practice, as in this case of a walking machine moving on a natural terrain. The model of the process including the environment is, however, very important for the robust model-based controllers. Therefore the development of a model-based force controller was abandoned.

5.1.1 Model of force process in actuator

The force control of the weight carrying vertical actuator was analyzed and studied in detail, because it was assumed to be the most difficult case. The outlines of the mechanism of the test leg in this case can be seen in Fig. 36. The weight of the MECANT I body is carried by three pairs of similar but larger legs.

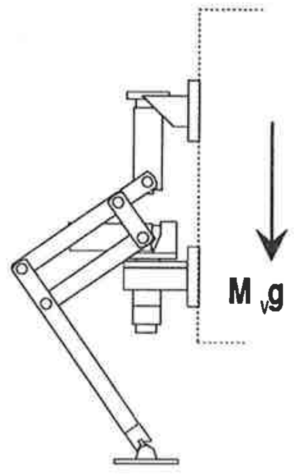

Fig. 36. Body weight is supported by six similar legs.

It was, very surprisingly, not possible to find hardly any model of the force process in the literature. Most of the previous studies (like in (Watton 1989) and (Pyrhönen 1984)) concentrate on the dimensioning of hydraulic equipment in order to reach velocity references with different load situations.

Since the vertical and horizontal actuators are decoupled, the movement or force exerted by one of them does not affect those of the other. There are two exceptions. The lever arm of vertical movements is attached to the cover of the horizontal actuator and forces caused by this lever arm bend the horizontal actuator. The leg is more compliant in the vertical direction, the more the piston of the horizontal actuator is extended. Similarly the horizontal direction is more compliant, the more the vertical actuator is extended i.e. the ankle lifted.

The previous Fig. 36 can be simplified in order to model the actuator forces. Only the vertical actuator is needed in the model, because the other leg of the pair opposes the horizontal forces. The simplified version can be seen in Fig. 37. A part of the weight of the body pulls the piston downwards. The lever arm attachment point and the actuator sleeve (the outer jacket of the actuator, i.e. the tube) can be considered mechanically connected together. The horizontal bar of the arm mechanism bends, since the force against the ground is exerted through this horizontal bar. The compliance of the lever point is combined with the compliance of the horizontal bar.

If the compliance of the leg and the viscous friction of the actuator are concentrated further, a quite simple model of the actuator can be used. This model can be seen in Fig. 38. The actuator is fixed at the top of its sleeve and the reduced body weight (*M*) as a mass, is attached to the piston. The compliance of the leg is modelled by a spring and the viscous friction as an absorber. If the weight of the body is M_v, the reduced mass (*M*) is $4*M_v/N$, since *N* legs support the weight and the actuator has to produce a four times larger force than the

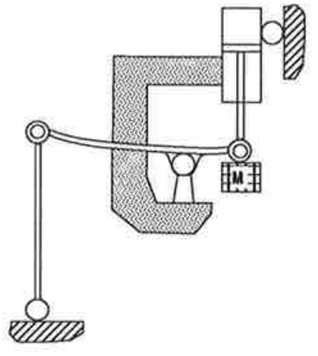

Fig. 37. Mechanical simplification of vertical force control case.

weight it is lifting due to the lever arm in the mechanism. The extracting pressure on the extracting side in the smaller chamber of the cylinder has to carry the weight of the body.

The basic principles of force modelling and simulation repeated as a loop are:

- previous pressures and velocity of the piston are assumed to be known
- the acceleration of the piston is calculated based on pressures, external forces and friction
- piston velocity and position are calculated based on the acceleration

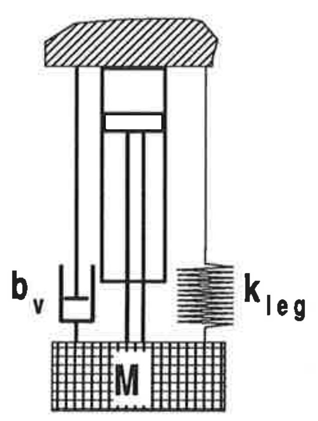

Fig. 38. Simplified leg model for force modelling.

- changes in pressures are calculated based on relative flows and oil compressibility; flow is a function of the pressure difference over the valve orifices and the control voltage

- since the net force that moves the piston of the actuator fluctuates, the piston may move a little bit, since the mechanism is bent due to this force; these changes in position can not be evaluated in the force equilibrium equation; the movement, however small, clearly affects the pressures.

The force estimation can be calculated based on the two pressures. The estimation can be a calculation input for a simulated controller, that gives a new output voltage fed back to the loop above.

The hydraulic system is modelled further according to Fig. 39. Most of the key equations are given in the following sections. The piston acceleration is derived according to Eq. (62). F_{co} is the Coulombian friction force, M the reduced mass, g gravity and b_v the damping factor. The compliance of the leg does not cause any force on the actuator, since the forces that bend the leg are internal forces of the leg mechanics. The speed and position of the piston are given by double integration of previous values starting from the acceleration. Calculations may give piston positions outside the working area. Such cases have to be cut to be inside the mechanical limits and the speed estimate updated accordingly.

$$M\ddot{x} = p_b A_b - p_a A_a - Mg - sign(\dot{x})F_{co} - b_v \dot{x} \tag{62}$$

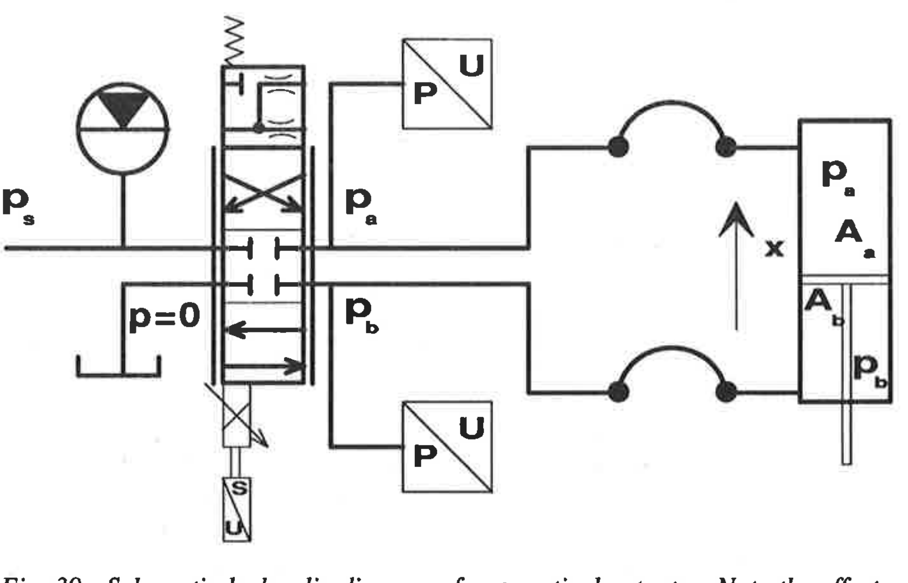

Fig. 39. Schematic hydraulic diagram of one vertical actuator. Note the effect of piping to the actuator forces.

A certain position of the piston is chosen to correspond to the case, where the leg starts to lift the body so that the other leg(s) on this side will no longer properly support the weight of the body. This is taken into account by gradually doubling the reduced mass caused by the weight of the body (M_v) in the simulation model within a share of the total working area (stroke) of the piston. So, if the position of the piston is less than the limit, the mass is a normal share of the weight of the vehicle and if it is larger than another limit, the mass is doubled. If the position is between these two limits, the mass is increased linearly to the doubled mass.

The mechanical deflection due to flexibility of the leg mechanism is calculated based on piston net force and spring factor k_{leg}. If the deflection (and the force generated by the piston) is not the same as previously, the difference is added to the position of piston. This method may cause some inaccuracies in the simulation, because the dynamic situation is considered by a static model of the deflection of a spring. However, it is assumed, that the error is not significant, because a short simulation interval is used.

The flexibility of a leg will clearly affect the pressures and easily cause instability with the numerical double integration. As a matter of fact, the double integration itself is easily unstable. The tendency to instability was overcome by using the fourth-order Runge-Kutta integration ((see for example (Press et al. 1988)) for speed and pressures and trapezoidal integration for position. Change in position is, in the trapezoidal integration, the time interval multiplied by the averages of the derivatives at the previous and the next simulation instants.

The compressive oil volumes can be calculated, when the position and the speed of the piston are known. They are the sum of volume in the hoses, pipes and actuators on both sides of the piston. The well known relation between changes in pressure and volume is according to Eq. (63), where B_{oil} is the compressibility. It is also called bulk modulus (Watton 1989). The compressibility depends on the position of the piston, because there is a considerable volume of oil in the chambers of the actuator.

$$\frac{\dot{V}}{V} = -\frac{\dot{p}}{B_{oil}} \tag{63}$$

The difference in pressure is according to Eq. (64).

$$\dot{p} = -B_{oil} \cdot \frac{\dot{V}}{V} \tag{64}$$

The pressure derivative of hose volume (dV_{hose}) is added to the equation above, because the flexibility of the hose is considerable. It is believed that the oil which compensates for the compressed oil volume flows via the valve to the system. The oil flow balance can be calculated using Eq. (65) and (66), because the velocity of the piston and valve characteristics are known. The control voltage (U) is assumed to be negative in the equations.

$$\dot{p}_a \left[\frac{V_{oil}^a}{B_{oil}} + dV_{hose}^a \right] = \dot{x}A_a - Uk_f \sqrt{p_s - p_a} + q_v \tag{65}$$

$$\dot{p}_b \left[\frac{V_{oil}^b}{B_{oil}} + dV_{hose}^b \right] = -\dot{x}A_b + Uk_f \sqrt{p_b} - q_v \tag{66}$$

With positive control voltage the situation is different:

$$\dot{p}_a \left[\frac{V_{oil}^a}{B_{oil}} + dV_{hose}^a \right] = \dot{x}A_a - Uk_f \sqrt{p_a} + q_v \tag{67}$$

$$\dot{p}_b \left[\frac{V_{oil}^b}{B_{oil}} + dV_{hose}^b \right] = -\dot{x}A_b + Uk_f \sqrt{p_s - p_b} - q_v \tag{68}$$

Leakage (q_v) from the chamber of larger pressure to the chamber of smaller pressure is also included in spite of the small amount of leakage with modern sealing systems. Leakage can be assumed to behave according to Eq. (69) i.e. linearly according to the difference of the pressures. Note, that the equation is only one possible model for the leakage. The sign of the flow q_v is decided depending upon which of the pressures is larger.

$$q_v = c_v \, \Delta p \tag{69}$$

K_f is a valve type specific factor based on the data of the valve. If any of the pressure differences processed with square root in the equations (65)..(68) above is negative, the oil flow is reversed. The oil would flow from the actuator into the pressure source or from the tank into the actuator. Backward flow from the tank is usually prevented by one directional valves in practise. However, the other actuators can use small amounts of backward flowing oil.

Changes in the pressures of both chambers (and piping) can be calculated according to either of the equation pairs above using Runge-Kutta integration of fourth order (Press et al. 1988).

The equations above are a model of the force process in a hydraulic actuator. There are many factors, like jitter, valve pressure gain and pressure source fluctuations, which should be included, but are difficult to model. For example in a stationary case, where equilibrium is reached, the control voltage will finally be zero according to the equations, but in practice it seems to be a couple of per cent of the maximum voltage. This is obviously caused by the dead zone of the valve and internal frictions in the valve.

The equations, however, offer a possibility to create a simulation test bench for the development of different force controllers.

The equations were completed taking into account several experience based practical factors like:

- output resolution of the DA converter
- output changed and measurements done after a 40 ms servo interval
- oil volumes on both sides of the piston are functions of the position of the piston and
- piston positions outside the working range of the piston are cut off.

5.1.2 Simulated force process

The control loop has to be closed in the simulation in order to estimate the state of the process by calculating the control voltage and the related oil flows. A PI controller with constant gains was used in the simulations and with the force process equations given in the above section. A PI controller was used, because it is the most common in the literature for the task as described in section 1.1.3. The case simulated resembled the case of the test leg and the body it could have carried. The force reference was to carry the normal weight of the vehicle and, in addition, generate an extra 600 N in order to lift the vehicle. The final force reference was then 3347 N. The simulation interval was 2 ms; the servo interval was 40 ms.

It was soon noticed, that small values of leakage, well acceptable in practical hydraulic systems, did not change the simulation results at all. Therefore zero leakage was used in the following figures.

The initial position of the piston was 60 mm. Lifting the body was simulated by setting such a limit position of the piston, above which the mass carried by the leg was increased. The position limit to start "to increase the pay-load of the actuator" was 63 mm. Above 76 mm it would be twice the expected normal pay-load due to the normal share of the mass of the body. The initial pressure on the carrying (extracting) side was less than necessary to carry the weight and generate the extra 600 N. The force estimation of such a simulation can be seen in Fig. 40. The corresponding control voltage and position of the piston are in Fig. 41.

It can be seen in Fig. 40, that the force control is stable. The piston starts to move upwards immediately and accelerates until it reaches the limit of 63 mm (Fig. 41). The estimated force rapidly exceeds the reference, but gradually returns to the reference. Note that the piston finally reaches a level, where the opposing force is the same as the force reference. The force reference can not be reached, if there is no corresponding opposing force.

The behavior of the pressures in the same simulation is presented in Fig. 42. The pressures are presented as relative to the pressure of the atmosphere. Some fluctuations in the estimated force follow the changes in output voltage. The

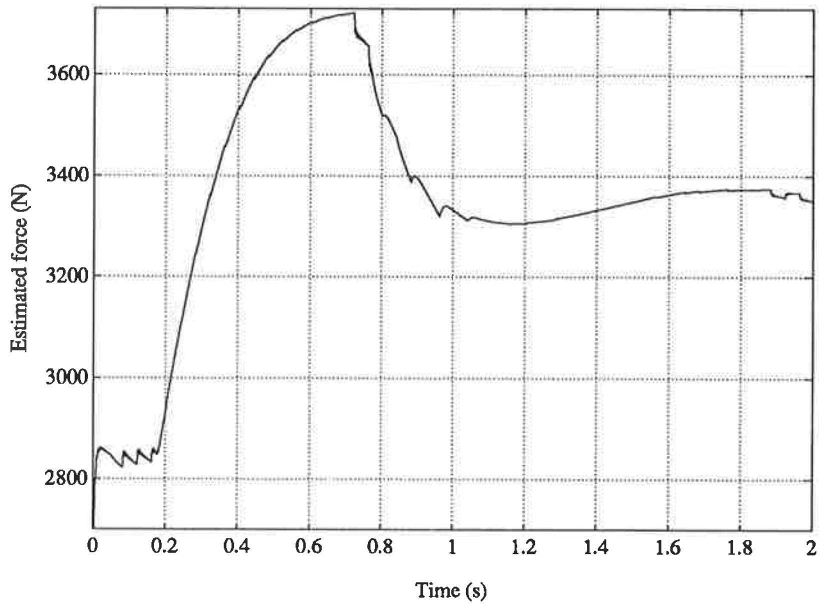

Fig. 40. Simulated force control case; one leg lifts body with 600 N force.

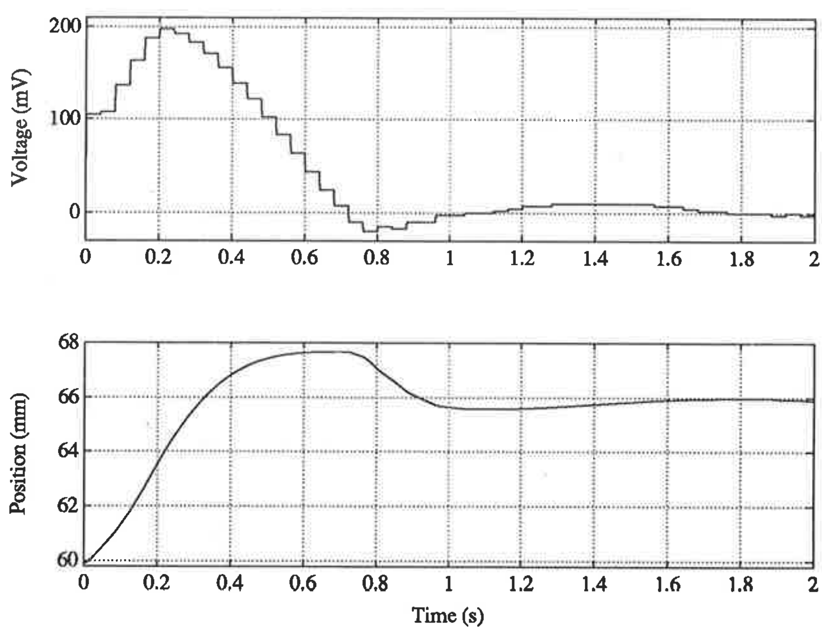

Fig. 41. Simulated control voltage and position of piston.

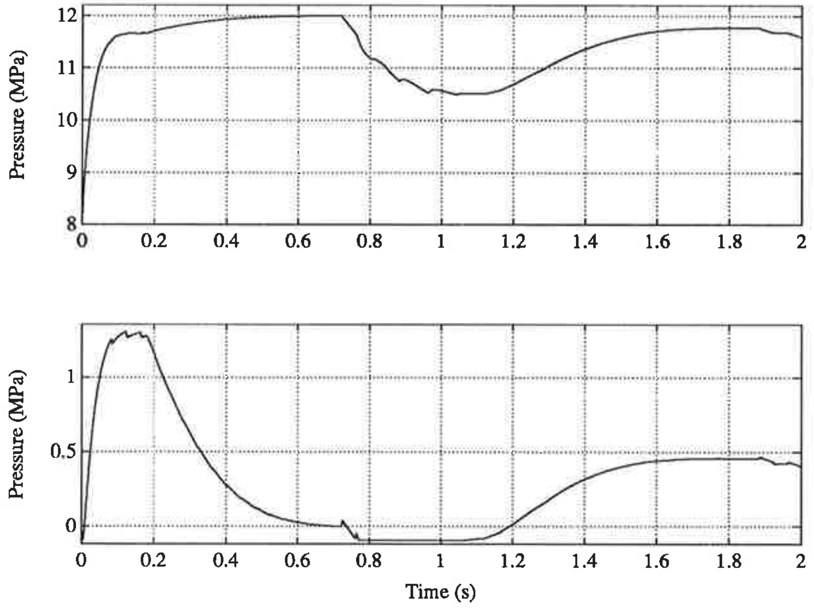

Fig. 42. Simulated pressures. Upper is the carrying pressure of the chamber of the smaller area.

pressure in the larger volume is constant for a while as seen in the lower part of Fig. 42 between 0.75 and 1.2 s from the start. The phenomenon is called cavitation in hydraulics. It happens when the external force drag the actuator, but oil flow is not possible, because the valve is closed. The pressure is then constant, because the oil would start boiling i.e. some of it is changed to gas form.

The uneven fluctuations in the simulation figures are mainly caused by the 40 ms control interval of the system, the frictions and the non-linear state changes in the process. Viscous friction coefficients of 2000 N/m/s were used in the simulation. The worst change happens 0.75 s from the start. The flow of oil is then reversed.

As seen in the simulation above, the opposing force of the actuator is a very important factor in the creation of pressures and actuator force. However, the force references change rapidly during walking, when the body and the center of gravity move to different locations or the soil does not support the leg (or legs) or the control system stabilizes the rolling of the body.

When the leakage constant was increased to an impractical level, the effect of it could be seen in the simulations as disappearance of the higher frequencies.

5.1.3 Experimental modelling

Since force control in hydraulics was assumed to be rather difficult in advance and a model-based controller was also considered, experimental identifying of the hydraulics process was the obvious thing to be done. An FFT analyzer (Advantest R9211B FFT Servo Analyzer) specially developed for servo analysis was used.

The idea behind the FFT process identification is to add noise or sweeping frequencies to the control voltage of the system and to measure the effects of that multifrequency noise on the system output. The result is actually a transfer function of the measured system often called the Bode diagram.

A force sensor (Kistler 9251A) was used, because an analog force signal was not available in the process. It was fast enough for the necessary frequencies lower than 50 Hz.

Measurements with a closed PI force control loop was tried first by adding noise to the control signal of the valve. The brake of the mechanical slide of the test leg was active, thus the leg was not able to move. That can be considered as the most difficult force control situation. The control loop was kept closed in order to keep the process within an approximately constant (and hopefully linear) area. The best identification result can be seen in Fig. 43, where frequencies from 0.1 to 100 Hz were used. Three different frequency sweeps were used in different decades. The process seems to be a "pure integrator", since the magnitude decreases constantly with each 20 db/decade. As seen in the phase plot, the quality of process identification was quite low.

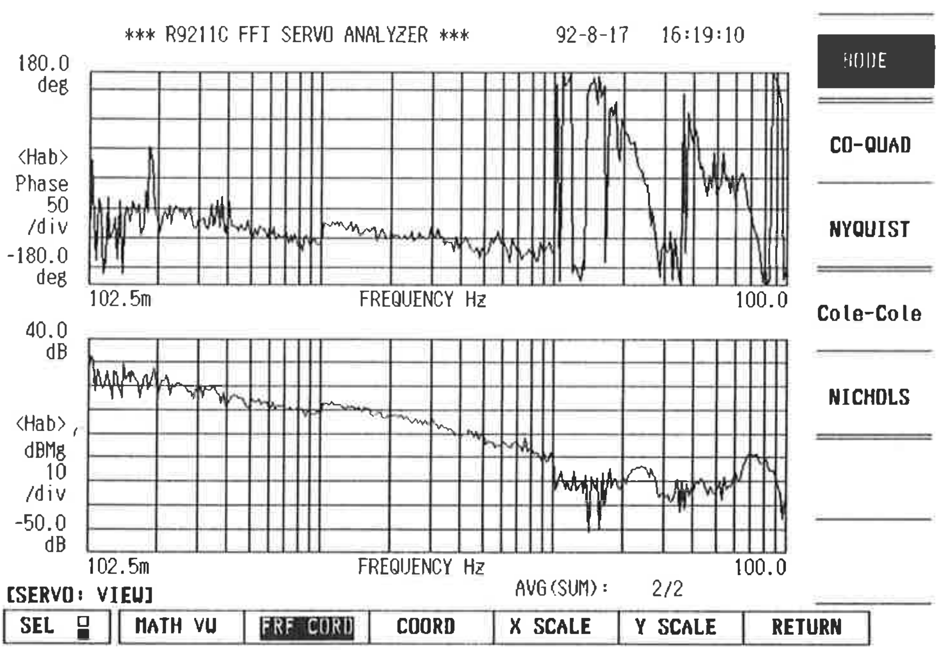

Fig. 43. Bode diagram of closed loop identification (ref. 2000 N).

Another series of frequency analysis based tests were made by using the leg controller and force estimation. The control loop was opened in order to get an undisturbed picture of the force process. The control voltage was chosen randomly with the following restrictions in order to keep the leg forces constantly downwards: random variation was added to a constant bias so that the voltage was always positive. Since the voltage was changed at 40 ms intervals, the maximum frequency information given by this kind of FFT was 12.5 Hz.

Absolute magnitudes of each frequency sample were calculated for the random input signal and the process output signal by FFT and these two magnitude vectors were divided element by element. Altogether 8000 samples were originally taken. The result is the absolute magnitude of the system transformation function. Once again, the result was something very close to a "pure integrator".

A following integrator model between the control voltage of the valve and the force response can be concluded based on the frequency response tests explained above. The behavior is in practice limited by saturation of the hydraulic system in high and low frequencies.

$$F(s) = \frac{K_{fm}}{s} U(s) \tag{70}$$

Other basic ideas and elementary methods of frequency response analysis are presented by Rintanen (1991). More simple tests to model the force process were needed. The step response test is the most simple. A constant control voltage was suddenly changed and the response monitored. One such test with a sudden change of the valve control voltage from 20 to 50 mV after a supporting contact was reached can be seen in Fig. 44. The result was surprising: the process seems to be a simple first order process with a rise time of approx. 4 s. The noise caused by the pump can also be seen in the figure.

Fig. 44 also reveals, that there are severe friction forces in the actuator. Although the estimated force (generated by the pressures) changes rapidly, the real force measured in the ankle does not change correspondingly. Friction seems to sustain 250 N of the generated force in the actuator itself.

Evaluation with sinusoidal references according to Rintanen (1991) was the next step. The open system was excited first with a constant 200 mV signal and then with a sinusoidal voltage with a 400 mV bias and a 200 mV amplitude. The estimated and the measured forces were logged to files. Two such tests can be seen in Figs. 45 and 46 with frequencies of 0.5 and 2.0 Hz correspondingly.

There is a sizeable delay (phase shift) between the estimated and measured forces: about 90 degrees in both cases. Note that the dominant 4 s first order rise time can also be seen in Figs. 45 and 46.

A model of the first order corresponding to the case of step wise change of the control voltage is presented in Eq. (71). The gain parameter K_{fm2}, that is a relation between the changes of force and control voltage, depends on their initial and final levels. The time constant is also a variable. It changes according to the final voltage, because the oil flow is related to the opening of the valve and the initial pressure. The force is changed faster with a larger opening of the valve.

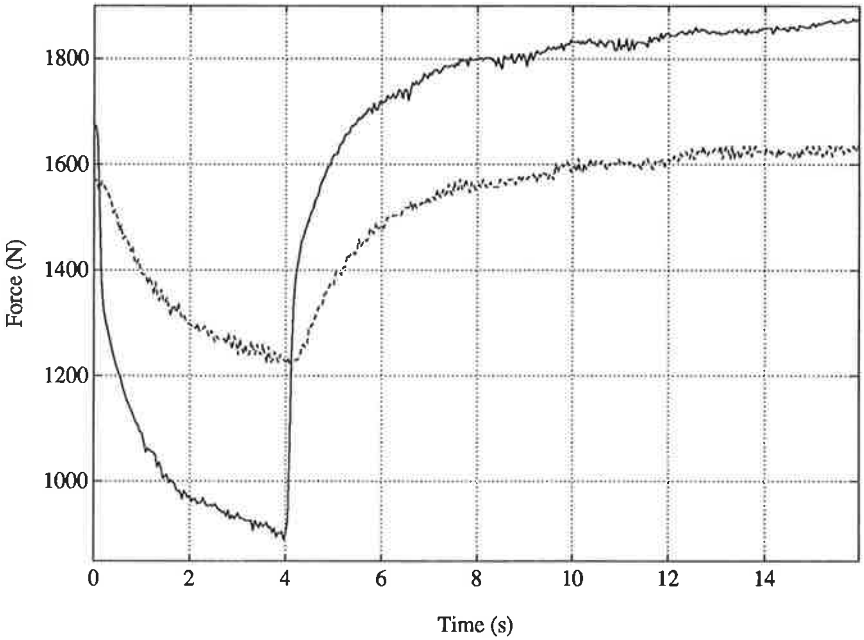

Fig. 44. Force history after stepwise change of control voltage.

$$F(s) = \frac{K_{fm2}}{1 + \tau s} \tag{71}$$

Larger changes in the control voltage were not tested, since large amplitudes would obviously have broken the mechanism. The forces in the piston are a process of the first order with small control voltages, since the oil flows through a small orifice and the leg mechanism is actually a spring. The piston may make a small displacement due to the changed output force. When all the oil corresponding to this displacement has flowed, the pressures stabilize and the oil does not flow any more. The integrator characteristics are explained by the amount of oil which has flowed and the spring characteristics of the mechanism, because energy is stored or discharged from the compliant mechanism. Friction causes additional non-linearity. Another conclusion is that friction severely affects the force control. The force control seems to be rather impossible with frequencies higher than 10 Hz.

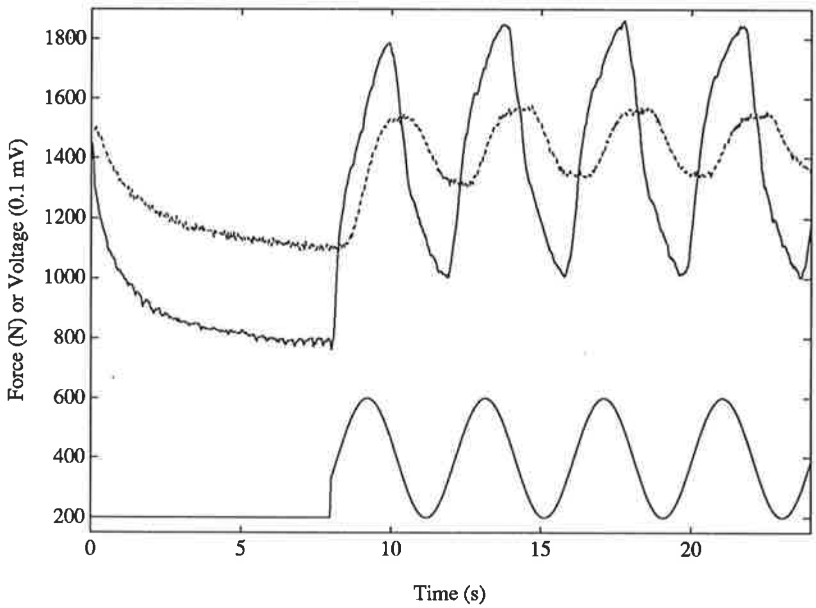

Fig. 45. Estimated and measured force of sinusoidal control voltage.

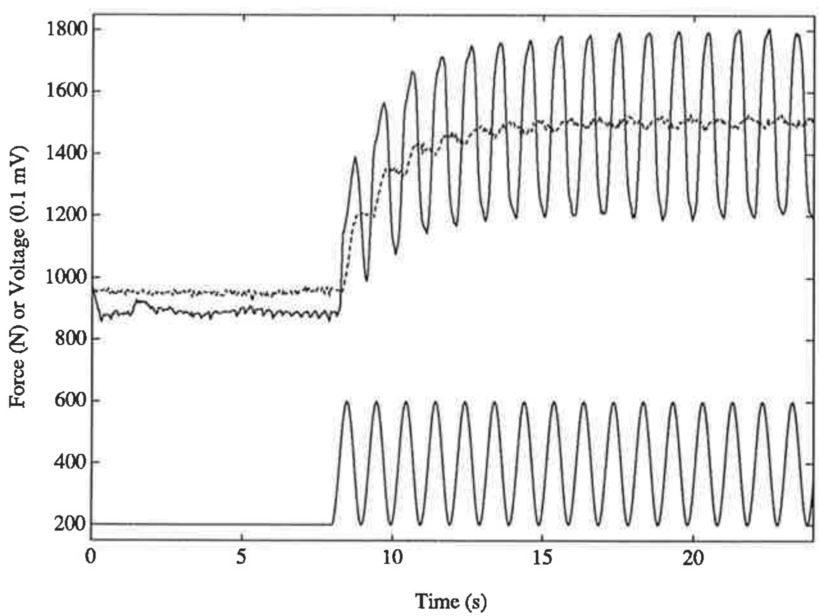

Fig. 46. Sinusoidal test with 2.0 Hz.

5.2 ACTUATOR FORCE ESTIMATION

The main factor in the estimation of the output force of an actuator is based on the hydraulic pressures and effective working areas of the actuator. That is not, however, the force that affects the external mechanics. The theoretical force is reduced by stiction (i.e. opposite friction force, before the actuator moves), acceleration of the load mass, and coulombian friction.

A three axis force sensor based on piezo material (Kistler 9251A) and its amplifier unit (Kistler 5041B) were used in the force estimation studies. The force estimation based on pressure measurements is given by:

$$\hat{F} = p_a * A_a - p_b * A_b \tag{72}$$

Because the source pressure is generated by a rotating pump, there are some high frequency fluctuations in the source pressure. The force control is based on force estimation. If the source pressure fluctuations do not arrive in the actuator chambers simultaneously, the fluctuations can be seen as noise in the force estimation. The pressure in the force estimation is the average of the pressure readings at the instant of the control calculations and 10 ms earlier. This somewhat filters the pressure readings, that contain quite a lot of noise.

5.3 JOINT LEVEL CONTROLLERS

Several force controllers have been developed for the test leg. These controllers and their function are considered in the following sections. A servo cycle of 40 ms is used. The controllers are:

- compliance based control; i.e. position reference of the actuator is compensated for by a factor, that is resolved by PI control of force error

- PI control where the output voltage for the valve is calculated based on force error

- a fuzzy controller (Ying et al. 1990)

- a hybrid controller based on force and position error of an actuator.

The force controllers described in the literature (like in Nevala 1991) are usually PI-controllers. An auxiliary amplifier board based on PI-control could have been connected to the servo control boards of the valve to do a "pressure control or combined volumetric pressure function". This was not done, because the combined board system could have done force control only in one direction.

Efforts were mainly concentrated to different versions of PI-controllers in this study also. PID-controllers were also tested, but it was noticed that the D-term caused instability. A force estimate based PI-controller was chosen based on tests, since it had the smallest tendency to oscillate, had a small number of parameters to be tuned and the calculation capacity requirements of the PI-control are relatively small.

The force process started to oscillate easily, when the controller gains were chosen for immediate response. The highest possible gains, that limited oscillations almost completely, led to step response rise times between 200 and 300 ms.

5.3.1 Compliance based controller

A compliance based force control is based on the nominal position x_{ref} of the piston of an actuator and the estimated force error. The force error and its integral (thus PI controller) is used to calculate a position compensation factor, that is added to the nominal position reference of the actuator. The control method is schematically visualized in Fig. 47.

The compliance controller was tested first. It was quite obvious from the beginning, that the compliance control would be unstable, since small changes in the actuator position may cause large changes in the actuator load.

A test is shown in Fig. 48. The test leg was driven towards hard ground, until the necessary support force was detected. The PI force control of a compliance type and the data logging of the estimated force was started at the same instant. The leg mechanism was locked to the support pedestal all the time. This is the hardest case for the force controller and simulates the case where a leg has to support a great deal of the weight of the MECANT I after the leg has reached the ground. The force reference for the actuator was 2000 N, the P parameter 0.0040 mm/N and the I parameter 0.0020 mm/N. The best response was achieved with these parameters.

There are severe oscillations in Fig. 48. Using filters is an obvious method to calm down these oscillations. Filtering the controller output was tested. An "exponential filter" was used. The previous "correction distance caused by the recent series of force errors" was weighted with 0.885 and the new correction distance with 0.115. As seen in Fig. 49, the frequency of the oscillations is

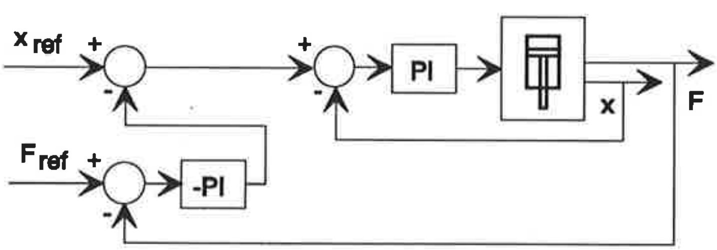

Fig. 47. Compliance based controller contains a position loop closed by a force loop, that changes the nominal position reference of the piston.

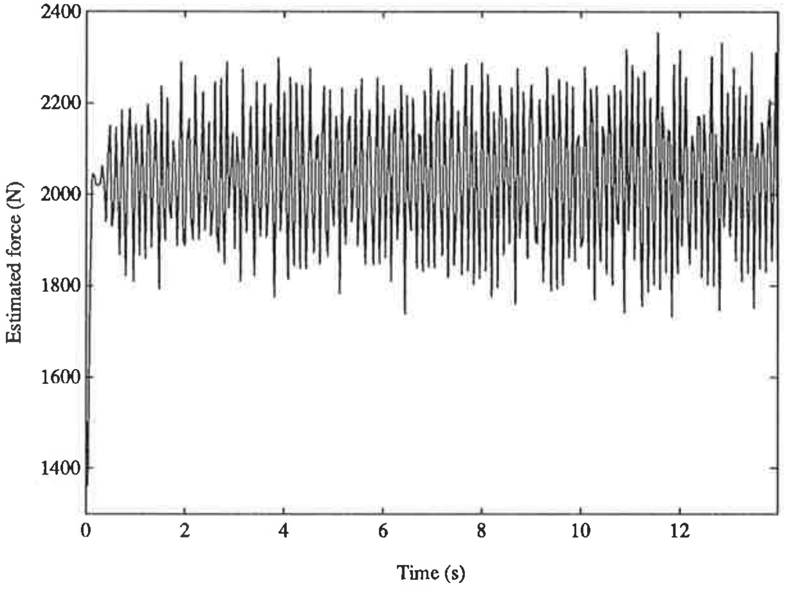

Fig. 48. Vertical force estimation with PI compliance control in a stiff case, reference 2000 N.

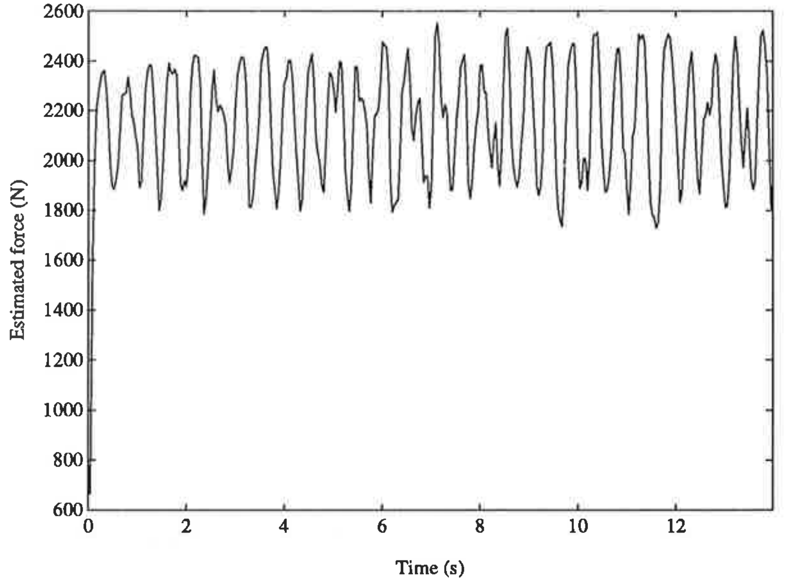

Fig. 49. Effect of controller output filtering of PI compliance control, reference 2100 N.

somewhat reduced, but not the amplitude. Because mechanical systems can tolerate (i.e. dampen) high frequencies better than low ones, reducing the frequency of the oscillations by filtering may cause problems in practice. Separate filters are not usually used with controllers, that may also have filtering effects.

The framework of the compliance controller was used in the "maintain support force scheme", that was tested with MECANT I. The force control of a leg did not react in the scheme, when the detected force was within an accepted force range, but increased or decreased the "position compensation distance" when the estimated force was less or more than the corresponding lower and upper limits. These tests were made before a stable force control algorithm for the vertical actuator was achieved. Even this crude method improved walking on uneven ground; therefore motivated development of a more extensive force control.

5.3.2 Load adaptive PI force controller

The well known PI control was used for force control of hydraulic actuators, because it seemed to be the most promising in the literature (Nevala 1991). The control was done according to Fig. 50.

The control is based on the difference between the estimated output force (the P term) and the time integral of these differences (the I term). The maximum absolute value of this integral is limited in order to get good response when extensive external forces cease to affect.

Three different tests of the controller with the test leg are presented in Fig. 51. The force control (and the data logging) is activated after a constantly increasing opposite force of at least approx. 1000 N is detected.

The control parameters of the tests in Fig. 51 are not the same. It was noted during the tests, that different I-factors give the best responses to different load

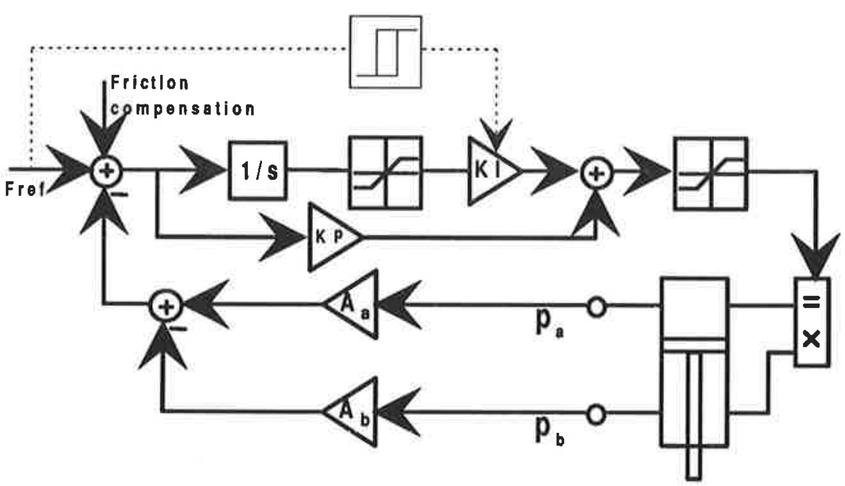

Fig. 50. PI force control based on actuator pressures.

references. A small change in the P-factor does not affect the result greatly. Therefore a constant P-factor (relatively small) is used. Two examples of the partly linear functions between the force reference and the best I-factors (positive direction of the vertical actuator and negative direction of the horizontal actuator) are presented in Fig. 52. When the force reference is changed by more than 10 percent, a new I-factor is calculated by interpolation using these functions. The differences in the functions are caused by, for example, different compliances in the mechanisms corresponding to these two actuators.

The method above is one of the most reliable of adaptive control methods, because the whole working area of the controller is tested during the tuning phase of the parameters. The method has been called, for example, "on-line parameter scheduling" with industrial robots. The usability of the method and the shape of the parameter functions show that the force process in hydraulic actuators is very non-linear. Usability of the method was shown during tuning of the parameters for the legs of MECANT I; the same set of parameters could be used for all legs. The friction and stiction characteristics of the legs seemed to vary within a magnitude of two or three.

The I-term values of the vertical actuator in Fig. 52 were tuned by testing movements and evaluating responses by visual methods. The other sets of terms were tuned by calculating a performance index I by summing the square of error for an interval longer than any time constant of the system.

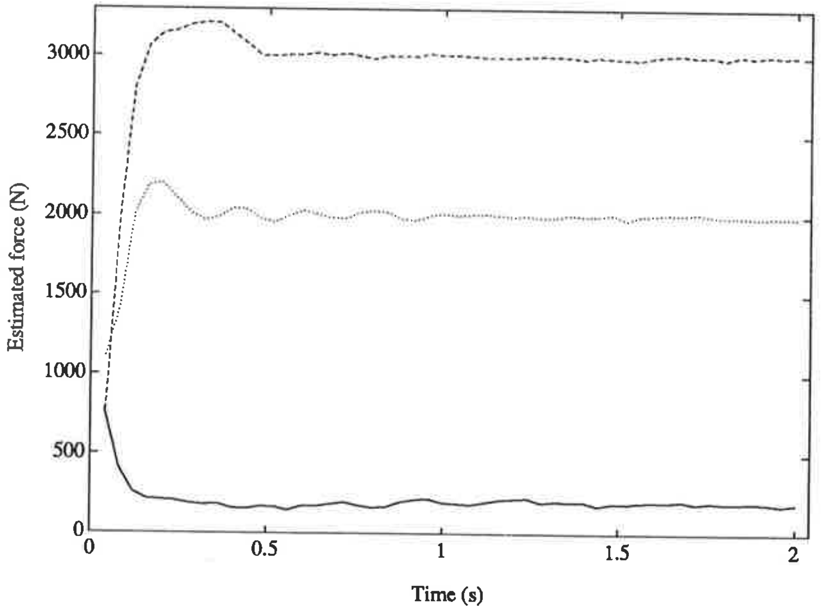

Fig. 51. Force estimates of three different test drives after ground contact. Force references 200, 2000 and 3000 N.

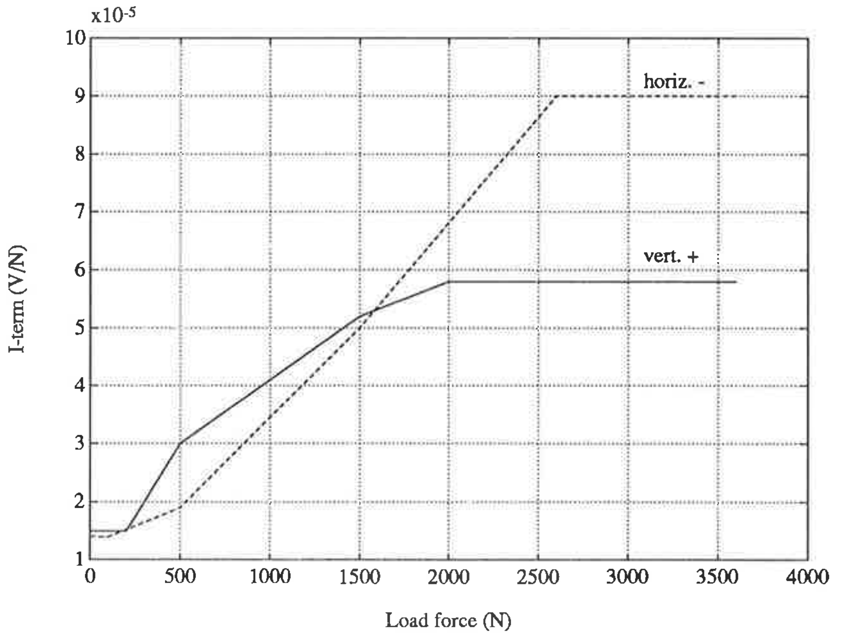

Fig. 52. Best I-terms of PI-force controller of two actuators of the test leg as a function of load.

The performance index I was calculated according to Eq. (73). Factor k varied depending on the axis. It was usually about 0.01. About 600 samples (K) were typically used.

$$I = \sum_{n=0}^{K} \left[e^2(n) + k \left| \Delta e(n) \right| \right] \tag{73}$$

The e is the servo error. The absolute difference between two succesive servo errors was used in order to reduce the possibility of parameters, that would cause oscillations.

Typical tests using force reference of the square wave type can be seen in Fig. 53. The real actuator response (the dashed line) measured by the force sensor used only for development purposes is clearly smoother than the force estimate. The effect of the hysteresis caused by friction can also be seen; the measured forces exceed the estimated forces, but follow the force reference quite well. The result is not good with small changes in the force reference. An example of such a control can be seen in Fig. 66. The negative effects of hysteresis caused by friction are minimized with friction compensation (see section 5.4).

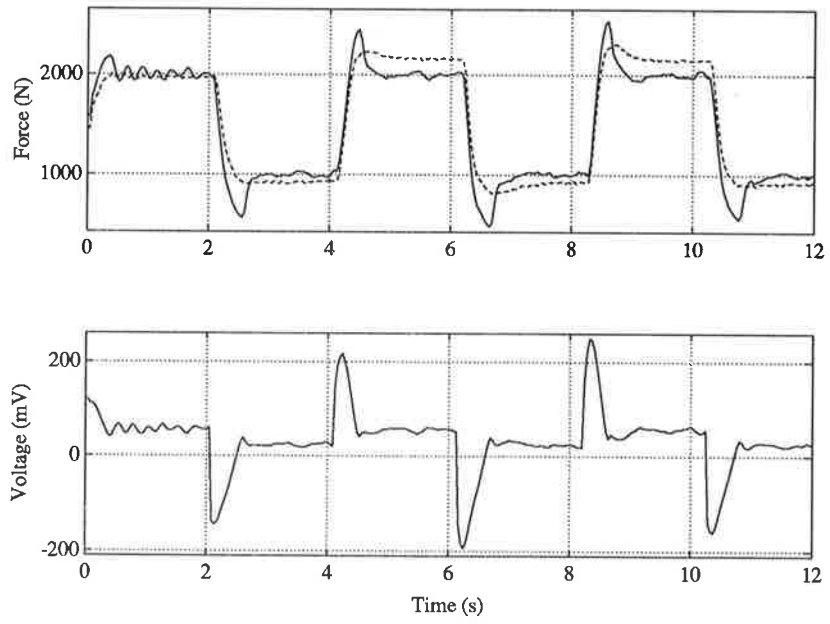

Fig. 53. Estimated and measured actuator forces and control voltage of vertical cylinder of the test leg. Force references 2000 and 1000 N.

5.3.3 A fuzzy controller

Fuzzy control methods (Lee 1990) seem to be developing quite rapidly to control various difficult non-linear applications. Measurable variables or other variables derived from the measured variables of a process are classified so that each variable belongs to two classes. The output value for each class of measured variables is known. By using the degree of membership of each class (fuzzification) and the corresponding output classes for each membership class, a proper control signal is calculated by averaging (defuzzification). Several output varibles can also be calculated based on a common set of measured variables. There are also several slightly related defuzzification methods.

It must be noted, that fuzzy control methods are do not often better control results than other more classical control methods, but fuzzy control methods offer a method to design and tune rather similar controllers for various non-linear control applications. General applicability can be seen in the development of fuzzy control boards (Omron FP-3000 and Yamamoto Electric EF-005) and various consumer products (Self 1990), for example cameras and washing machines, that contain fuzzy controllers.

Fuzzy control has been tested in the position control of a hydraulic piston by Virvalo & Koskinen (1992). They showed that a fundamental Fuzzy Logic Controller (FLC) can be made more robust and has at least as good performance as a model based state controller has (Virvalo & Koskinen 1992, p. 237).

The main problems of fuzzy controllers are the relatively young history of fuzzy control and the difficulties in choosing the best fuzzy control parameters. It is quite difficult to choose among dozens of slightly different fuzzy control methods and their variations. The best parameters for fuzzy control are usually tuned by trial and error. This takes time, especially when new elements (rules, signals or signal derivatives or integrals) are continuously included into the fuzzy controller.

A fuzzy control method based on the examples of (Fuzzy guide book, Omron) was programmed in the test leg environment. A stable response was not reached. Another simple fuzzy control method based on the method described in (Ying et al. 1990) and on the area concept of (Fuzzy guide book, Omron) was tested. Quite good results were achieved with the method.

The control is based on the evaluation of the control error and the time difference of the error (rate) (Ying et al. 1990). The error and the rate contribute separately at first by fuzzyfying according to the membership functions in Fig. 54 i.e. they are both transformed to two real values called membership. Four membership values called error.positive (e.p), error.negative (e.n), rate.positive (r.p) and rate.negative (r.n) are formed as in (Ying et al. 1990).

The measured value (either rate or error) is y in the example in Fig. 54. The e.p is 0.25 and the e.n is 0.75. They would be 1 or 0 outside the range (*-L*, *L*). *L* is a constant, since the argument (measured values of error or rate) is scaled with "gain for error" or "gain for rate" in order to unify the membership calculation.

The four **membership values** are defuzzified into one output value by using the "output membership" functions in Fig. 55. Four "rules" are used to calculate the "weight" for each output rule. The rules (r_i) are:

if (e.p & r.p) r_1 = output.negative (o.n)
if (e.p & r.n) r_2 = output.zero (o.z)
if (e.n & r.p) r_3 = output.zero (o.z)
if (e.n & r.n) r_4 = output.negative (o.p)

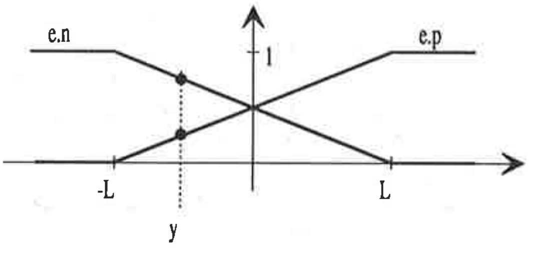

Fig. 54. Functions to scale input to two membership values (0..1).

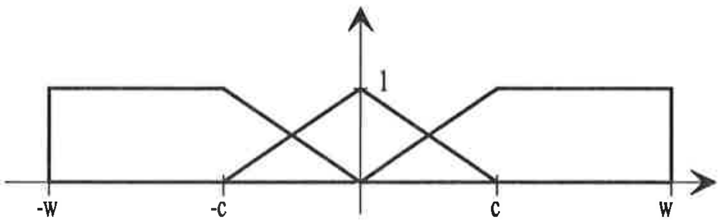

Fig. 55. Membership functions of fuzzy output.

Such a minimum height is given for each rule that is true for both the memberships of the rule. The minimum of the membership values of a rule is thus chosen. The height h in Fig. 56 is a minimum value of a rule reflected in the corresponding output rule. The areas under the height h of the output membership function of each rule are calculated. Two examples of such areas are in Fig. 56. The area of the polygon is given by Eq. (74) and that of the triangle by Eq. (75). The **relative output** value of the algorithm is the "center of gravity" of all these areas, when their weights are -1, 0, 0 and 1 according to the order of the rules.

$$A_1 = h(W - \frac{Ch}{2}) \tag{74}$$

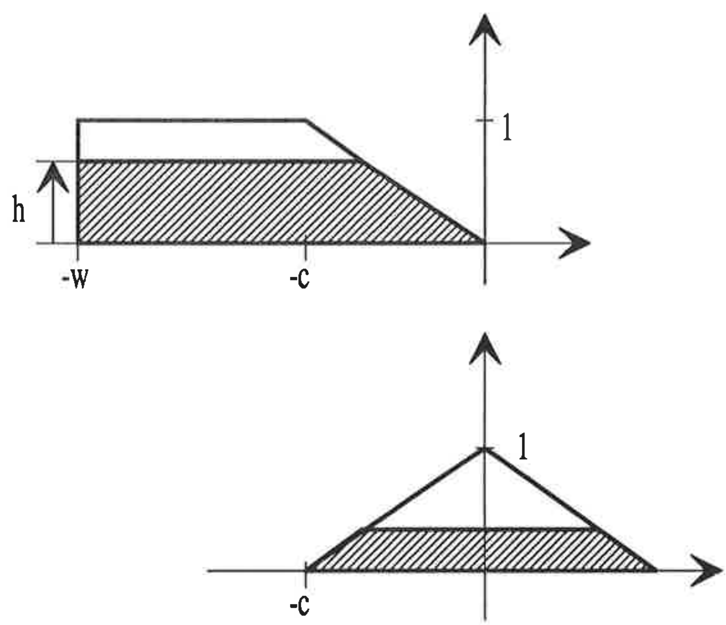

Fig. 56. Fuzzy output areas of a rate or an error.

$$A_2 = h\ C\ (2 - h) \tag{75}$$

The **relative output** is multiplied by the scaling factor (output gain) and added to the previous output voltage. Thus the control is based on the previous control values.

A matrix of fuzzy control values were calculated and transformed to a three dimensional figure in order to illustrate the characteristics of the fuzzy control presented. Error and rate were incremented between two limits for the data matrix. The matrix is displayed in Fig. 57. The control is 0.0 and is in the middle where the rate and error are 0.0. The uppermost and lowermost corners correspond to the cases where rate and error have their maximum absolute values. The values used in this figure are based on a tuned case. It can be seen, that the fuzzy control algorithms compensate for the non-linearities of the valve characteristics.

The minimum number of parameters to be tuned is five. They are:

- the gain in error to unify the error to membership,

- the gain in rate to unify the rate to membership

- the gain in scale of the **relative output** to the voltage to be added to the previous control voltage,

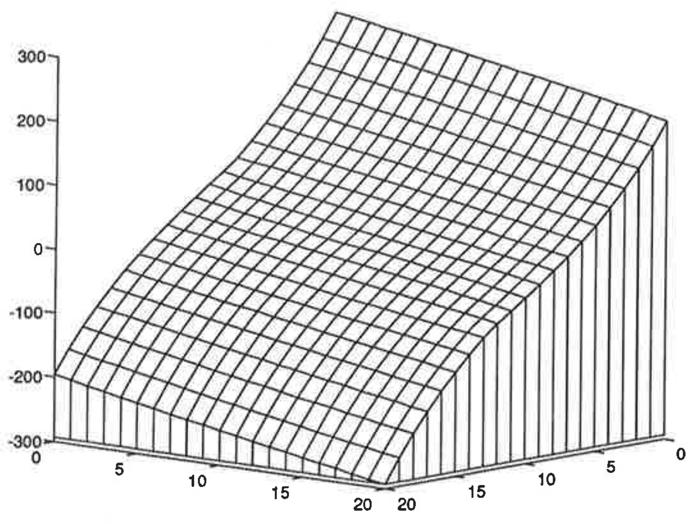

Fig. 57. Three dimensional view of fuzzy control output, when error and rate would have increased gradually in rows and colums; they were zeroes in the middle.

- C (in Fig. 55), the largest absolute value, that belongs to the zero.output class and

- W, the maximum relative width of the area of output membership evaluation.

According to several tests, three sets of the parameters mentioned above were needed; different sets for small, medium and large forces. They were tuned by searching for a minimum of sum of error (Eq. (73)), where a small factor based on the rate was also added. Including the rate in the error integral reduced the risk to choose parameters that caused oscillations. The force reference was one of the two values within the force range for which the parameters were tuned. The reference was changed to the other value after a couple of seconds.

Fig. 58 shows a typical test in the medium force area. The continuous line represents the estimated force and the dashed line the measured force.

A tendency to oscillate was noticed. Oscillations were severe with smaller forces and had a frequency of about 9 Hz. The reason for the oscillations is obvious. When the control has stabilized, noise in the pressure measurement values causes even more noise in the estimated force. This means that rate is very noisy in a stable situation. A noisy rate causes rapid changes in the fuzzy control output. This can be seen in the control voltage.

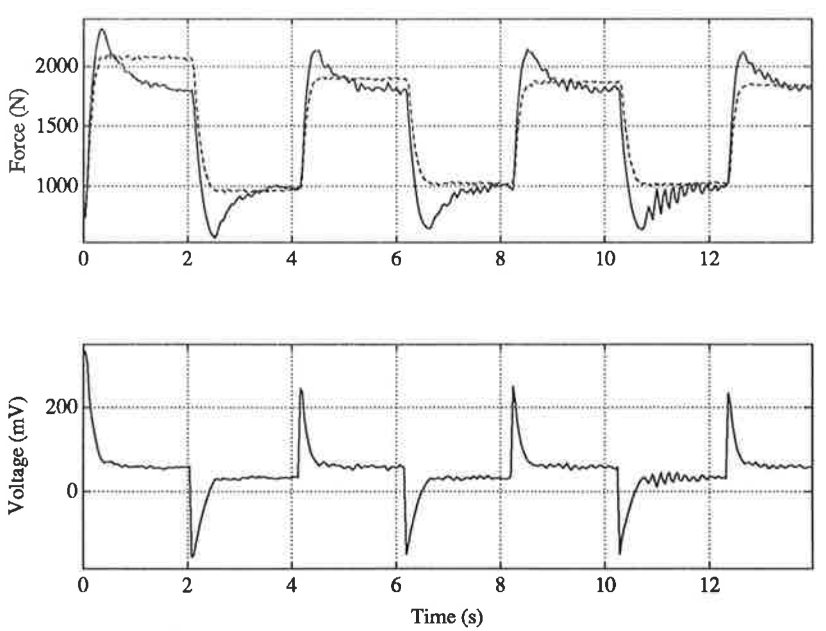

Fig. 58. A test with fuzzy controller and medium forces.

An obvious choice is to reduce the effect of noise by filtering the rate. This causes even more oscillations, although completely new sets of parameters were tuned for the filtered cases. The oscillation was somewhat larger in amplitude in the filtered cases and the frequency of oscillations was about 4 Hz with small forces. Lower frequency oscillations are less filtered by the mechanical structure, so rate filtering was not an improvement, and therefore not used.

The evolution of fuzzy oriented control hardware will obviously enable stable fuzzy control with hydraulic force control also. It would be interesting to use the fuzzy control chip capable of 625,000 fuzzy control commands per second (Miki et al. 1993).

5.3.4 A hybrid controller

The basic idea of a hybrid controller is to calculate the control variable based on the addition of several factors derived from the measurements. The factors are often position error in one or two directions of the task space and force error in the orthogonal direction or two orthogonal directions. This usually leads with revolute joints to such torque references, that depend on both force and position errors. When the error of one of the terms becomes large, then the corresponding effect on the controller output becomes significant and the error in the process is supposed to decrease. Thus hybrid controllers can respond to various control needs. The disadvantage is, that none of the measured variables are steered to the reference value. Instead the process controlled with a hybrid controller stabilizes to state, where all steered and measured variables are in balance.

Since force error and position error to the nominal path are easily available, a hybrid controller of the form of Eq. (76) was tested. The co-effients K_{fe} and K_p could depend on the corresponding position of the leg and the Jacobian matrix. This would enable inaccurate force control of the legs according to the directions of the rectangular leg coordinate system.

$$u = -K_f(f_{ref} - f_{est}) - K_p(x_{ref} - x_{est}) \tag{76}$$

A test with a tuned set of parameters is shown in Fig. 59. A leg was activated to move nominally downwards towards the ground with a constant speed. The leg was asked to provide a varying support force simultaneously. The force reference and the estimated force are drawn in the upper subfigure of Fig. 59 and the nominal and measured position of the actuator in the lower subfigure. The leg reached the ground after about 50 servo intervals, long before it should have according to the the nominal path. At the instant of ground contact the estimated force immediately became larger than the force reference. The estimated force is constantly larger than the force reference due to the position error.

As the example shows, hybrid controllers are not qualified for accurate force control, since they do not follow the force reference accurately. On the other hand the use of a hybrid controller would mean, that the compliance of a leg is increased. If an opposing force is suddenly released i.e. decreased, an actuator

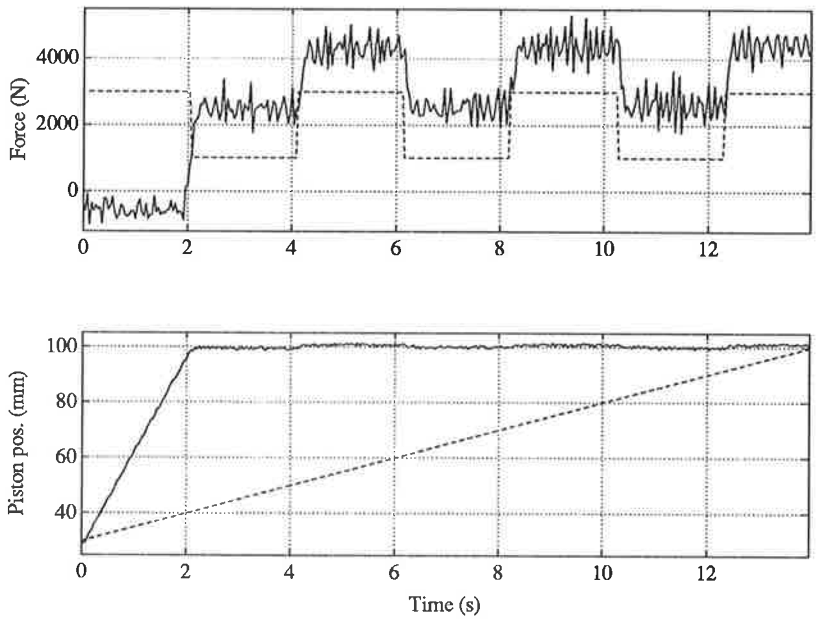

Fig. 59. Force and position and their references of a linear movement controlled with a hybrid force controller. The leg was in the air in the beginning.

with a hybrid controller would stabilize to a new position. Large compliance in the actuator or the mechanism of the leg would do the same.

Hybrid controllers are, however, potential alternatives to be tested with the walking machine, because nominal paths for the actuators can be continuously generated. Another hybrid controller could be based on the velocity reference of the actuator or combination of all these factors: position, speed and force errors.

5.3.5 Explicit PI controller chosen

The fuzzy controller had in many cases the fastest response and could be tuned to be relatively fast and relatively stable. The PI controller was, however, almost as fast as the fuzzy controller and could be tuned to be even more stable. It was able to react within 400 ms to any change in the force reference. Note that the actuator output force was in most cases more stable than the estimated force. This is due to oil compressibility and flexibility of hoses. Hoses often vibrated slightly as an indication of instability.

Force control may sometimes become active, when the foot is still in the air and can not cause any opposing forces. A leg may also lose the supporting contact while the body is moving. Thus the leg should move quickly towards an

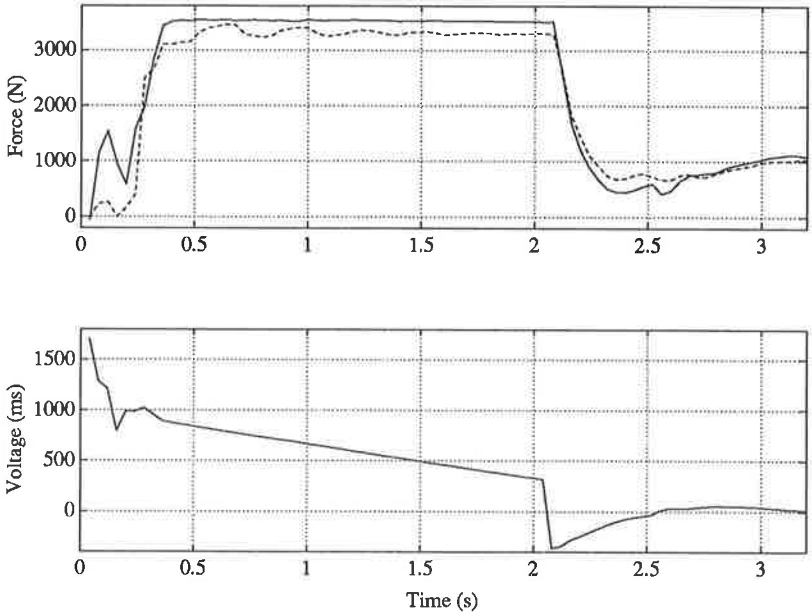

Fig. 60. A test started with a leg in the air.

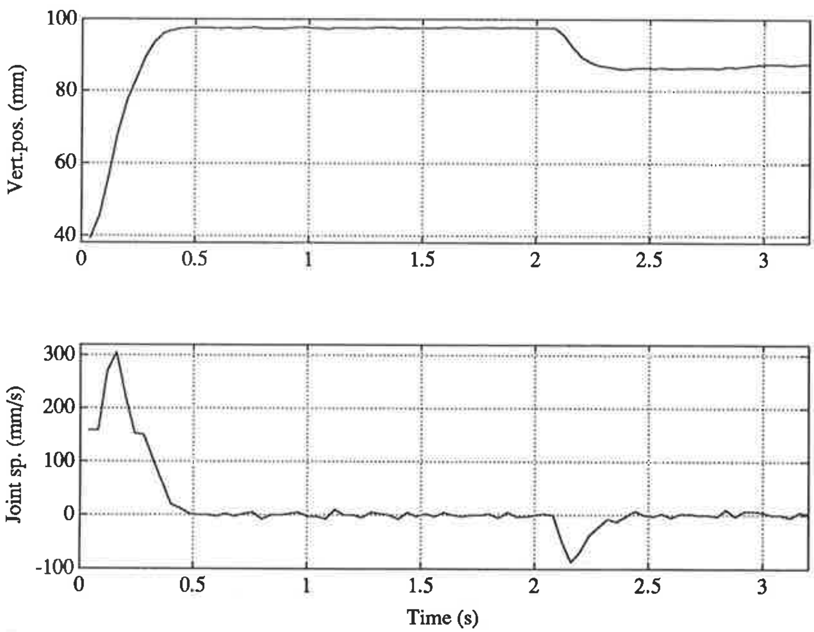

Fig. 61. Actuator position and speed of the test.

opposing object, that creates the forces needed. This is especially important in the supporting directions. The usability in this sense was checked with the chosen controller.

The results of a test, in which the leg was still in the air, when force control was started, can be seen in Fig. 60. The force reference is either close to maximum (3300 N) or 1000 N. The oscillations of the measured force close to 3300 N are caused by the mechanical oscillations of the pedestal of the test leg. It was partly lifted by the leg, because it was not attached to the floor. The estimated force of the actuator did not oscillate. It indicates, that the piston of the actuator did not move, despite the mechanical oscillations.

The control output can also be seen in Fig. 60. The control voltage is large, when the leg is in the air. This means a rapid movement. The rapid movement can be seen in another figure derived from the same test (Fig. 61). The position of the piston of the actuator and its time derivate (piston speed) can be seen in Fig. 61. The piston moves with a maximum speed of 300 mm/s; that means maximum leg movement speed of 1.2 m/s.

The leg moves slower towards the ground with smaller force errors (as in the case of small force references). The speed is also decreased due to the decrease of the I-term of the PI controller. The speed in the air is slower, but also the overshoot of the force reference after the ground contact is smaller.

The compliance of the mechanism (and the controller to some extent) can be seen in Fig. 61. When the force is increased from 1000 N to 3300 N, the piston of the vertical actuator moves about 10 mm (and the foot about 40 mm). This movement is caused partly by lifting the pedestal, by the compliance of the leg and the controller.

A quite similar test was also done later with several legs of the MECANT I. A test in Fig. 62 and 63 was made with leg number 2 after the parameters were initially tuned with leg number 3. As seen in the estimated force, the I term of the controller is integrated to so large an extent during the travel in the air, that the control voltage is increased close to +5 V. The piston of the actuator rises to the mechanical limit for a while, until negative error reduces the I term closer to zero again. The leg actually lifted the corresponding corner of the the MECANT I, although the other legs were not active. Keeping the integration term within limits gives faster response after a long constant (or large) force error. The limit was decreased after these initial tests, where friction compensation was not used.

A series of hysteresis tests were performed with the legs of MECANT I. The leg was commanded to provide a series of increasing and decreasing forces. The result was measured after each increment or decrement with a spring based weighing tool, thus the weight of the leg was also included in the measurement. The vertical force references were limited to about 4000 N, since larger forces would tilt the machine. The hysteresis of legs 3 and 5 are presented in Fig. 64. There are remarkable differences. As a matter of fact, tightening of every nut in the axes of a leg and clearances between the piston and the tube and seals affect these figures. The same force control parameters were used for all legs.

An enlarged example of actuator force control is shown in Fig. 65. Force reference of the vertical actuator of leg 3 of the MECANT I had been changed earlier to 6000 N from the previous value of 1000 N. Both estimated force and

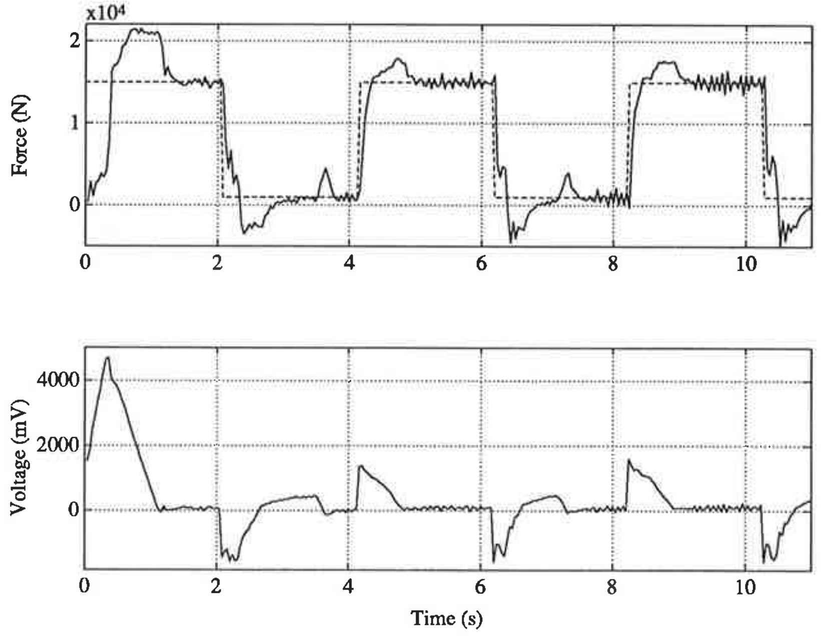

Fig. 62. A test with leg 2 of MECANT I in the air in the beginning.

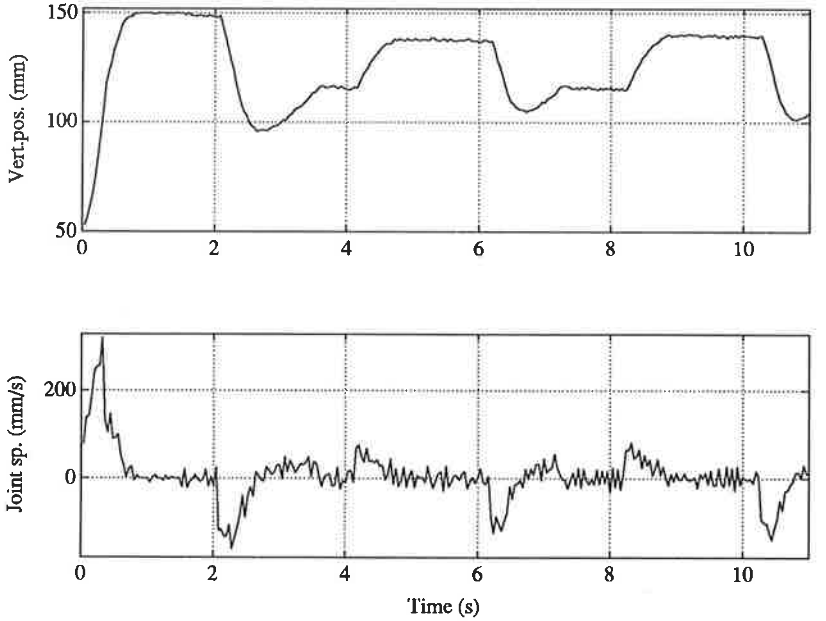

Fig. 63. Position and speed of a vertical piston of the MECANT I.

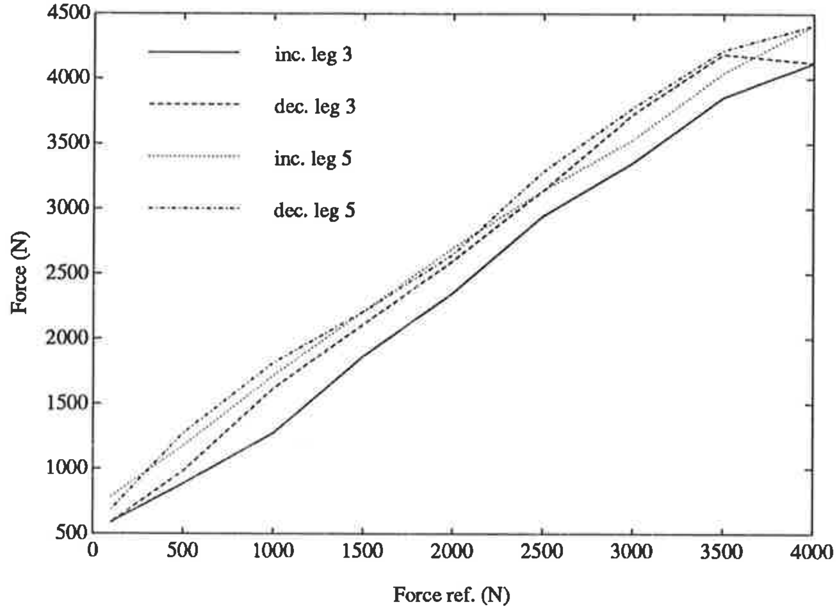

Fig. 64. Hysteresis of legs 3 and 5 measured with increasing and decreasing force references.

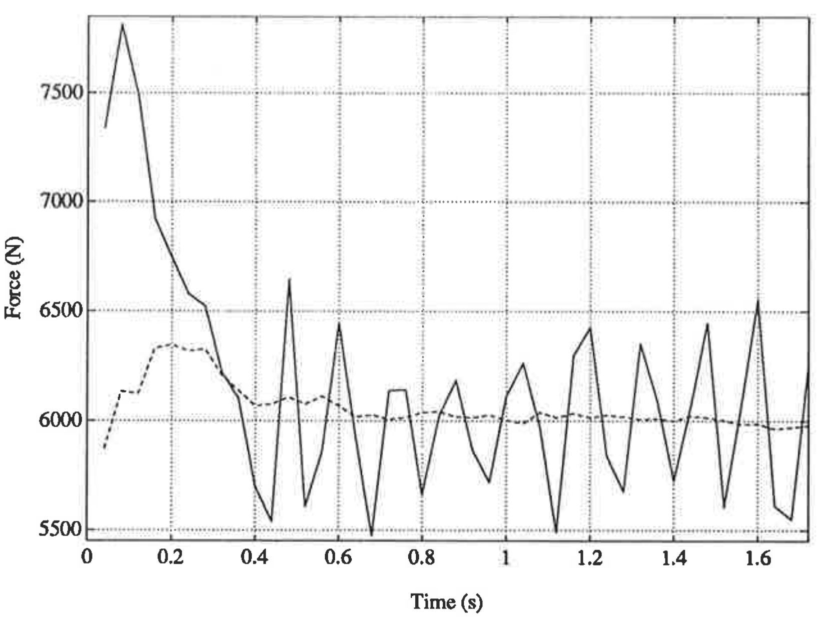

Fig. 65. Estimated and measured force after reference change to 6000 N of vertical actuator.

measured force are shown. The estimated force used for the control reaches the reference value in 100 ms and has many more fluctuations than the measured force. The force measured in the ankle is much more stable due to the compliance in the mechanisms and the compressibility of the oil and the hoses. The force reference is reached in 160 ms.

5.4 FEEDFORWARD FRICTION COMPENSATION

A considerable fraction of the actuator force generated by the pressure difference is used to overcome friction, because the force control of the actuators is based on control of the pressure difference. The friction value is estimated in advance based on the status of the actuator and a friction force reference is added to the force reference. The method is described as "feedforward".

Friction compensation is dealt with in two cases depending on whether the actuator moves or not. The friction in the first case is called static and in the latter case a combination of viscous and Coulomb friction. See for example (Ohkawa et al. 1992) for definitions and a plant model based friction compensation.

Note that the friction compensation methods presented in this section consider one actuator only. Friction could also be compensated for at the system level. This means, that the friction of many actuators is compensated for by realizing compensating forces created by the mechanism, which consists of many actuators.

It can be assumed, that friction also has stabilizing characteristics. For example, friction may prevent increasing of servo error. As a matter of fact, it was noted in the tests, that friction compensation for the body instead of all axes gave more stable control results. Friction compensation for axis control was developed before the body control was developed. The section below is, however, presented because there may arise other applications, where accurate force control of one axis is desired.

5.4.1 Static friction at rest

When the actuator does not move, but there are changes in the actuator force reference, the effect of friction causes problems in force control based on force estimation. The opposing friction force is not constant. When the force generated by hydraulic pressure increases gradually, the opposing friction force also increases gradually, until the actuator slips and moves a little bit. After the movement, the friction force may vanish, but most likely some friction force remains. That remaining friction force is similar to internal tension and may even point in another direction than the original force. It was noticed during the evaluation of the effects of friction, that when the force reference did not change and the actuator was not able to move for a while (several seconds), jitter and fluctuations in the control signal decreased the friction force gradually.

Two examples of force control (the fuzzy controller in this case), where some effects of friction can also be seen, are in Fig. 66. The actuator has not been able to move more than the compliance of the test leg allows. The case in the upper part of Fig. 66 has a larger deviation in the force reference. Reference values of 1000 N and 2000 N were used. The continuous line is the force estimate based on pressures measured close to the valve and the dashed line the measured force. The estimated forces are controlled to be the same as the reference in a few seconds, but there is steady state error in the measured forces.

Small changes, like from 2000 N to 2400 N and vice versa in the lower part of Fig. 66, are more difficult to control. The control changes the pressures fairly well, but the measured forces are hardly changed. The opposing friction force changes and does not allow the force created by the pressure difference to be seen in the actuator.

The idea of the friction compensation is to artificially cause such changes in the force reference, that the output force of the actuator reaches the reference value as soon as possible. It was noted, that small changes in the force reference are the most difficult to accomplish. It was necessary to overreact in order to get a small change in the output force.

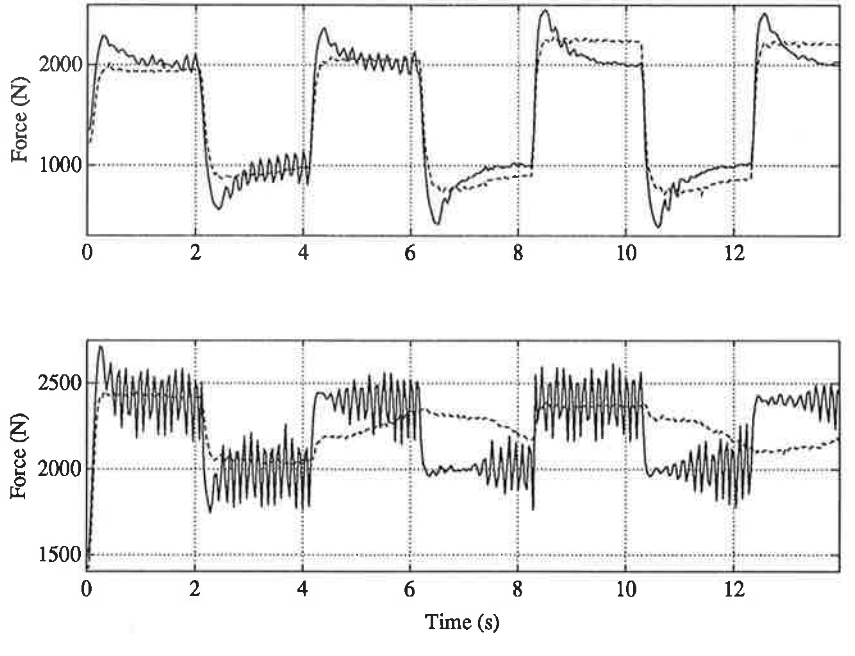

Fig. 66. Force reference is exeeded or not reached due to friction. Small changes are difficult. The continuous line is estimated force, the dashed line is the measured force.

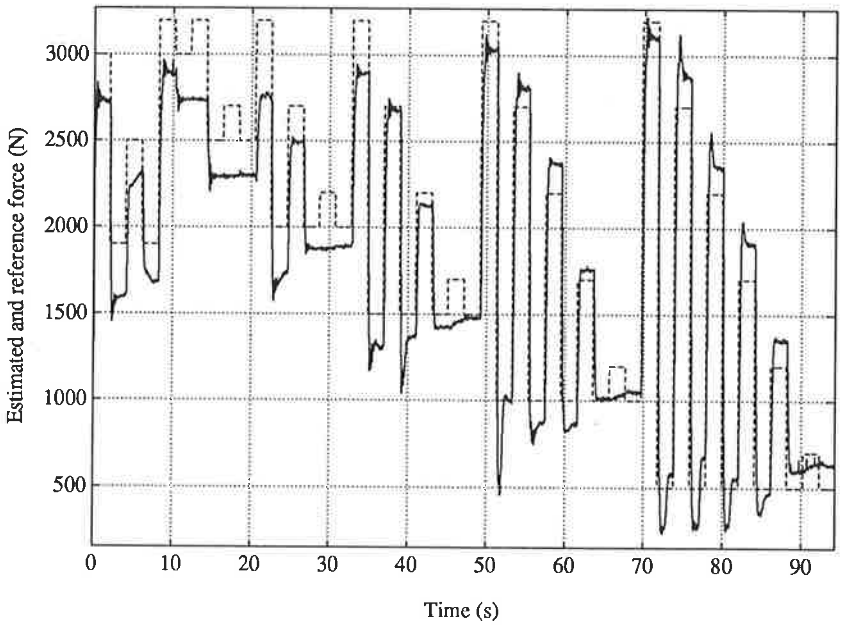

Fig. 67. A force control test without friction compensation. The dashed line is the force reference and the continuous line is the measured force.

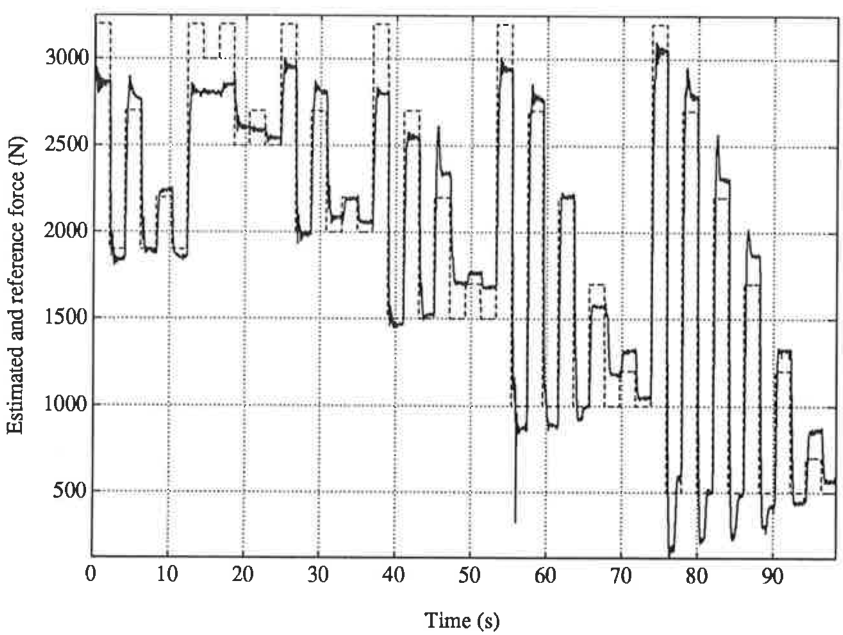

Fig. 68. The test of the privious figure with feedforward friction compensation.

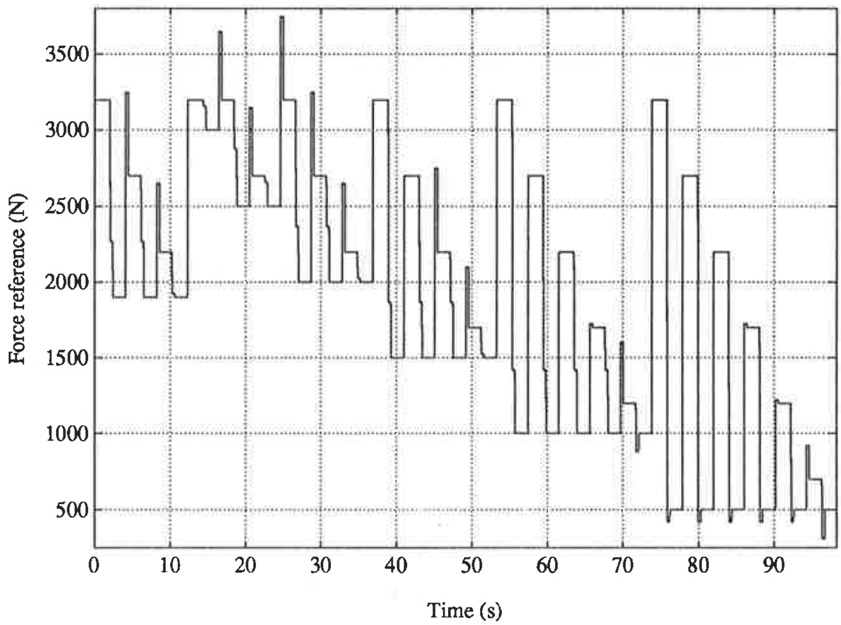

Fig. 69. Artificially friction compensated force reference of the test in the previous figure; note the narrow differences in the corners.

All changes in the force reference were classified according to the new reference and the absolute value of the change. The new reference may have nine different classes and the change three in the case of the vertical actuator. Positive and negative force directions are handled symmetrically.

The duration of such a compensational force reference has some importance. If it is too short, the actuator has no time to slip. If it is too long, the actuator may keep the artificial reference too long. About 360 ms seems to be the best duration with the vertical actuator of the test leg.

A repeatable sequence of force reference was created for tests. A test case without any friction compensation can be seen in Fig. 67, whereas compensation is active in Fig. 68. The integrals of the absolute error divided by the number of measurements in the tests are 237.7 and 189.1. The compensated case is better. Thus, the average error is reduced by 20 percent with the friction compensation. The reduction would be even more with small changes in reference forces. The corresponding artificial force reference of the test is shown in Fig. 69.

A more detailed friction compensated test can be seen in Fig. 70. The force reference has beeb 1900 N or 700 N. The control voltage is also shown. No compensation is done in the beginning.

Rather good results have been achieved with small changes and forces. The difficulties are emphasized in Fig. 71. The small changes in the references can not

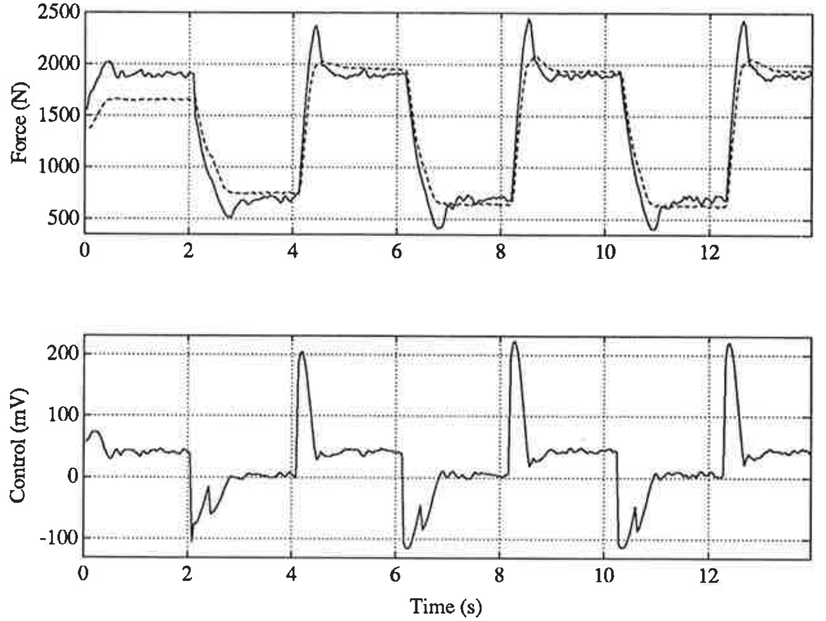

Fig. 70. A friction compensated test in the upper figure. Force estimate (continuous line) measured force (dashed line) and control voltage in the lower figure can be seen.

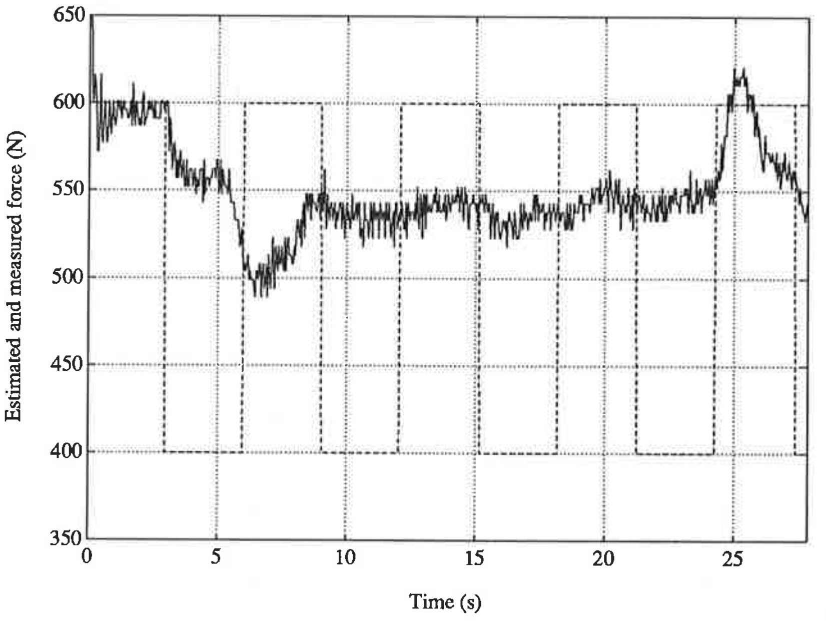

Fig. 71. Small forces and changes difficult to accomplish. The continuous line is the measured force, the dashed line is the desired force.

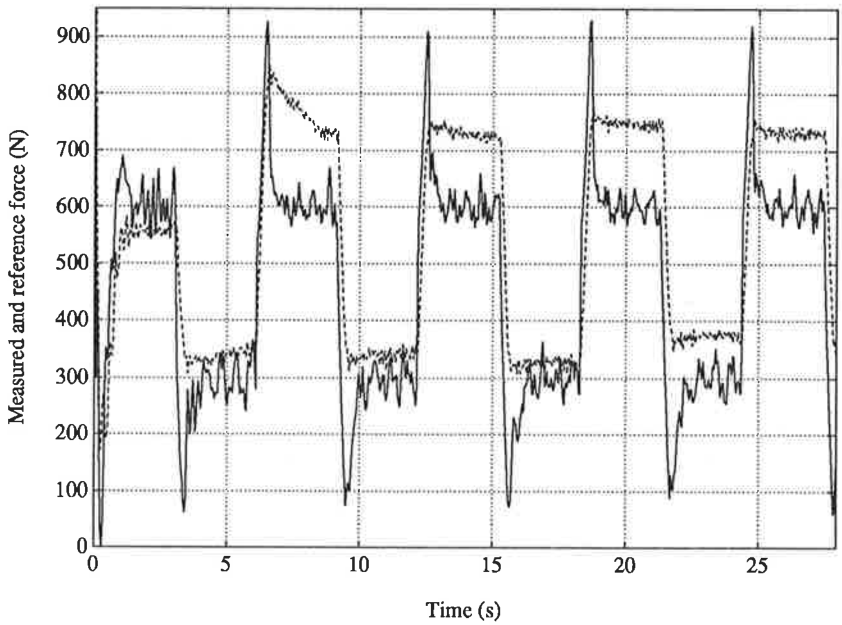

Fig. 72. Result of friction compensation with small forces.

Table 3. Compensation classes and values of static friction.

to force class	change < 450 N	change > 450 N
x small < 260	-190/250 N	-80/-570 N
small < 1100 N	-120/220 N	420/-540 N
med. < 2100 N	25/400 N	370/25 N
large < 3600 N	100/450 N	375/550 N

be followed. When the reference orders are compensated for according to Table 3, the result is greatly improved and is shown in Fig. 72. The compensation values are presented in Table 3. They are defined with the vertical actuator of the test leg with the slide mechanism locked to the pedestal. It is, however, assumed that linearly scaled versions of the parameters (classifying limits and magnitude of compensation forces) can be used with the other actuators, since the internal friction behaves most probably rather similarly. The two values on the different sides of '/' in Table 3 are the compensation values for negative and positive changes (of the absolute values of forces). If an absolute value of a negative force changes, the sign of the compensation value is changed. Very small forces are difficult to control. Such forces (< 260 N) may be reduced to zero during the compensation period of 360 ms as exceptions to Table 3.

5.4.2 Viscous friction compensation

Viscous and Coulomb friction reduce the actuator movements when the actuator moves. The friction force is always against the direction of the movement. The magnitude of the Coulomb friction is constant, but the viscous friction depends linearly on the speed of the actuator. The estimated friction force is compensated for according to Fig. 73, that is, a partly linear function. The friction compensation magnitude depends on the force change and the final value within a small speed range close to zero. This case i.e. the static friction was dealt with in the previous section 5.4.1.

The corner values for the friction curves of each actuator were determined based on tests started with the leg in the air. For example, a constant force of about 1000 N opposed the movement (speed 300 mm/s) of the vertical actuator, until the leg reached the ground. The values were underestimated by about 15 per cent in order to reduce the possibility for oscillations.

The possibility of oscillations due to friction compensation is small, because only the movements in the direction of the reference force are friction compensated.

If the leg is pushed to the opposite direction with a force larger than the reference, the leg moves slowly in the direction of the opposing force. The leg is actually quite an effective absorber. It is willing to decrease the force error by moving backwards. This is not a usual case, since legs usually move in the direction they are desired to move, but this behaviour increases the tolerance of the force control concept in abnormal cases.

One example of the compensation of the viscous friction was measured with leg 1 of MECANT I. The leg was hanging in the air (under position control), when force control with a 12 kN actuator force reference upwards was activated. The ankle started to move downwards. The force estimate and the viscous friction compensated force reference can be seen in the upper subfigure of Fig. 74. The speed estimate can be seen in the lower subfigure. The rapid movement in the beginning causes a speed compensative change in the force reference, that is however, somewhat smaller, than the estimated friction force during the same movement. There is a small delay until the compensation becomes active. This is due to the use of a slightly filtered speed estimate in order to reduce repetitive changes in compensation, when the real speed is close to the activation limit.

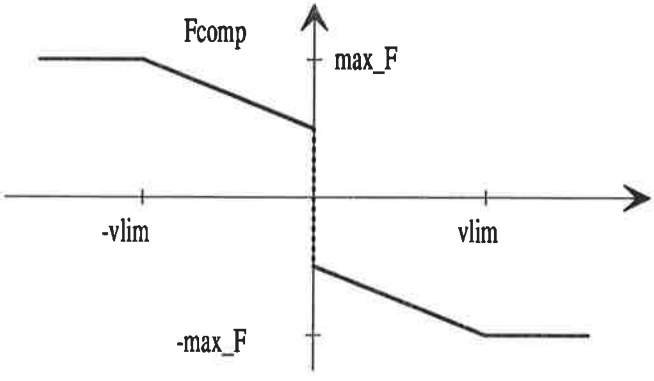

Fig. 73. Speed dependent friction compensation force.

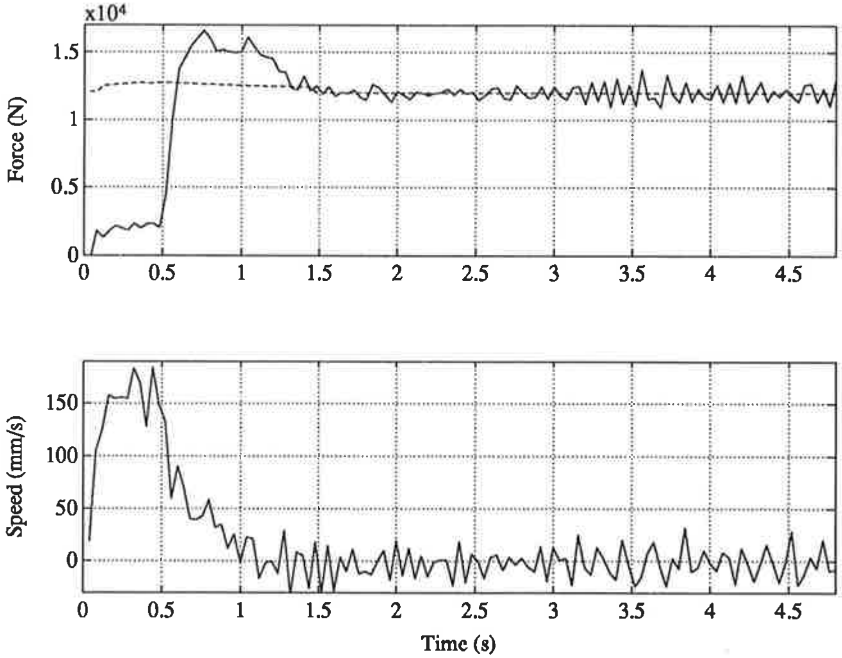

Fig. 74. Viscous friction compensation test.

6 INTEGRATION OF FORCE CONTROL AND LOCOMOTION

Force control of a body of a walking machine may also be usable while the machine is used as an operative platform. The body could participate in the close maneuvering tasks like docking or create forces needed in the operation. However, the main benefits of force control are assumed to be gained during walking on soft soil. Therefore it is essential, that force control is also used during walking.

Leg force distribution used as an auxiliary triggering factor in gait selection or stability estimation and stability optimization and a method combining position and force control in gait control, i.e. locomotion, are presented in this chapter.

One of the main problems of force controlled walking is the unspecified nature of leg movements during force control. This is especially true, if the walking is done on slippery terrain or for example on relatively large stones, where the leg may loose its foothold suddenly. A force controlled leg would generate the support force reference even after a slippage, provided that it has not reached the limits of the mechanical working areas. A slipping foot would spoil the repeating nature of traditional periodic gaits.

6.1 FORCE DECOMPOSITION HELPS TO CHOOSE SUPPORTING LEGS

Force control or leg force distribution can be combined to evolving free gait methods. A promising method under development for the MECANT I (Halme et al. 1993) uses estimated distances from the actual position of a foot to the closing border of a CWV (constrained working volumes, see for example Fig. 21) as the basis for choosing the next leg to be lifted. The method presented in this section is a supplement to these methods. It could reveal, in some cases, an incoming possibility to instability. If a leg configuration is maintained i.e. the same set of legs continuously support and the body moved to a specific direction, calculated support forces will decrease linearly. The instance when a support force of a leg becomes upward indicating a start of tilting, could theoretically, be estimated based on the linearity.

As noticed in the leg force distribution section, leg force distribution is a consistent method to evaluate the inherent stability of a leg posture. Since all the factors like orientation of body, direction of force reference and so on are considered in the evaluation of the body force reference, all the same factors are included in the stability analysis via leg force distribution.

Since the solution for leg force distribution is based on pseudoinverse, it is a minimum-norm solution to the problem. One or many unrealistic leg force references could reveal, that the leg configuration should be changed i.e. one or more legs should be lifted and replaced by legs still hanging in the air. Thus leg force decomposition may be used to check support patterns before they are selected and activated.

Indications to change the set of the supporting leg can be seen in the extreme corners of the support pattern. Small and large force references may exceed the capabilities of the actuators. The force references may become very small or even gain upward direction, which is impossible to realize with a leg in practice. These unrealistic (too large and too small) force references often happen together. They mean that the leg posture has to be changed. Examples are given in the following sections with conclusions to leg configuration selection.

An example of a situation close to instability (i.e. high probability to tilt) is presented in Fig. 75. The support polygon is drawn with dotted lines to the downward vertical view. As seen, it is quite difficult to estimate instability based only on the support polygon, when the center of gravity gets close to a border of the polygon. Horizontal acceleration references were, in the case of Fig. 75, 0.2*g and 0.1*g. As a matter of fact, if the horizontal acceleration request had been to the opposite direction, one of the legs would have had a clearly upward force reference. Instability may be suspected based on the force references, since the force demands of the rear legs are small and at the same time that of the front legs are very large in Fig. 75. Small forces tend to reveal, that the body may tilt at the

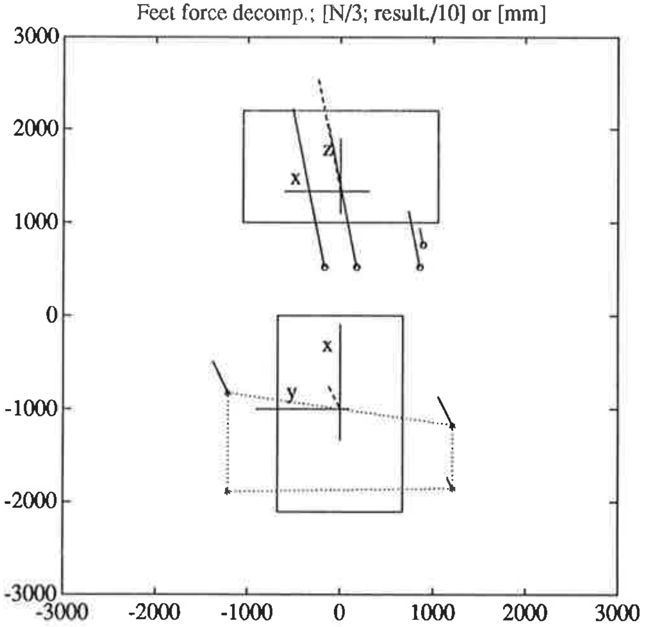

Fig. 75. Close to instability with four rear legs supporting.

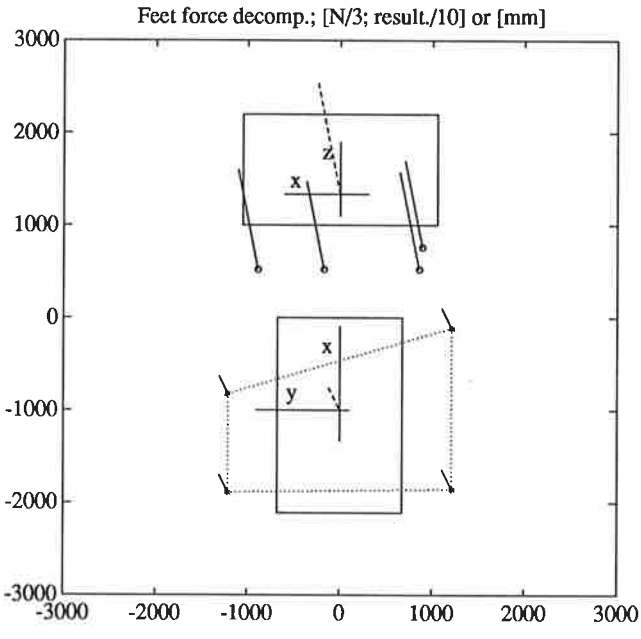

Fig. 76. Improved and stable leg configuration.

opposing edge of the support polygon. Note, that the instability may also be expected to be classically based on the short distance to an edge of the support polygon.

When an indication of the instability has been noticed, it is quite easy to select a new set of footholds (configuration), that maximizes the future stability by transferring the center of gravity more distant from the edges of the new support polygon. The locomotion algorithm should find out the configuration alternatives and other measures of usability. Those aspects are beyond the scope of this work. The leg force distribution of the alternatives may, however, help in choosing the best alternative.

A more stable case will result, if leg 4 is lifted and leg 2 is moved to the extreme edge of the CVW and is changed to the support state. This is visualized in Fig. 76. The leg forces are then very evenly distributed, as seen.

A case, where instability may exist and the center of gravity is well inside the support polygon, is presented in Fig. 77. Three legs are supposed to support the weight and the same accelerations as previously (0.2*g and 0.1*g). However, it can be seen, that only two legs will support and the third one (leg 1) will not. Its force reference is actually a small force upwards. This indicated that the machine will tilt about the opposing edge of the support polygon. Leg 1 will lift off the ground and the frame close to leg 6 will contact the terrain. Leg 6 should be transferred to the front edge of its CWV and changed to the support state in

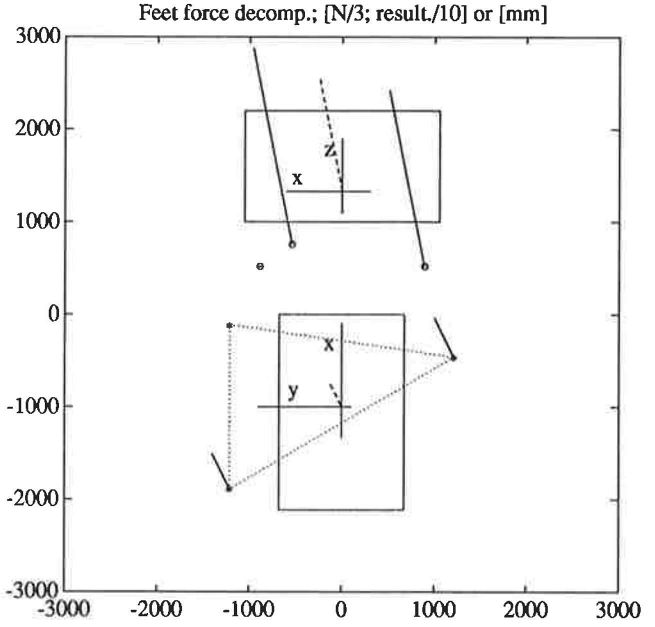

Fig. 77. The center of gravity is within the support polygon, but the situation is unstable due to the horizontal acceleration.

this case. In addition, only two legs carry the whole weight of the body.

Note, that the method of instability detection presented above also considers the dynamic aspects of the body, since forces caused by inclined terrain and by real acceleration are integrated and handled similarly i.e. as equal sources for body force demands.

It can be assumed as a rule of thumb based on the figures above, that if the center of gravity is outside of the support polygon, the most distant leg or legs will have upward force references and the force references of the legs closest to the corresponding edge of the support polygon will have large vertical values, since they have to compensate for the upward force references of the distant legs. Horizontal acceleration (and force) demands will cause exceptions to this rule of thumb.

6.2 DECOMPOSED FORCE AND POSITION CONTROL OF BODY

The leg force decomposition methods presented in the earlier sections generate three degrees of freedom (d.o.f.) force for each leg. The direction of movement of a leg is not known precisely in advance, although the direction of the body movement is controlled. Therefore locomotion is difficult to establish, since the future position of a leg can not be accurately estimated.

A novel method is presented in this section. Known or new position controlled gaits can be combined with force controlled altitude and two attitude angles of the vehicle. The method is an alternative to the movement control of a walking machine, that uses locomotion (lateral movements) developed for position controlled legs, but however enables moving on soft terrain with vertical force control.

The method is based on decomposition of the d.o.f. of the body to two sets. The first set contains the upward movement v_z and the rotations about the horizontal axes X and Y). They can be controlled by the vertical actuators only. The other set of lateral movements v_x and v_y and rotation about the vertical axis Z are taken care of by the thrusting (horizontal) actuators. The coordinate systems and the decomposition are presented in Fig. 78.

The method is outlined in Fig. 79. The body attitude control uses the positions of the ankles, the estimated altitude and attitude angles of the body and the estimated, i.e. measured and filtered, horizontal thrust forces to calculate the support forces to be created by the vertical actuators of all supporting legs. They carry the vehicle at the altitude reference and keep the attitude (i.e. inclination) reference, and also compensate for the tilting effects of the thrusting forces caused by position controlled lateral actuators. Periodic and other position controlled gait methods can therefore be used. The vertical force control takes care of proper support even on varying terrain conditions.

The model based altitude and attitude control presented in section 4.1.3 is to be used here together with position controlled horizontal degrees of freedom of the body in quite a similar manner. The main difference is the usage of the estimated thrust forces instead of calculated lateral forces in Eq. (46) and (47). This is based on the assumption, that the position controlled legs also provide altitude and attitude changing forces, when the body is in an inclined orientation.

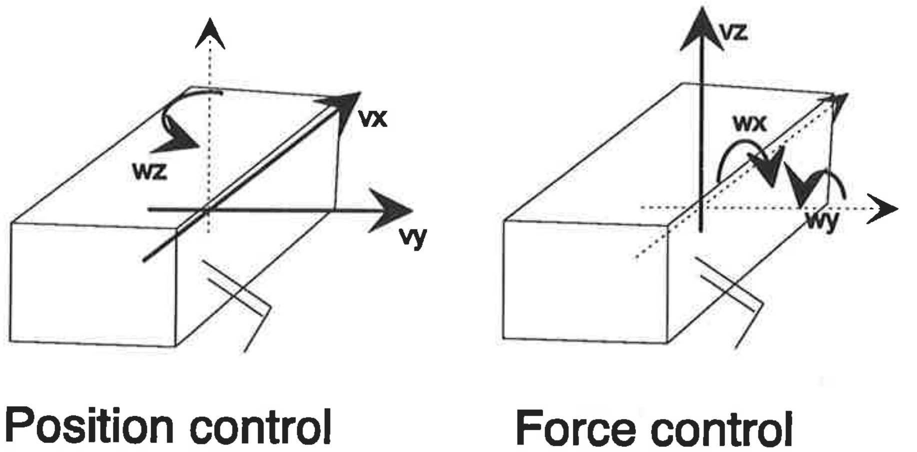

Fig. 78. Decomposition of position/force control of body.

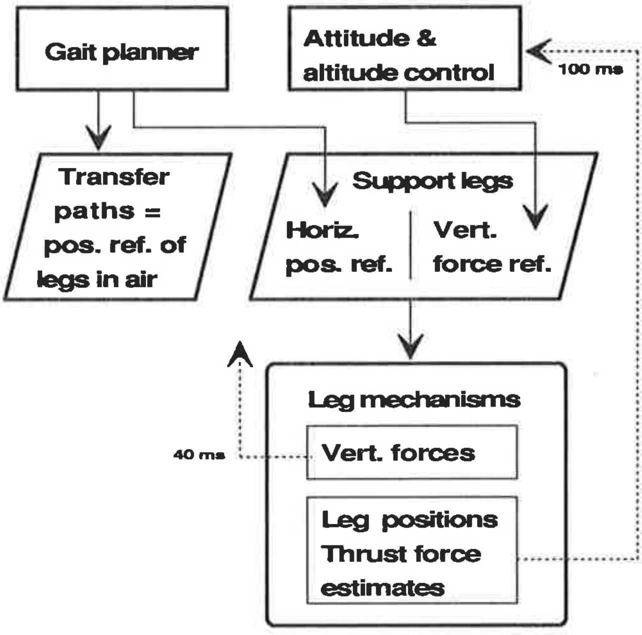

Fig. 79. Control information flow with decomposed body control.

One might wonder, why the force reference changing altitude is not changed according to attitude angles, because an inclined attitude causes a share of the force reference along the Z axis and also causes translation in the horizontal level. This translation is actively compensated for by the position controlled horizontal actuators, and the attitude angles are so small, that the vertical error component vanishes with the friction.

The method described above requires that the positions of all the supporting legs and the horizontal thrust forces are continuously available for the calculation of the next support force sequence. Gorinevsky & Shneider (1990) used an inspiring method with a periodic gait, where the optimum force distribution was calculated in all sets of leg positions where a leg contacts or is to be lifted, and the leg force commands were linearly interpolated between two such instants.

Those dynamic forces, that could be controlled with vertical forces, could be included in the force control scheme in a similar manner as thrust forces and acceleration reference via left hand side of Eq. (48) and further to Eq. (53), since estimation of ground speed and the acceleration (time difference of speed) are available.

Such a test with four force controlled supporting legs, where the support of one leg was released, has been made. The leg was lying on a fork lift, the fork of which was suddenly released. The altitude of the body did not change and the attitude remained within a few degrees. The legs did not have coordinated force control in this case.

The first tests of the altitude and attitude control presented have been made with six legs supporting the body on the floor without taking any steps. The altitude of the body was measured by estimating the support plane based on the measured positions of the legs. Attitude angles and angular velocities were estimated by using inclinometers. Reference altitude and attitude angles were given by control sticks of the operator interface system.

Logged data of a test are given in the following figures. All the data were stored during the same test. The altitude of the body (continuous line) and its reference (dashed line) can be seen in the upper subfigure of Fig. 80. The altitude is actually the distance from the origin of the body coordinate system to the estimated support plane in the so called path coordinate system i.e. the vertical distance from the floor to the origin. The distance is about 400 mm, when the body is lying on the floor with all legs supporting with small forces.

The altitude reference was increased from time to time by a control stick. Thus the operator still had the previous speed control interface to the MECANT I.

The force reference for the body (dashed line) can be seen in the lower subfigure of Fig. 80. The continuous line is the sum of the estimated support forces of the six supporting legs. One can notice after 20 s has passed, that the body stops about 1.5 s after the braking force has been activated. Similarly the movement upwards starts 1.5 s after the upward force reference has been activated after 30 s have passed. The dead-zone was exceeded immediately after 30 s had passed.

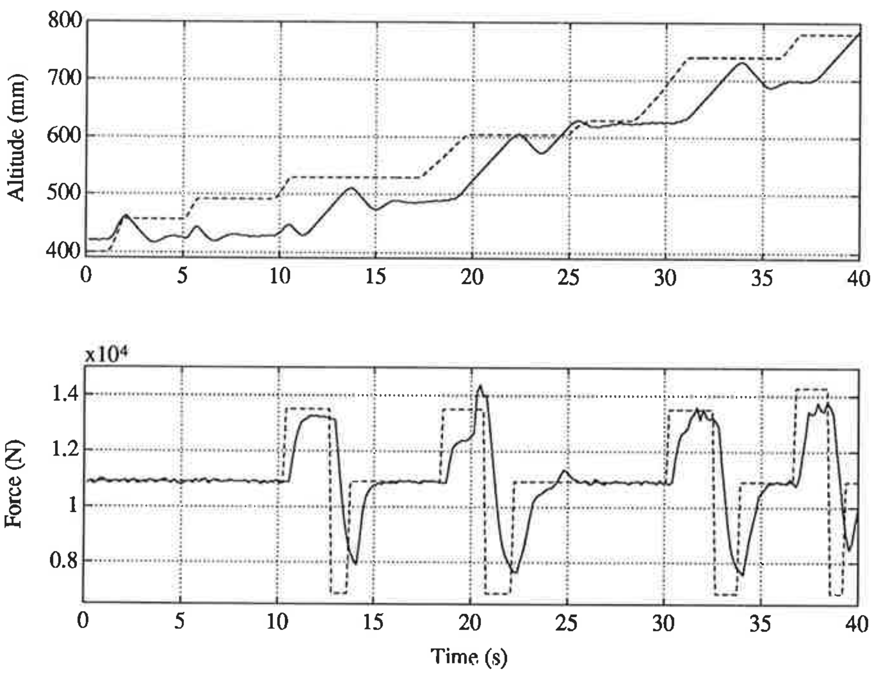

Fig. 80. Altitude and its reference and force order along the Z axis of the body coordinate system and the sum of estimated forces with six legs supporting.

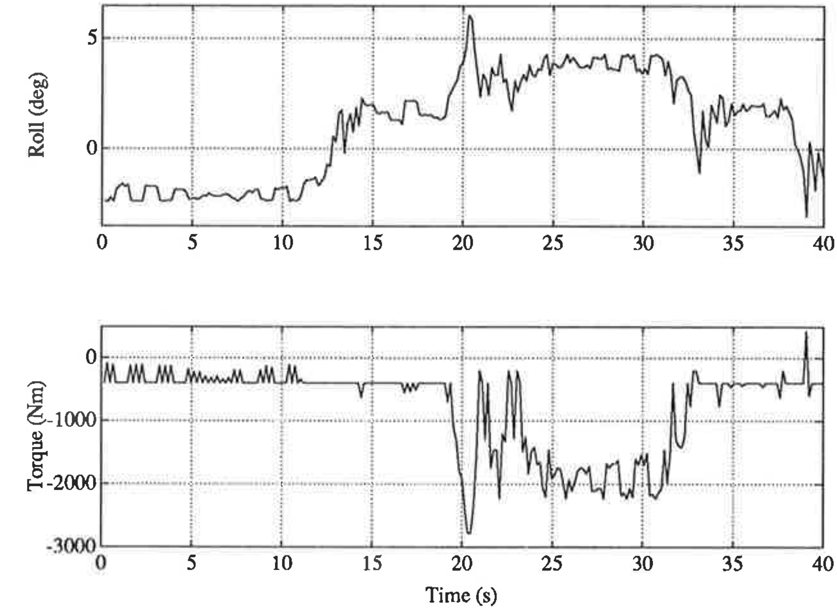

Fig. 81. Attitude about the X axis (roll) of the body coordinate system and the correcting torque. Roll reference was 0.0 degrees.

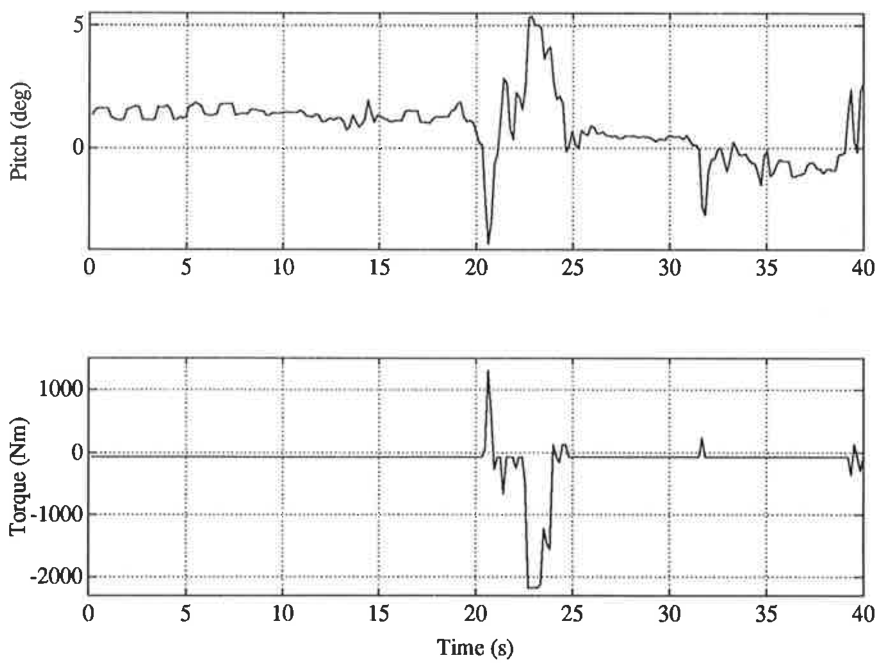

Fig. 82. Attitude about the Y axis (pitch) of the body coordinate system and the correcting torque. Pitch reference was 0.0 degrees.

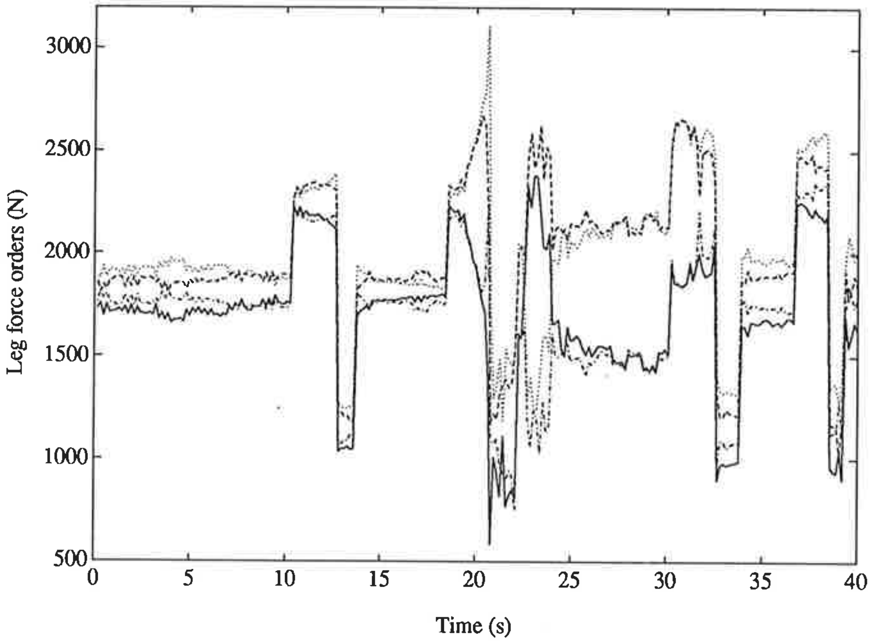

Fig. 83. Leg force orders along the Z axis of the body coordinate system of the front and rear legs.

The attitude about the X axis i.e. roll can be seen in the upper subfigure of Fig. 81. The correcting component of the torque can be seen in the lower subfigure. Hysteresis can be seen to cause limited oscillations in the beginning. Note especially the attitude drift of 5 degrees after 20 s have passed and how this drift is corrected within the next 1 s. The constant offset of the torque is predefined in advance and caused by the offset of the center of gravity from the origin of the body coordinate system.

The attitude about the Y axis i.e. pitch and the corresponding torque can be seen in Fig. 82. It is more stable than roll and the torque reference remains rather small.

The corresponding leg force references can be seen in Fig. 83. The solid line corresponds to leg 1, the dashed line to leg 2, the dashdotted line to leg 5 and the dotted line to leg 6. For example a reflection of the torque peaks about the Y axis (pitch) i.e. the peaks in the lower subfigure of 82 can be seen in Fig. 83, where the force references for front (1 and 2) and rear (5 and 6) legs are divided into two separate groups during the peaks. Note, that the orientation errors are corrected rapidly with the leg force references.

7 SUMMARY AND CONCLUSIONS

Walking machines have been realized so far only in research institutes. Most of them have more or less been position controlled. Utilizing the results has been slowed done by the small number of international efforts in walking technology, but the situation is changing. Walking machines will come on the market certainly within ten years. Then and even earlier the results of this work can be utilized.

Force control of walking, utilized by walking machines on soft and uneven terrain typically found in forests, has been analyzed. The underlying idea has been to use force controlled legs to compensate for the continuously elastic behavior of the terrain and the rolling of the body of the walking machine caused by lift off of a leg or change from placing to the support state.

The development need from elementary force control of actuators to body force control has been analyzed and solved. The non-linearity of the force process of hydraulic actuators is outlined in the modelling section of this thesis. However, it has not been possible to utilize the model in the development of a force controller for hydraulic actuators, since the opposing forces are essentially part of the force outcome of hydraulic actuators.

Surprisingly enough, the bidirectional force control method i.e. the load adaptive PI force controller for symmetric or asymmetrical hydraulic actuators with symmetric valves designed for position control presented in this paper, is one of the first to be presented. It has obviously been assumed that this task was too difficult to be studied in the field of hydraulic technology. The method will be stable in a large variety of situations, since the parameters are tuned for the whole force capabilities of the actuator in question. It is, however, likely, that similar or improved non-linear controllers can be developed in the future for the same force control task. The actuator control method is not calculation intensive and can be used with a rather long servo interval; 40 ms in this case. This indicates, that rather low-cost hardware can be used to realize the control methods presented.

A fuzzy control method and a method to tune the controller parameters were also developed for force control of hydraulic actuators. The load adaptive force controller had slightly better characteristics than the fuzzy controller. However, the fuzzy controller developed can obviously be used in such other control duties, where measurements do not contain an excessive amount of noise.

The force control methods presented could be utilized in a wide variety of applications, because hydraulics is widely used in the practice. The possibility to use low-cost hardware is important in practical applications.

Although quite a lot has been written about the leg force distribution of walking machines, new aspects have been found. Despite of the criticism directed at the method based on pseudoinverse, a new method to select the optimization planes has been developed. It will both keep the horizontal forces small in order to minimize risk of slippage and also effectively indicate a bad leg configuration. It can be therefore be utilized in the foot-hold selection of free gait algorithms.

An intermediate method for combining vertical force control and lateral position control has also been presented. This means that the commands to move the body horizontally can be transferred to position control oriented locomotion commands, where the altitude and the attitude of the vehicle are handled independently by the control system based on force control. This control type enables effective movements on soft soil.

The results of attitude and altitude control have been presented in figures from Fig. 80 to Fig. 83. It is assumed, that walking will cause much more instability than the attitude control itself. Therefore it can be assumed that the results of four previously mentioned figures will turn out to be very useful in walking.

Finally a few concluding words. Force control of walking machines will speed up the exploitation of walking machines in natural, soft and uneven terrain, like forests. Force control will soften the unpredictable impacts caused by the non-linearities and the variable shapes and support characteristics of natural terrain. Force control also prevents the internal force peaks caused by inaccuracies of position references and position control itself in position controlled walking.

Reference velocity or utility forces provided by the body can be transformed to a six degrees of freedom body force reference. As literature has shown, there are numerous methods to decompose the body force to a set of leg force references. A new version of pseudoinverse methods has been developed. It minimizes the possibility of slippage of the legs.

Pseudoinverse methods may give unrealistic upward force references. There is, however, substantial value in such sets of force references. Such sets can not be used in practice, but they are a powerful indication to change the leg configuration by lifting or placing a leg. The method can be considered powerful, because dynamic factors are also included in addition to static stability. Therefore the six degree of freedom body force control would also help locomotion control of free gaits.

The force based attitude and altitude control developed, can be integrated with position controlled locomotion by controlling the vertical actuators by force and the horizontal actuators by position. This is the easiest method to test feasibility of force control of a walking machine.

The hydraulic system of the MECANT I was not especially prepared for force control. However, sufficient force control of actuators was established, even in the difficult case of symmetrical valves and the asymmetric linear actuators. Therefore one can state, that force control of practical hydraulic systems is possible with small mechanical improvements. This also opens possibilities for many new applications outside the technology of walking. The decrease of collision impacts with force control or force estimation could even reduce the safety hazards often met with hydraulic machines or hydraulic utility vehicles.

Suggested future research

Research on the technology of walking is very fruitful due to the numerous new subjects which have come up. Here a description is given of the goals of several walking oriented future projects. The main subject of future research of force controlled walking for soft and uneven terrain would be the integration of a free gait to the total force control of the body. The concept is clear. The body can provide forces in any latheral direction, thus it would also move in that direction. An algorithm is needed to lift the most suitable leg, before any of the legs reach any limit of its working area. For this, relatively small modifications are needed to the free gait algorithms presented by Halme et al. (1993).

After the profitability of force controlled movements of walking machines is proven, one might consider the economy of actuator and valve combinations, that are also more proper for force control. This could mean two pressure valves instead of one valve or changing the pressure gain characteristics of the valves for a slower pressure responce in changes in voltage i.e. improve the resolution of the pressure control. The main research contribution in this area would be to redesign the mechanics and the hydraulic system to be force controlled, for example according to Nevala (1993). Improvements are likely. A faster response to changes in actuator force references can then be expected. Utilization of the energy stored in the compliant members of a leg could also be an interesting research subject.

A smaller research effort should be exerted on adaptive force control algorithms for hydraulic actuators. The characteristics of the force process in a hydraulic actuator depends on the temperatures of the environment and the hydraulic oil, the age of the oil and the wear of the actuator. Continuously estimating the control parameters of force control will decrease the difficulties, when walking utility machines are to be used in practice.

Lots of practical research subjects are suggested by the application areas of force controlled walking machines. It is challenging to develop a walking machine for a practical application keeping in mind the low price of the products that are accepted in the markets. This is even true for the new application areas, that will become possible with the utilization of technical walking. Tele-operated rescue duties after mine accidents are examples of such duties.

Several working machines have a manipulator arm or a boom in order to move application equipment. The boom could be used in active stabilization duties in a similar manner to legs. The boom could provide large, but short in time, torques to the body. They could help in some critical phases of forward locomotion even with wheeled vehicles.

A walking excavator for faster access to accident sites could be the next research topic. Legs are, as a matter of fact, better at providing force to the bucket than tracks. Legs could enlarge the working area of the bucket more than tracks enabling shorter lever arms for the bucket. The forces could thereby be enlarged.

There are numerous alternatives in the definition of the user interface to various tele-operation needs. Tele-operation of a walking machine in an application offers a complete research subject from user interface to co-operation of legs and the utility equipment of the vehicle.

If information of the terrain under the legs were available in the form of leg force directions allowed, the system could lock some leg force components in advance, insert these into the equations, transfer the known variables to separate groups and solve the best solutions to the remaining equations according to the principles shown. The inclusion of the terrain information to control the vehicle is another challenging research subject.

A multivariable control method related to the one developed for the ASV (see Eq. (5)) is another alternative to be evaluated in practice. Estimators related to terrain velocity and acceleration are to be developed for multivariable control. They may be based on inertial sensors.

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LEG KINEMATICS AND STATIC FORCE EQUATIONS

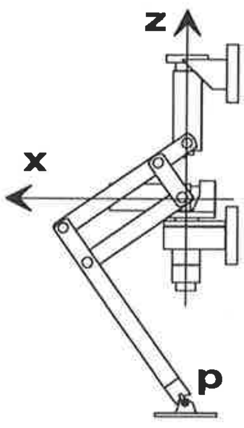

Fig 1. Rectangular leg coordinate system.

The kinematic equations for position and force control of the pantograph legs of the MECANT I are presented in this paper as simple as possible in order to speed calculations. The leg coordinate system is presented in Fig. 1. Some constant distances, that the mechanical design is based on, are used in the equations in order to simplify them. The direct kinematic equations (from actuator positions to ankle position in a rectangular leg coordinate system) of a pantograph leg are, with the notations, in Fig. 2 as follows:

$$p_x = (R_0 + K_r s_r)\cos\alpha \quad (1)$$

$$p_y = (R_0 + K_r s_r)\sin\alpha \quad (2)$$

$$p_z = H_0 + K_v s_v \quad (3)$$

K_r is the radial (i.e. horizontal) magnification ratio of the horizontal actuator. K_v is the magnification ratio of the vertical actuator. Note that, K_v is negative, because the ankle moves downwards, when the vertical actuator moves upwards.

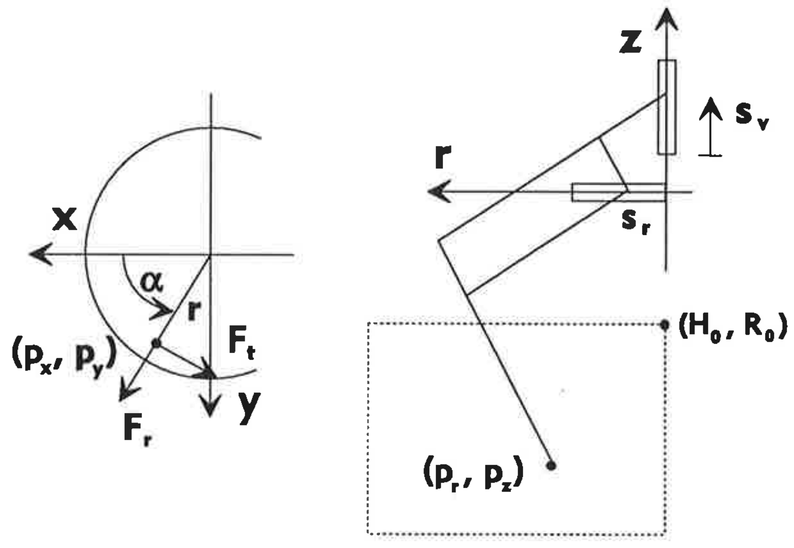

Fig. 2. Kinematic parameters of pantograph leg.

H_0 and R_0 depend on the mechanical design of the last shank bar and how it is bent. The pantograph mechanism of MECANT I is designed so that the ankle reaches the Z axis, i.e. R_0 is zero. *V* is the index for a vertical and *r* for a temporary radial coordinate system. The inverse kinematic equations are used to calculate such actuator positions that cause the ankle to move to the given position in the rectangular coordinate system. These calculations assume, that the desired position is in the reachable volume of the mechanics. The inverse kinematic equations are:

$$\alpha = \tan^{-1}\left(\frac{p_y}{p_x}\right) \tag{4}$$

$$s_v = (p_z - H_0)K_v \tag{5}$$

$$s_r = \left\{ \begin{array}{ll} \left(\frac{p_x}{\cos\alpha} - R_0\right)K_r^{-1}, & |\cos\alpha| \geq \frac{\sqrt{2}}{2} \\ \left(\frac{p_y}{\sin\alpha} - R_0\right)K_r^{-1}, & |\cos\alpha| < \frac{\sqrt{2}}{2} \end{array} \right\} \tag{6}$$

The inverse solution is ambiguous on the z axis i.e. any rotation angle can be accepted on the z axis. Note that the decision to use four sectors in Eq. (6) is somewhat artificial, but effective and correct in practice.

Let us assume, the actuators can provide forces F_r, F_v and torque T_r. F_t and F_{ri} are the horizontal forces in the intermediate radial coordinate system. They are according to Eq. (7) and Eq. (8).

$$F_{ri} = \frac{F_r}{K_r} \tag{7}$$

$$F_t = p_r T_r \tag{8}$$

The leg pushes the ground with the following force (in the rectangular leg coordinate system). This is called forward force solution. It is presented in Eq. (9), Eq. (10) and Eq. (11).

$$F_x = F_{ri}\cos\alpha - F_t \sin\alpha \tag{9}$$

$$F_y = F_{ri}\sin\alpha + F_t \cos\alpha$$

$$F_z = \frac{F_v}{K_v} \tag{11}$$

The inverse force equations are used to calculate such actuator forces and torques, that generate the desired ankle force in the leg coordinate system. The inverse force equations are:

$$F_r = K_r (F_y \sin\alpha + F_x \cos\alpha) \tag{12}$$

$$F_v = K_v \, F_z \tag{13}$$

$$T_r = p_r (F_y \cos\alpha - F_x \sin\alpha) \tag{14}$$

The inverse force equations can be also checked or evaluated by partially differentiating the forward kinematic solution. The result is the so-called Jacobian matrix. It is usually used in robotics to relate joint velocities to Cartesian velocities of the tip of a robot arm. If the actuators are in order radial, vertical and rotating actuator, the Jacobian matrix is:

$$J = \begin{bmatrix} K_r\cos\alpha & 0 & -(R_0+K_r s_r)\sin\alpha \\ K_r\sin\alpha & 0 & (R_0+K_r s_r)\cos\alpha \\ 0 & K_v & 0 \end{bmatrix} = \begin{bmatrix} K_r\cos\alpha & 0 & -p_r\sin\alpha \\ K_r\sin\alpha & 0 & p_r\cos\alpha \\ 0 & K_v & 0 \end{bmatrix} \tag{15}$$

The inverse force equations are then (as conducted in section 5.9 of Craig (1986)) in matrix format:

$$\begin{bmatrix} F_r \\ F_v \\ T_r \end{bmatrix} = J^T \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \qquad (16)$$

REFERENCE

Craig, J.J. 1986. Introduction to robotics, mechanics & control. Massachusetts: Addison-Wesley Publishing Co. P. 303. ISBN 0-201-10326-5

SYMBOLIC DEDUCTION OF PSEUDOINVERSE OF MATRIX B

Let us assume, that matrix $\boldsymbol{B}$ is:

$$\boldsymbol{B} = \begin{bmatrix} 1 & 1 & \dots & 1 & 0 & \dots & 0 \\ 0 & 0 & \dots & 0 & 1 & \dots & 1 \\ -r_{1y} & -r_{2y} & \dots & -r_{Ny} & r_{1x} & \dots & r_{Nx} \end{bmatrix} \tag{1}$$

Pseudoinverse of matrix $\boldsymbol{B}$ is matrix $\boldsymbol{B}^+$ as follows:

$$\boldsymbol{B}^+ = \boldsymbol{B}^T(\boldsymbol{B}\ \boldsymbol{B}^T)^{-1} \tag{2}$$

Then the matrix of Eq. (2) to be inverted is:

$$\boldsymbol{B}\ \boldsymbol{B}^T = \begin{bmatrix} N & 0 & -sy \\ 0 & N & sx \\ -sy & sx & s^2y+s^2z \end{bmatrix} \tag{3}$$

The result of the inversion is:

$$(\boldsymbol{B}\ \boldsymbol{B}^T)^{-1} = detBBt^{-1} \begin{bmatrix} ns2xy-sx^2 & -sxsy & Nsy \\ -sxsy & ns2xy-sy^2 & -Nsx \\ Nsy & -Nsx & N^2 \end{bmatrix} \tag{4}$$

The symbolic form of $\boldsymbol{B}^+$ is then, without the scalar factor, caused by the determinant:

$$
\begin{bmatrix}
ns2xy - Nsy\, r_{1y} - sx^2 & N r_{1y} - sxsy & Nsy - N^2 r_{1y} \\
ns2xy - Nsy\, r_{2y} - sx^2 & N r_{2y} - sxsy & Nsy - N^2 r_{2y} \\
\vdots & \vdots & \vdots \\
ns2xy - Nsy\, r_{Ny} - sx^2 & N r_{Ny} - sxsy & Nsy - N^2 r_{Ny} \\
N r_{1x} sy - sxsy & ns2xy - Nsx\, r_{1x} - sy^2 & N^2 r_{1x} - Nsx \\
\vdots & \vdots & \vdots \\
N r_{Nx} sy - sxsy & ns2xy - Nsx\, r_{Nx} - sy^2 & N^2 r_{Nx} - Nsx
\end{bmatrix} \tag{5}
$$

When several intermediate variables are calculated in advance and the rows of the B^+ are multiplicated with the original force and torque orders, then equations for the horizontal leg forces of leg i (from 1 to N) are given by:

$$
F_{ix} = detBBt^{-1} \begin{Bmatrix} (xpx - nsy\, r_{iy}) F_b^{xref} + \\ (nsx\, r_{iy} - sxsy) F_b^{yref} + \\ (nsy - np2\, r_{iy}) T_b^{zref} \end{Bmatrix} \tag{6}
$$

$$
F_{iy} = detBBt^{-1} \begin{Bmatrix} (sxsy - nsy\, r_{ix}) F_b^{xref} + \\ (ypy - nsx\, r_{ix}) F_b^{yref} + \\ (np2\, r_{ix} - nsx) T_b^{zref} \end{Bmatrix} \tag{7}
$$

The intermediate variables calculated in advance in order to speed up the repeated calculations of Eq. (6) and (7) are:

$$
cpc = ns2xy - sc^2 \quad , c = x, y \tag{8}
$$

$$
nsc = Nsc \quad , c = x, y \tag{9}
$$

$$
sxsy = sxsy \tag{10}
$$

$$
np2 = N^2 \tag{11}
$$

SYMBOLIC DEDUCTION OF PSEUDOINVERSE OF MATRIX C

Let us assume, that matrix C is:

$$C = \begin{bmatrix} 1 & 1 & \dots & 1 \\ r_{1y} & r_{2y} & \dots & r_{Ny} \\ -r_{1x} & -r_{2x} & \dots & -r_{Nx} \end{bmatrix} \tag{1}$$

Pseudoinverse of matrix C is matrix C^+ as follows:

$$C^+ = C^T(C\ C^T)^{-1} \tag{2}$$

Then the matrix of Eq. (2) to be inverted is:

$$C\ C^T = \begin{bmatrix} N & sy & -sx \\ sy & s^2y & -sxy \\ -sx & -sxy & s^2x \end{bmatrix} \tag{3}$$

The result of the inversion is:

$$detCCt^{-1} \begin{bmatrix} s^2xs^2y-sxy^2 & sxsxy-s^2xsy & s^2ysx-sxysy \\ sxsxy-s^2xsy & Ns^2x-sx^2 & Nsxy-sxsy \\ s^2ysx-sxysy & Nsxy-sxsy & Ns^2y-sy^2 \end{bmatrix} \tag{4}$$

The symbolic form of C^+ is then without the factor caused by the determinant, a 3 x N matrix, that otherwise have similar elements on the three columns, but leg position variables (r_{ix} and r_{iy}) correspond to different legs. The colums from left to right are:

$$r_{ix}(sxysy-s^2ysx)+r_{iy}(sxsxy-s^2xsy)+s^2xs^2y-sxy^2 \tag{5}$$

$$r_{ix}(sxsy-Nsxy)+r_{iy}(Ns^2x-sx^2)+sxsxy-s^2xsy \tag{6}$$

$$r_{ix}(sy^2-Ns^2y)+r_{iy}(Nsxy-sxsy)+s^2ysx+sxysy \tag{7}$$

When several intermediate variables are calculated in advance and the rows of the C^+ are multiplicated with the original force and torque orders, equations for the vertical (Z) leg forces of leg i (from 1 to N) are given by:

$$F_{iz} = detCCt^{-1} \begin{Bmatrix} (k_1 r_{ix} + k_2 r_{iy} + k_3) F_b^{zref} + \\ (k_4 r_{ix} + k_5 r_{iy} + k_2) \dot{T}_x - \\ (k_6 r_{ix} + k_4 r_{iy} + k_1) \dot{T}_y \end{Bmatrix} \tag{8}$$

The intermediate variables calculated in advance in order to speed up the repeated calculation of Eq. (8) are:

$$k_1 = sxysy - s^2ysx \tag{9}$$

$$k_2 = sxysx - s^2xsy \tag{10}$$

$$k_3 = s^2xs^2y - sx^2 \tag{11}$$

$$k_4 = sxsy - Nsxy \tag{12}$$

$$k_5 = Ns^2x - sx^2 \tag{13}$$

$$k_6 = Ns^2y - sy^2 \tag{14}$$

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Title

Force based motion control of a walking machine

Abstract

Force control of legs of evolving walking machines is assumed to be essential in natural soft and uneven terrain. The main duties of a leg are to support and propel the vehicle in co-operation with the other legs. Force control fills the support requirement also when a leg or many legs penetrate the terrain. It also prevents rolling of the body due to lift-off or placement of legs.

Due to the relatively large mass and inertia of the body, dynamic equations of a free object are a basis for "computed-torque" based calculations of desired body forces to move or participate in the applications as desired. The large and varying amount of friction in the leg mechanisms while the body is carried and the practical delays and saturation in the hydraulic system increase the complexity of the process to be controlled.

The main contributions in this thesis are as follows. The body forces are transformed to the supporting legs in two phases: sets of minimum forces perpendicular to the resultant body force and forces parallel to the same resultant. This method minimizes the possibility of slippage with walking machines, where the desired body force is often close to vertical due to the weight of the body.

A load adaptive PI force control method for the hydraulic actuation system of MECANT I consisting of an asymmetric cylinder and a symmetrical valve has been developed. The I term of the controller is changed according to the desired load.

A rule based altitude controller and a dead-zone and saturation based attitude controller have been designed. The first tests with force controlled vertical actuators show the usability of the method and fast responses to deviations in body orientation. The deviations are usually corrected within 1 second.

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