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AUTOMATIC LOCOMOTION MODE CONTROL OF WHEEL-LEGGED ROBOTS

Ilkka Leppänen

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HELSINKI UNIVERSITY OF TECHNOLOGY

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P.O. Box 5500
FIN-02015 TKK
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e-mail ilkka.leppanen@tkk.fi
Tel +358-9-451 5143
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Abstract
Traditional manipulator-type robots are mostly mounted in a fixed position and no locomotion is needed. During the past two decades, robots have slowly moved from factories to more open areas, such as metro stations, hospitals or mines. These mobile robots, called field and service robots, have to move and act on partly closed working sites or in ordinary environments, therefore the significance of their locomotion has increased.The main land locomotion principles, wheeled and legged locomotion, can be combined as hybrid to help find an optimal solution for greatly varying ground conditions. Hybrid locomotion can also be called rolking (rolling-walking). The wheel-legged robot can move using different locomotion modes; it can drive with wheels, rolk (use wheels and legs at the same time) or even walk.

In this work, an automatic locomotion mode control for the wheel-legged robot has been developed. The developed locomotion mode control can utilize two locomotion modes, wheeled and rolking, depending on terrain properties. The developed generic solution is valid for wheeled locomotion systems with a 2-dof active suspension system for the wheel.

The basis for the automatic locomotion mode control is to measure characteristics of vehicle-terrain interaction, such as energy consumption, slipping and drawbar force of a wheel and terrain parameters, such as terrain slope and roughness. Algorithms for sensing these in real time, utilizing the locomotion system as a sensing system, have been developed. The characteristics of vehicle-terrain interaction and terrain parameters are used as criteria for indicating the functioning of a wheel in wheeled mode and terrain trafficability in rolking mode. These criteria are used to determine if a mode change is required. The criteria are mainly based on sensing forces and energy consumption by utilizing the sensor system used for the locomotion control; a minimum number of additional sensors is needed.

The automatic locomotion mode control was successfully implemented and verified in the wheel-legged service robot, WorkPartner. It can use rolking mode on soft terrain or in negotiating obstacles and use wheeled mode for moving faster on flat terrain automatically. In the future, the developed sensing methods can also be used in developing new locomotion modes, such as free gait-based moving in which the motion control switches a single wheel to a different mode, depending on terrain properties.

Keywords Wheel-legged robot, rolking , locomotion mode switching

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Jalka-pyörämekanismilla varustetun robotin liikkumismoodin automaattinen vaihto

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Tiivistelmä
Perinteiset manipulaattorityyppiset robotit ovat useimmiten kiinnitettyjä tiettyyn paikkaan. Parin viime vuosikymmenen aikana robotteja on alettu hyödyntää tehdasympäristön lisäksi julkisilla paikoilla, kuten metroasemilla, sairaaloissa ja kaivoksissa. Näiden robottien, joita kutsutaan kenttä- ja palveluroboteiksi, pitäisi kyetä liikkumaan ja toimimaan tavallisessa ympäristössä ihmisten keskellä. Pääliikkumisperiaatteet eli pyörä- ja jalkaliikkuminen voidaan yhdistää, jotta saavutettaisiin parempi liikkumiskyky vaihtelevassa maastossa. Yhdistelmäliikkumista voidaan kutsua pyöräkävelyksi (pyöriminen-käveleminen). Jalka-pyörämekanismilla varustettu robotti kykenee liikkumaan eri tavoin: ajamaan pyörillä, pyöräkävelemään tai jopa kävelemään.

Tässä työssä on kehitetty jalka-pyörämekanismilla varustetun robotin liikkumismoodin automaattinen vaihto. Moodinvaihto käyttää maastoon parhaiten sopivaa liikkumistapaa. Kehitetty geneerinen ratkaisu toimii liikkumisalustoilla, joissa on kaksidimensionaalinen aktiivinen pyöränripustus.

Automaattinen liikkumismoodin vaihto perustuu sekä robotin ja maaston vuorovaikutuksen, kuten energian kulutuksen, luiston ja pyörän tuottaman voiman, että maaston kaltevuuden ja epätasaisuuden reaaliaikaiseen mittaamiseen käyttäen hyväksi robotin liikkumisjärjestelmää. Näitä maaston sekä robotin ja maaston vuorovaikutuksen ominaispiirteitä voidaan käyttää kriteereinä pyöräajossa ilmaisemaan pyörän toimivuutta ja pyöräkävelyssä maaston kuljettavuutta pyöräliikkumista ajatellen. Liikkumistavan vaihto määritetään näiden kriteereiden avulla. Kriteeristö perustuu voiman- ja energiankulutusmittausten hyödyntämiseen käyttäen hyväksi liikkumisjärjestelmän anturisysteemiä siten, että lisäanturointia tarvitaan vähän.

Liikkumismoodin automaattinen vaihto on onnistuneesti implementoitu ja testattu jalka-pyörämekanismilla varustetulla WorkPartner-palvelurobotilla. WorkPartner kykenee hyödyntämään liikkumismoodeja automaattisesti siten, että se pyöräkävelee pehmeässä maastossa tai ylittäessään esteitä ja liikkuu pyörillä kovalla tasaisella maalla. Kehitettyjä mittausmetodeja voidaan hyödyntää kehitettäessä tulevaisuudessa uusia liikkumistatapoja, kuten vapaa-askellajiin perustuvaa liikkumista, jossa pyörät voivat olla eri moodissa maaston ominaisuuksista riippuen.

Asiasanat Jalka-pyörärobotti, pyöräkävely, liikkumismoodin vaihto

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PREFACE

This study concerning locomotion of robots was carried out at the Automation Technology Laboratory of Helsinki University of Technology.

I wish to express my sincere gratitude to professor Aarne Halme, head of the Automation Technology Laboratory, for his encouragement, inspiration and patience during this relatively long period of work.

The roots of this study are in the MECANT project concerning walking machine technology funded mainly by the Finnish Funding Agency for Technology and Innovation (Tekes) from 1990-1993. Research about locomotion of the robots continued under the WorkPartner project during 1998-2005 and the Aktiivipyörä project during 2006-2007, both mainly funded by Tekes. Financial support for these research projects is gratefully acknowledged. I would also like to thank the Emil Aaltonen and Henry Ford Foundation, and also Tekniikan edistämissäätiö for their financial support.

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I also thank my preliminary examiners, Professor Matti Juhala and Research Professor Pentti Vähä for their reviews and comments on the thesis, and my opponent Professor Manuel Armada for finding time to make the journey to Finland to examine and debate my views.

Finally, I thank my wife Sanna and children Lydia, Amanda, Emil and Aksel for their patience during the days and nights when I was preparing this thesis. You mean the most to me.

Espoo, July 2007

Ilkka Leppänen

CONTENTS

LIST OF SYMBOLS

{M}	main coordinate system of the vehicle
{P}	path coordinate system of the vehicle
{T}	terrain coordinate system of the vehicle
a_x	longitudinal acceleration of the vehicle
b	diameter of the plate
c	cohesion of soil
g	acceleration due to gravity
k	soil deformation modulus
k_c	cohesive modulus of soil deformation
k_φ	frictional modulus of soil deformation
l	length of contact area
m	mass of the vehicle
n	soil deformation exponent
p	ground pressure
r_R	rolling radius of the wheel
s	travelled distance
t_i	time window of criterion i
v	velocity of the vehicle
x	soil deformation
z	sinkage
A	ground contact area
C_{resist}	resisting force of the wheel criterion
C_{rolk}	energy consumption of rolking per travelled distance criterion
C_{roll}	energy consumption of the wheels per travelled distance criterion
C_{roll_w}	energy consumption of a single wheel per travelled distance criterion
C_{static}	static motion resistance criterion
C_{static_w}	static motion resistance of a wheel criterion
C_S	slipping of the wheel criterion
$C_{transfer}$	motion resistance of a transfer leg's wheel criterion

C_χ	terrain roughness criterion
E_j	energy of the wheel j or the joint j
E_W	energy of the wheel
F_a	adhesion force
F_c	cohesive traction force of the wheel
F_{DP}	drawbar pull
F_h	hysteresis force
F_H	soil thrust
F_f	frictional traction force of the wheel
F_{FR}	frictional force
F_N	normal force
F_{resist}	resisting force of the wheel
F_{RR}	rolling resistance of the wheel
F_T	traction force of the wheel
F_V	vertical ground reaction force
F_{x_leg}	x-component of the leg force in main coordinate system {M}
F_{y_leg}	y-component of the leg force in main coordinate system {M}
F_{z_leg}	z-component of the leg force in main coordinate system {M}
J	moment of inertia
K_i	weight coefficient of criterion *i*
L_i	threshold value of the criterion *i*
L_s	threshold value of sum of criteria
L_W	load of the wheel
Q_{rolk}	energy consumption of rolking per travelled distance
Q_{roll}	energy consumption of the wheels per travelled distance
Q_{roll_w}	energy consumption of a single wheel per travelled distance
Q_{static}	static motion resistance
Q_{static_w}	static motion resistance of a wheel
R_g	gravitational resistance of the vehicle
R_i	threshold-reached flag for criterion *i*
S	wheel slip
T_j	torque of the joint *j*

T_K	torque of the knee joint
T_T	torque of the thigh joint
T_W	torque of the wheel
W	weight of the vehicle
α	angle of the joint
β	duty factor
θ_p	pitch angle of terrain slope
θ_r	roll angle of terrain slope
μ	friction coefficient
μ_a	adhesion coefficient
μ_h	hysteresis coefficient
χ	terrain roughness
χ_p	angle between the lengthwise virtual axles
χ_r	angle between the sideways virtual axles
γ	soil weight
τ	shear stress
τ_s	maximum shear stress of soil
φ	angle of soil internal friction
ω	angular velocity of the wheel

LIST OF ABBREVIATIONS

ABS	Antilock Breaking System
AGV	Automated Guided Vehicle
AMC	United States Army Materiel Command
ASV	Adaptive Suspension Vehicle
ATHLETE	All-terrain Hex-Limbed Extra-Terrestrial Explorer
CAN	Controller Area Network
CI	Cone Index
CIV	CRREL Instrumented Vehicle
CRREL	Cold Regions Research and Engineering Laboratory of US Army
EC	Electronically Commutated
ESP	Electronic Stability Program
ESTEC	European Space Research and Technology Centre
ETH	Swiss Federal Institute of Technology, Zurich (Eidegenössiche Technische Hochschule)
FEM	Finite Element Method
GE	General Electric
GPS	Global Positioning System
HUT	Helsinki University of Technology
Hybtor	Hybrid Tractor
JSC	Johnson Space Center
LMS	LocoMotion System
MECANT	MEChanical ANT
Mini-ITX	Standard for motherboard of PCs

NASA	National Aeronautics and Space Administration
NRMM	NATO Reference Mobility Model
NWVPM	Computer simulation model for off-road wheeled vehicle
OSU Hexapod	Ohio State University Hexapod
PC	Personal Computer
PC/104	Standard for PC-cards
QNX	Realtime operating system software
RoboTRAC	Roboter-TRACtor
SAP	Pneumatic Actuated System
TACOM	United States Tank Automotive Command
TCS	Traction Control Systems
UGV	Unmanned Ground Vehicles
USACE	United States Army Corps of Engineers
WES	Waterways Experiment Station
WLAN	Wireless Local Area Network
dof	degree of freedom
rolking	rolling-walking
2D	Two Dimensional
3D	Three Dimensional

1 INTRODUCTION

1.1 Background

The capability of locomotion is a natural feature of people and animals. Without locomotion capability, everyday life is complicated, although handicapped people have long been taken into account in planning living environments. In nature, locomotion really means surviving the attacks of predators. For example, a newborn elk calf can walk and follow the elk mother just after birth. Nature has evolved legs over the past 100 million years as an optimal locomotion mechanism for unstructured terrain.

Exploitation of robots started first in industry, where manipulator-type robots do monotonous tasks in predetermined environments in a very efficient way. The traditional manipulator-type robots are mostly mounted in a fixed position, as no locomotion is needed. During the past two decades, robots have slowly moved from factories to more open areas, such as metro stations, hospitals or mines. These mobile robots, called field and service robots, should locomote and act in ordinary environments and among people, or in a closed area, as in mining.

A locomotion system makes a vehicle move, negotiate terrain and reach its goals during the execution of its task. Good locomotion is critical to the successful execution of a mobile robot's tasks. Robotic locomotion differs from traditional forms of locomotion in the sense that the robot should move in a controlled manner without the aid of a human operator. This means that the robot should be able to perceive terrain and environment, plan the path, navigate, and, of course, avoid the obstacles and move to the target place without getting stuck.

In general, locomotion on the ground can be realized using the following principles: rolling, walking, running, jumping, crawling or wriggling [Todd, 1985]. Land locomotion of mobile robots is often based on wheeled locomotion because rolling enables fast and energy-efficient motion on hard flat terrain. The mechanical simplicity of the wheel also helps in using them. Humans have built a lot of roads and even urban areas to make wheeled locomotion possible. Wheeled vehicles have limited access to natural terrain, which produced an impulse to study walking systematically since the beginning of the 1960s. Improvements in computer technology accelerated walking research, because the total control of movements of a walking machine is a calculation-intensive task. Although walking technology has been studied over forty years, the mobility of legged robots is still far away from the mobility of animals.

The main locomotion principles can also be combined as hybrids to help find an optimal solution for greatly varying ground conditions. For example, WorkPartner, a service robot for outdoor tasks used in this study as the test platform, has a hybrid locomotion system that consists of four wheeled legs and an articulated body [Halme et al., 2003]. The locomotion system of WorkPartner allows motion with legs only, with legs and wheels powered at the same time or with wheels only [Leppänen et al., 1998]. With the help of a multimode locomotion system, this robot can move over different types of terrain and negotiate obstacles successfully. There still exists the problem that the robot cannot utilize the multimode locomotion system in an optimal way without the aid of a human operator. The purpose of this study is get the WorkPartner-type robot to utilize the multimode locomotion system in a clever way, i.e. to use wheeled or *rolking* (rolling-walking) mode at the right time, depending on the terrain properties. The same kind of analogy appears in the moving of a one-year-old child. For example, if the child encounters stairs, in order to go upstairs he or she will switch to crawling mode. Underlying this natural behaviour is a versatile locomotion system that the child can utilize with the help of an efficient vision and sensing system based on learning and training.

The work described in this thesis tries to take a short step towards more autonomous robotic locomotion over unknown off-road terrain. The work concentrates on ground locomotion of the mobile robot, especially studying vehicle-terrain interaction and sensing terrain parameters in order to utilize locomotion modes in an optimal way. The thesis does not concentrate on obstacle avoidance or path planning, though the results of the thesis can also be applied in obstacle detection and terrain trafficability evaluation.

1.2 Motivation and problem definition

In the past few decades, several safety features, such as antilock breaking systems and stability and traction control for wheeled locomotion has been introduced. These automatic controls operate so well that most drivers do not notice when safety functions actuate the vehicle control. These safety features are based on the latest developments of control electronics and sensor technology. In mobile robotics, the same development helps to develop a more adaptive hybrid locomotion system for greatly varying ground conditions. The hybrid locomotion system helps the mobile robot negotiate bad situations, such as soft swamp or terrain obstacles. In addition, the features of hybrid locomotion systems improve wheeled locomotion, enabling support force distribution and body level control. Versatile locomotion capability is needed in operating unknown natural terrain. Typical applications where locomotion is critical are exploration, rescue tasks and maintaining power distribution systems far from roads.

In this thesis, only land locomotion of the mobile robot is of research interest; in particular, wheeled, walking and hybrid locomotion has been analysed. Hybrid locomotion in this study is defined as *combining wheeled and legged locomotion*.

A robot that has a hybrid locomotion system can move in different ways, driving with wheels, rolking, i.e. using wheels and legs at the same time, or even walking. In this case, the hybrid locomotion system of the robot vehicle consists of wheels that are connected to the robot body with an at least 2-dof (degree of freedom) active suspension system. The 2-dof-wheel active suspension can be composed of leg-type mechanics, for example. For smooth omni-directional walking, 3-dof legs are needed.

The objective of this work is to get a mobile robot that can drive with wheels and rolk to autonomously use the optimal locomotion mode, depending on terrain properties.

The optimal locomotion mode best suited to a particular situation depends on the requirements for locomotion. These requirements may be low energy consumption, for example, or moving without damaging the terrain or driving as fast as possible.

The wheeled and rolking locomotion differ with respect to how they interact with terrain. Therefore, the robot should sense characteristics of the vehicle-terrain interaction and geometry of terrain in order to select the optimal locomotion mode. Typical characteristics of the vehicle-terrain interaction are energy consumption, motion resistance and drawbar pull.

The autonomous switching of locomotion modes requires a good sensing system to measure characteristics of the vehicle-terrain interaction and also terrain parameters, such as terrain slope and roughness. These characteristics can be measured utilizing the locomotion system as a sensing system, and then the locomotion system can be called a *multifunctional* locomotion system. Pre-existing information about terrain and soil would be useful for robot locomotion, but is not usually available. In cross-country operations, perceiving soil characteristics without touching the ground is still impossible.

A multifunctional locomotion system also requires a good control system. In order to locomote in a sophisticated way, the robot should control all joint and wheel movements in real time.

1.3 Scientific contribution of the dissertation

The first scientific contribution of this thesis is the introduction of new methods to measure the functionality of the wheel in off-road operation and in real time. In wheel-soil interaction, the main two tasks of the wheel are to carry the load and to produce traction force to overcome motion resistances. By measuring the drawbar force of the wheel using the suspension system of the wheel and estimating the traction force generated by an active torque motor, the lost energy in the wheel-soil interaction can be determined.

The second scientific contribution is terrain characterisation using the robot's propulsion and sensing system. The terrain slope and roughness can be determined for estimating terrain trafficability. In addition, the robot can perceive the separate terrain obstacles that prevent wheeled locomotion. Then the robot can overcome these obstacles using rolking-type locomotion.

The third scientific contribution is a generic method for controlling locomotion mode automatically. The proposed method can utilize a multimode locomotion system in a correct way. The wheeled legged robot uses the wheels over easy and even ground, but, in soft and rough terrain, it automatically utilizes more propulsive rolking. The proposed method is expandable with respect to the amount of sensor info used.

1.4 Outline of the dissertation

This thesis describes research where the goal has been to create a generic automatic locomotion mode control for the wheel-legged robot. The basis for the automatic locomotion mode control is to measure terrain characteristics and vehicle-terrain interaction. In this work, sensing methods for these two topics have been developed and tested with a real wheel-legged robot, the WorkPartner robot.

The dissertation is organised as follows:

Chapter 1: *Introduction.* The introductory chapter describes the meaning of locomotion for the autonomous mobile robot in task execution. It also presents the research problem of how to utilize multimode locomotion system in an efficient and clever way.

Chapter 2: *State of the art.* This chapter reviews the current state of the art in the field of mobile robots ground locomotion. Walking, wheeled and hybrid locomotion has been studied. Terramechanics – the mechanics of vehicle-terrain interaction – has also been analysed with respect to automatic locomotion mode control. In addition, the sensing of terrain parameters is studied in detail.

Chapter 3: The p*roblem of automatic locomotion mode control.* The research problem is analysed in order to find an optimal generic solution for wheeled mobile robots that have at least a 2D active suspension system. This chapter clarifies the main characteristics of vehicle-terrain interaction.

Chapter 4: *Sensing characteristics of vehicle-terrain interaction and terrain features.* Sensing methods for evaluating vehicle-terrain interaction are described. In particular, sensing methods for measuring characteristics of wheel-soil interaction in real time in off-road conditions are studied in this chapter. Terrain characterisation methods for automatic locomotion control are described.

Chapter 5: A *generic method for* a*utomatic locomotion mode control.* This chapter presents a generic locomotion mode control method that is expandable with respect to utilizing more sensor information. The criteria for locomotion mode control are examined. Finally, the different types of optimisation strategies are discussed.

Chapter 6: *Experimental verification.* Firstly, the test vehicle, i.e. the WorkPartner wheel-legged robot, is explained in detail. Then, the test experiments with the WorkPartner robot are reported. The test experiments are divided into three parts: in the first part, the results of verifying the sensing methods for vehicle-terrain interaction and terrain characterization are shown; in the second part, the experiments of verifying functionality of criteria separately are described; finally, in the third part, test runs of locomotion mode switching are reported.

Chapter 7: *Conclusions.* This chapter summarizes the results of the test experiments and the main contributions of the thesis. Recommendations for future works are also presented.

2 STATE OF THE ART

Land locomotion, especially walking, wheeled and hybrid locomotion, is reviewed throughout. Terramechanics – the mechanics of vehicle-terrain interaction – has also been analysed in order to find methods for sensing wheel-soil interaction. In addition, sensing terrain parameters is studied in detail.

2.1 Locomotion of mobile robots

Good locomotion capability is the key characteristic of field robots working on uneven outdoor terrain. They should be able to operate in sand, snow, swamp or even over rocky terrain. The service robot must also have almost the same mobility as people, because the future service robot will work with people. The service robot must be able to work in indoor and/or outdoor surroundings. In indoor environments, this mostly means having the capability of moving up or down stairs.

The service robot must have a wide speed range to be able to move alongside a running or cycling man. Energy consumption must be low to guarantee a long operation time, say several hours of work. A typical task for the service robots will be the transportation of goods or people [Robosoft], cleaning [Siemens] and entertainment [Sony].

Requirements for locomotion of the robots are less demanding in industry, as industrial robots are mostly mounted in a fixed position and do monotonous tasks efficiently. In general, industrial processes can be predetermined and the raw material flow can be arranged in such a way that a need for mobile robots is quite minor. Typical industrial mobile robots in use are automated guided vehicles, AGVs [Muller, 1983]. A service robot can be stationary in applications where movement is not needed. A good example of a stationary service robot is a coffee robot that serves customers by making them a cup of coffee. However, most service robots are mobile and need a locomotion system.

Most mobile robots are composed of a set of subsystems. Halme [HUT] has divided the mobile robot into the eight subsystems shown in Table 2.1.

Table 2.1 Subsystems of a mobile field and service robot [HUT].

Power and energy system
Motion system
Motion control system (piloting system)
Navigation system
Perception system
Motion and action planning system
Man-machine interface and remote control system
Work tool system including manipulator

Two subsystems, the motion system and that of motion control, take care of the robot motion. The motion subsystem consists of the mechatronic locomotion system including the actuating system. The motion control subsystem, which can be called the *piloting system*, controls the motion of a robot. Of course, the motion control system should utilize sensing information coming from the robot's perception system. Overall motion planning takes place in the motion and action planning subsystem with the help of the navigation subsystem. The automatic locomotion mode control is part of the motion control system.

The robot motion system can also be utilized in manipulation tasks. In order to enlarge workspace or to produce more force, the robot moves during the manipulation work. This kind of simultaneous motion of the manipulator and the platform requires combined motion control [Luksch et al., 2003].

Application-dependant requirements should be taken into account in the design process of a locomotion system for a robot. The main factor is the environment where the robot has to operate. Typical design factors also are speed, stability and payload requirements. Nowadays, ecological factors also, such as impact on the environment and energy consumption, have to be considered.

Locomotion over the ground can be realized using the following principles: rolling, walking, running, jumping, crawling or wriggling [Todd, 1985]. Rolling-based locomotion systems, such as wheels and tracks, are the most commonly used in mobile robots because rolling enables fast and energy-efficient motion over hard flat terrain. The main locomotion principles can also be combined as hybrids to help in finding an optimal solution for greatly varying ground conditions. Typical mobile robots having hybrid locomotion system are WorkPartner [Leppänen et al., 1998] and Roller-Walker [Endo and Hirose, 2000].

2.1.1 Wheeled locomotion

The popularity of wheeled locomotion is based on human-made roads where the wheel works well rolling with high speed and energy efficiency. The wheel can also carry a large load over flat hard ground. An ultimate example of a wheeled vehicle with a large load capacity is a steel-wheeled train running on the railway. The high energy efficiency of the rolling wheel on hard surfaces is based on the continuous motion of the wheel as opposed to legged locomotion where the legs reciprocate.

The rolling resistance of tyres on hard surfaces is primarily caused by the hysteresis of tyre materials due to the deflection of the carcass while rolling. Friction between the tyre and the road caused by sliding, the resistance due to air circulating inside the tyre, and the fan effect of the rotating tyre on the surrounding air also contribute to the rolling resistance of the tyre, but they are of secondary importance. However, the wheel does not work well in soft ground or during off-road operation. When the wheel sinkage is significant, the wheel compresses soil and looses energy. In addition, a bulldozing resistance also is taken into account in the calculation of the total motion resistance of a tyre [Bekker, 1969]. Motion resistance, which depends on ground deformation, is very hard to measure reliably; using energy consumption or wheel-moment information, the motion resistance can be estimated. To reduce rolling resistance in off-road operation, the diameter and width of a tyre will be increased [Wong, 2001]. Lower inflation pressure decreases slip of a tyre and reduces ground penetration, which means minor motion resistance, too [Gillespie, 1992].

Quite often, the rear tyres of a vehicle travel in the ruts formed by the front tyres and the motion resistance of the rear tyres is smaller. However, on deformable surfaces, such as sand or snow, the motion resistance of a tyre can be too large to locomote with wheels. The average values of coefficient of rolling resistance for various types of tyres over different surfaces are summarised in Table 2.2. In addition, the wheel cannot produce enough traction force on soft ground [Bekker, 1969]. In order to increase grip between the wheel and terrain in slippery conditions, spiked tyres or tyre chains are often used.

Table 2.2 Coefficient of rolling resistance, adapted from [Wong, 2001].

SURFACE			
TYRE TYPE	Concrete	Medium Hard soil	Sand
Passenger car	0.015	0.08	0.30
Truck	0.010	0.06	0.25
Tractor	0.02	0.04	0.20

There are two ways to increase mobility of a wheeled vehicle in natural soft terrain. The first is to add more wheels and increase the size of each wheel. The second is to use tracks. The tracked vehicle (e.g. tracked forwards or tanks) carries its own road with it, thus enlarging the operation area of uneven soft terrain [Wong, 2001]. A tracked vehicle has a larger contact area, which means lower ground pressure and lower sinkage, too. Lower sinkage of the wheel or the track means smaller motion resistance. In cohesive soil, such as snow or clay soil, the track produces a larger propulsion force compared to the wheel for the reason that, in cohesive soil, propulsion force, based on shear stress under the track or wheel, depends mainly on the size of the contact area [Wong and Huang, 2006].

Most wheeled vehicles have a suspension system to filter unevenness of terrain and to distribute load on the wheels. Most wheel suspension systems are passive, like the wheel suspension of a normal car. Passive suspensions consist of conventional components with spring and damping (shock absorber) properties. Passive elements can only store energy for some portion of a suspension cycle (springs) or dissipate energy (shock absorbers). No external energy is directly supplied to this type of suspension. The second wheel suspension category is semi-active, containing spring and damping elements, the properties of which can be changed by an external control. External power is needed to supply to these systems for the purpose of changing the properties. The third wheel suspension category is fully active suspensions, which include actuators to generate the desired forces in the suspension [Gillespie, 1992].

Wheeled vehicles, especially tracked ones, cause environmental damages. On soft terrain, the wheel sinks and leaves a rut behind. Likewise, the tracks affect the terrain badly in turning manoeuvres.

2.1.2 Walking locomotion

Nature has evolved legs over 100 million years as an optimal locomotion mechanism for unstructured terrain. The human has built a lot of roads for transportation, but still more than half of the land areas in the world are rough. Walking locomotion is suitable for uneven terrain, especially in soft ground where it is impossible to go with wheels. Todd [Todd, 1985] summarized the advantages of legs as follows:

- legs can step over obstacles and up and down stairs
- legged locomotion can, in principle, even carry a vehicle over wide chasms or extremely broken ground
- a legged vehicle can achieve a smooth ride on rough ground by varying the effective length of its legs to match the undulations of the ground
- on soft ground a wheel is always climbing out of a rut of its own making; this wastes power
- legs do less damage to the ground than tracks and many wheels

It is important also to notice that walking enables omni-directional movement over uneven terrain. Legged locomotion uses discrete footholds that optimize support and traction, whereas a wheel requires a continuous path of the support.

One of the earliest systematic attempts to build a walking machine was the GE Quadruped developed by General Electric in the 1960s [Mosher, 1969]. The GE Quadruped was a hydraulically powered four-legged vehicle with a human operator controlling the joint motions of legs directly with his own arms and legs. The front legs of a vehicle followed the movements of the driver's arms, while the back legs followed those of the driver's own legs. The walking machine performed well, but proved extremely demanding on its driver, who could not manage to control it for more than a few minutes at a time. This experiment showed clearly that, without computer control, it is impossible to coordinate the movement of the many joints of a walking machine as is needed for smooth motion in off-road operation.

The first recognised computer-controlled legged machine, Phoney Pony, was built by McGhee and Frank in 1966 [Todd, 1985]. It was a quadruped weighing 50 kg, with a 2-dof leg. After that, several computer-controlled legged vehicles were built in the 1970s and 1980s, most being connected to an external computer system, and a power system, too. Development of legged machines accelerated in the 1980s with the help of practicable on-board computers. For outdoor locomotion, the first self-contained legged machine was Sutherland's hexapod built by Carnegie Mellon University in 1983 [Todd, 1985]. It was a hydraulically powered six-legged walking machine with an on-board control computer. Otherwise, as in the case of the GE Quadruped, the operator sitting in the vehicle controlled only the direction and speed of the robot body.

A six-legged vehicle of Ohio State University, named the Adaptive Suspension Vehicle or the ASV, has the most sophisticated artificial legged locomotion system of the 1980s [Pugh et al., 1990]. The ASV consisted of a hydraulic power and actuation system with high energy efficiency. The mechanical design of the legs also satisfied demanding requirements of the vehicle, walking at a maximum speed of 3.6 m/s. It broke new technological ground in operating over completely unstructured terrain, operating in soil conditions ranging from deep mud to hard concrete, over large obstacles and substantial gradients, and through closely packed obstacle fields. The ASV was not an autonomous robot; the operator sitting in the vehicle controlled the direction and speed of the robot body and also performed long-range sensing, path selection and navigation. It was a proof-of-concept vehicle, which has proven that it is technologically possible to build a fully self-contained, multilegged vehicle equipped with a hydraulic power system and on-board computers. A more comprehensive and detailed description of the ASV can be found in [Song and Waldron, 1989].

Legged locomotion can be realized with two basic mechanisms: slide or lever. Locomotion of most legged robots is based on a lever mechanism. A legged robot having the slide mechanism is the six-legged robot, Ambler. It was designed at Carnegie Mellon University for planetary exploration, the immediate target planet being Mars [Krotkov, 1993], [Bares and Whittaker, 1993]. A typical example of a legged robot based on a lever mechanism was MECANT, as can be seen in Figure 2.1. MECANT was a fully independent hydraulic six-legged walking machine that had a 2D pantograph with vertical rotation axis, thus having three dofs [Halme, 1994].

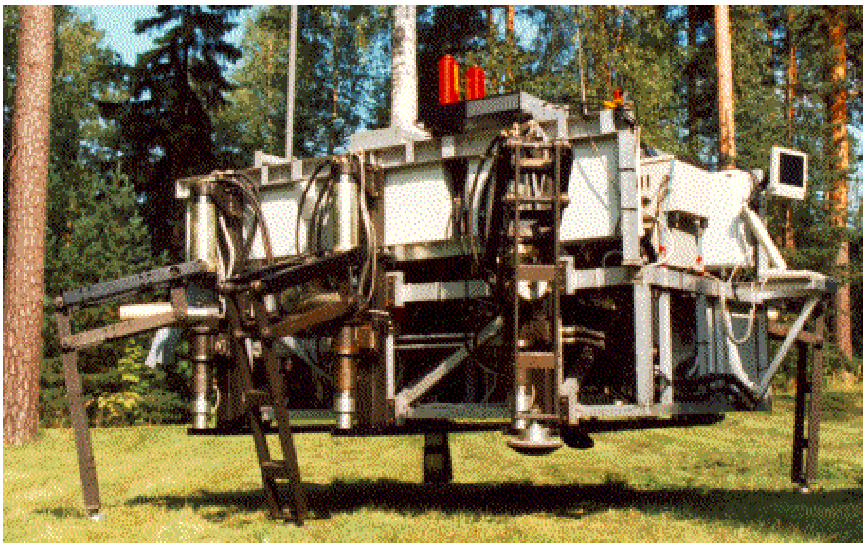


Figure 2.1 The six-legged walking machine, MECANT.

The reader who is interested in studying legged locomotion in depth is referred to [Todd, 1985] and [Song and Waldron, 1989]. A very comprehensive directory of research projects on the subject legged locomotion can also be found in [Walking Machine Catalogue].

Although legged locomotion has been studied over fifty years, autonomous legged robots are still clumsy and slow, and they have problems in obstacle negotiation. A reason for this is that subsystem development of legged robots is still at an early stage. The actuating system does not fulfil velocity and force requirements for fast locomotion. The inertia of the leg limits the velocity of the walking machine using stable gaits. The recovery leg must accelerate very fast and then slow down in order to prevent collision. With regard to six-legged machines, for example, this can be seen in Figure 2.2. In this figure, “beta” (β) indicates the number of legs in the support phase in relation to the total number of legs. Leg transfer velocity increases strongly when more legs are in the support phase, i.e. when beta is bigger.

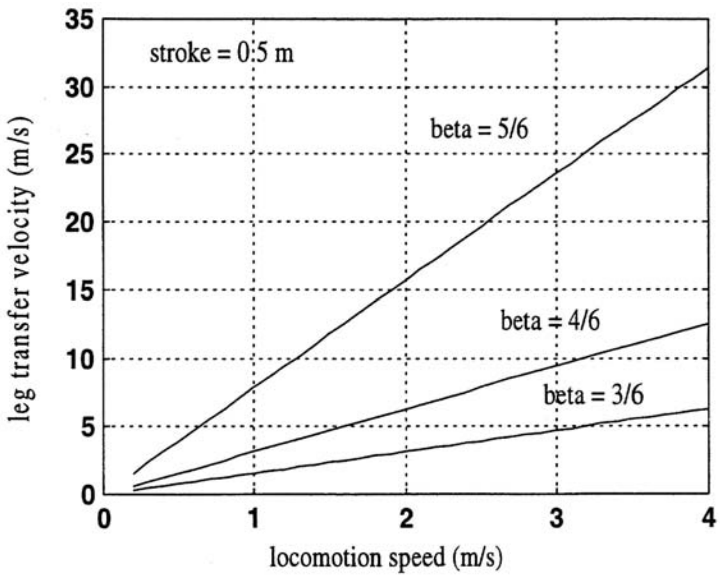


Figure 2.2 Transfer foot velocity vs. locomotion speed for 6-legged wave gaits with different duty factors, beta (β) [Hartikainen, 1996]. Transfer trajectory shape is a half circle and leg stroke is 0,5 m.

The other subsystems, such as the sensing and control system, are insufficient for outdoor operations on unstructured terrain. The sensing subsystem does not perceive adequate 3D information about terrain for locomotion control. The control system cannot control all the joint movements smoothly and in an energy-efficient way. Legged robots have not yet reached into real-life applications, but research results can be utilized in robot locomotion development.

2.1.3 Hybrid locomotion

A high degree of cross-country ability and manoeuvrability are the major requirements for mobile robots intended for operation on natural terrain. Many wheeled and tracked platforms have been developed in an attempt to satisfy these requirements, but a few decades ago, many researchers began investigating alternative means of locomotion to obtain higher mobility. Researchers realized that, while legged platforms have good terrain negotiating capability, wheeled locomotion was more efficient at higher speeds. The main locomotion principles, wheeled and legged locomotion, can be combined as hybrids to help find an optimal solution for greatly varying ground conditions. These hybrid machines have the potential of improved stability over rugged terrain, since the wheels can maintain contact with the ground for a large percentage of the time. The following references summarize the progression of the hybrid concept and will familiarize the reader with their current level of development.

Hybrid locomotion means combining the wheeled- and legged-locomotion modes so that the wheel and the leg joints generate the propulsive force simultaneously. The basic idea of combining wheeled and legged locomotion is to copy the best properties of wheeled and legged locomotion; high-speed locomotion of the wheel and good negotiating capability of legged locomotion.

Hybrid locomotion can also be called *rolking* (rolling-walking), as named in [Leppänen et al., 1998]. The term *rolking* is adopted internationally [Glaskin, 2004]. A term close to this one (roller-walker) has been used previously by [Endo and Hirose, 2000], but their rolking robot differs from WorkPartner [Leppänen et al.,1998] in that its wheels are not powered. Rolking, in this case, resembles skiing, but, instead of skis, wheels are used (however, skis are not active devices like the wheels of WorkPartner). Kemurdjian [Kemurdjian, 1990] used term *wheel-walking* to indicate combined wheeled and legged motion in which the wheel can swivel forward and backward with the help of a 1-dof mechanism.

Combining wheels with legs is not a new achievement. Von Sybel and Grosse-Scharman [Von Sybel and Grosse-Scharman, 1961] conceived a vehicle that cyclically rolls on the driving wheels by the length of one step, locks the wheels and then pulls them back with a hydraulic actuator by the length of a preselected stroke, see Figure 2.3. Thus, this vehicle with a 1-dof leg with a wheel produces two types of thrust: one like a regular wheel, and the other like a foot of wheel shape. This approach is simple but increases the mobility only a little. The ANT Robotic Vehicle developed by Zanthic Technologies also has the same type of leg-wheel propulsion system [Zhantic Technologies].

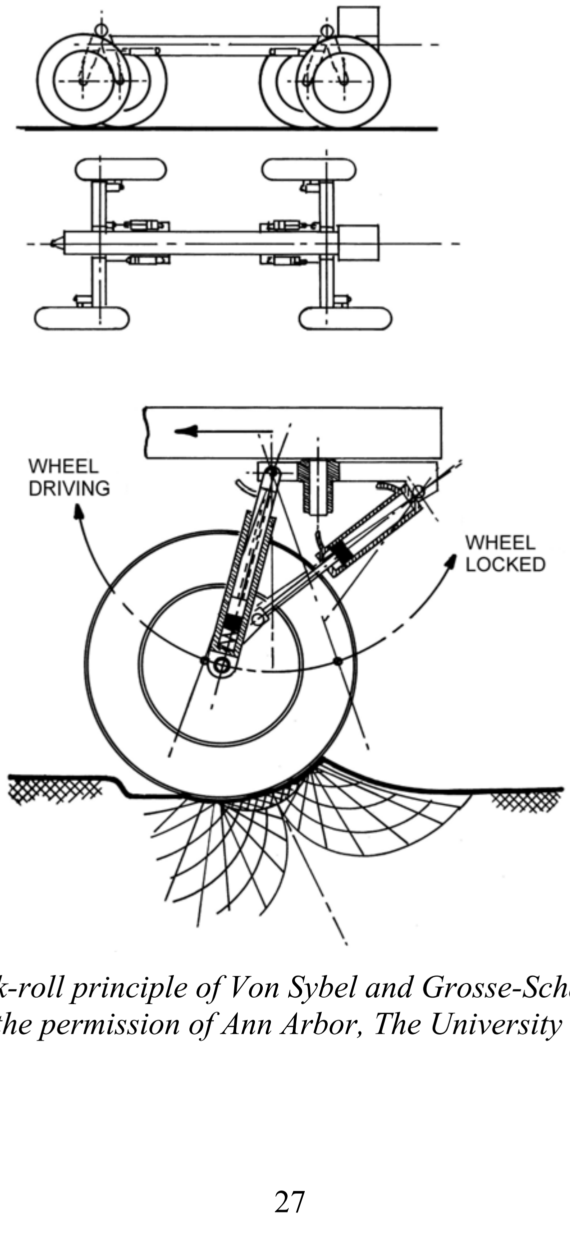


Figure 2.3 Walk-roll principle of Von Sybel and Grosse-Scharman's vehicle. Reproduced with the permission of Ann Arbor, The University of Michigan Press.

Many leg-wheel platforms have been developed within the framework of arctic and planetary exploration (i.e. Earth, Mars). In the Russian space robotics programs, wheel-walking locomotion has been utilized in rover locomotion, starting in the 1960s [Kemurdjian, 1990]. Figure 2.4 shows a six-wheeled experimental mock-up with a 320 kg rigid frame, utilizing a Chebyshev mechanism [Bogatschev et al., 2000]. The wheel of the mock-up can roll actively forward with respect to the body and then the locked wheel pulls the robot body during backward motion with the help of the Chebysev mechanism actuated by an electric motor. Although wheel walking is a simple forward and backward wheel motion without active lightening in forward motion, it helps a lot in soft sandy soil. In wheel mode, the mock-up can climb up an 18 degree slope surmounted with loose soil, but in walking mode, it can climb a 34 degree slope under the same conditions. The mock-up is able to move in wheel-walking modes with continuous or discontinuous walking. Maximum travel speed is, in wheel mode, 0.9 km/h, and in walking mode, 0.15 km/h.

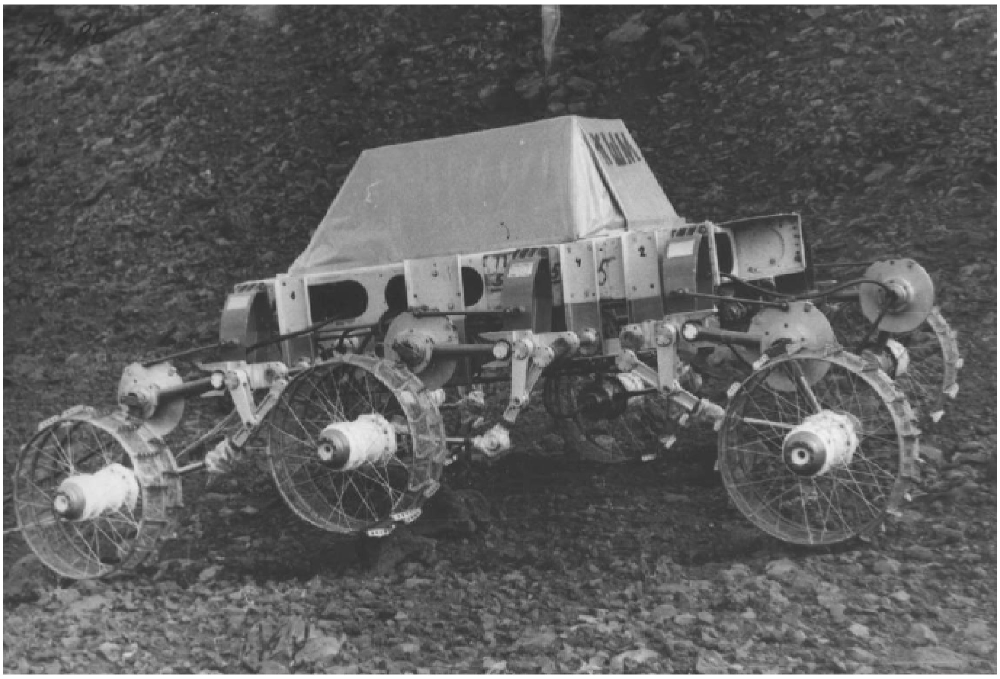


Figure 2.4 "KIIIM" running mock-up with the wheel-walking propulsive device developed by VNIITRANSMASH in Russia in 1972 [VNIITRANSMASH, 2002]. Reproduced with the permission of VNIITRANSMASH.

Depending on the articulated frame design, the wheel-walking mode may be realized by successive movements of the wheel axles or the robot's body. The Mars rover running mock-up shown in Figure 2.5 has two modes of chassis motion: wheeled and wheel-walking [Bogatschev et al., 2002]. The Mars rover has two additional dofs in the body frame in order to achieve worm type walking.

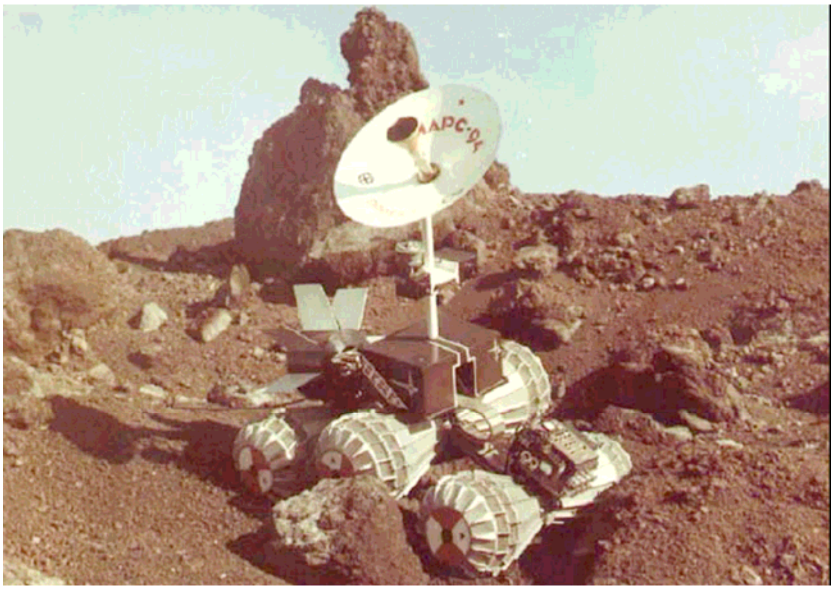


Figure 2.5 "Mir" Mars Rover running mock-up developed by VNIITRANSMASH / Rover LTD in Russia [VNIITRANSMASH, 2002]. Reproduced with the permission of VNIITRANSMASH / Rover LTD.

In very soft sandy soil, each pair of wheels is locked and the robot extends the body, thus producing greater propulsion force by means of the locked wheels. The sequence of the body motion is shown in Figure 2.6, where three axles move forward, starting from the front-most axle. A robot that has only two axles can also wheel-walk. Then, the sequence of motion is short: first, the front axle is moves forward, then the rear axle follows.

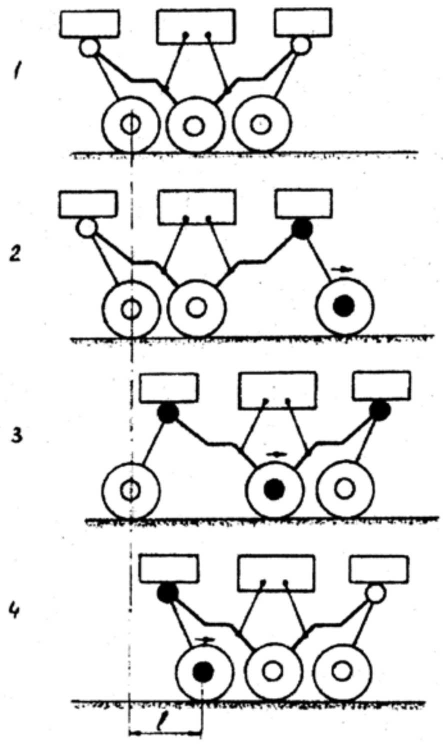


Figure 2.6 Scheme of body motion of Mars Rover mock-up in wheel-walking mode (walking is due to axle movement) [Bogatschev, 2000]. Reproduced with the permission of VNIITRANSMASH / Rover LTD.

The Kemurdjian Science & Technology Rover Centre/Rover Company Ltd. (RCL, Russia) proposed the six-wheel chassis concepts for the ExoMars rover [Kucherenko et al., 2004]. These rover concepts have a passive wheel-load-equalizing suspension. The wheels are attached to the passive suspension system by a 1-dof leg in order to enable wheel-walking, i.e. the wheel can swivel forward and backward. The principle of this wheel-walking motion is the same as that of Von Sybel and Grosse-Scharman's vehicle.

Hylos [Ben Amar et al., 2004] is a wheel-legged robot with sixteen dofs. It has four legs each combining a 2-dof suspension mechanism with a steering and driven wheel. Hylos also has a worm-type locomotion mode called *crawling symmetric gait*. It is a cyclic gait in which each pair of wheels in the frontal plane moves only when the other one is firmly braked on the ground. This gait is actually the same as the Russian Mars Rover has.

A different approach of combining wheeled and legged locomotion is to have the machine with two legs attached in the front and two wheels attached to the back of the body, like WHEELEG in Catania University of Sicily [Lami, 2000], Alduro in Duisburg Germany [Müller et al., 1999], SAP in the University of Versailles [M`Sirdi et al., 1998], RoboTRAC [Zimmermann et al., 1991] and [Caurin and Tschichold-Gurman, 1994] in the ETH Switzerland. These kinds of machines are the subject of quite famous research projects, but in these machines, the legs limit the speed of the machine, while the wheels limit the mobility, though the idea has been to gain the load and speed capacity of wheels and the mobility of legs.

A better idea for increasing mobility is to put a wheel on the end of every leg (like a normal 3-dof leg) to replace the foot. The wheel can be either passive or active. In Tokyo Institute of Technology, they have studied passive wheel-leg combination [Endo and Hirose, 2000]. In their roller-walker machine, the wheeled locomotion resembles skating. In WorkPartner robot [Leppänen et al., 1998] and [Halme et al., 1999], a mammal-type leg with three dofs and an active wheel on every leg has been used. In this way, both the speed of a wheeled vehicle and the mobility of a legged vehicle have been realized.

For maintenance and disaster-prevention applications in the power industry, leg-wheel typed mobile locomotion for step climbing has been studied in Japan [Ichikawa et al., 1983], [Oomichi and Ibe, 1984], [Kimura, 1991] and in Italy [Belforte et al., 1988]. The locomotion of all these research platforms is based on wheels, but to increase mobility, a wheel can be lifted in order to step over an obstacle with the help of a 1- or 2-dof leg. When the wheel is lifted, the robot rolls forward with the other wheels. More sophisticated rolling-walking has not been reported.

For exploration of the Moon, the Jet Propulsion Laboratory is developing a large and highly mobile six-legged lunar vehicle called ATHLETE (All-terrain Hex-Limbed Extra-Terrestrial Explorer) [Hauser et al., 2006]. The robot has six 6-dof legs with an active wheel. ATHLETE can roll rapidly on rotating wheels over flat smooth terrain and walk carefully on fixed wheels over rough terrain. Hauser [Hauser et al, 2006] has not written anything about hybrid locomotion in relation to ATHLETE, but it seems that this locomotion mode is possible with the help of six 6-dof legs with an active wheel.

A small autonomous wheeled climbing robot, Octopus [Lauria et al., 2002], with 8 wheels and fifteen dofs has a special sophisticated locomotion mechanism. The purpose of this complicated locomotion system is to gain more terrain adaptability. The payload support and the two bodies on each side are linked in a passive differential configuration. The two arms and the body on each side of the robot are linked in a motorized parallelogram configuration. The forearms are linked to the arms by a motorized joint. Each forearm has two motorized wheels attached to it. This mechanism architecture allows the robot to have all the wheels touching the ground at the same time, independently of the terrain profile. In this way, the Octopus robot has good step-climbing capability. The wheels only generate the drawbar force and the leg links are not used for walking, but only for terrain adaptability.

One of the more advanced hybrid vehicles to date is the WorkPartner-service robot, which is able to move in walking, hybrid or wheel mode, depending on surface conditions, see Figure 2.7. Mobility is based on a hybrid system, which combines benefits of both legs and wheels to provide good terrain-negotiating capability and a large velocity range on variable ground. Rolking of WorkPartner is studied in detail because the rolking of this robot is the most terrain adaptive.

Figure 2.7 The WorkPartner-service robot.

Rolking of WorkPartner works like the following. Consider a normal walking sequence. When a leg is in the supporting state, the propulsive force is generating by the leg joints. When the leg is in the transferring phase, it is not lifted in the air, but lightened and moved along the ground by touching it all the time, while applying a slight forward moment to the wheel. This is illustrated in Figure 2.8 where, in part a), a normal step is taken and, in part b), a rolking step is taken. All the joints are thus controlled actively all the time. In the transferring phase, it is possible to 'feel' the shapes of the ground and detect obstacles by measuring the actuator currents and the joint angles. The robot can then move on an uneven terrain by "probing" it like a blind animal.

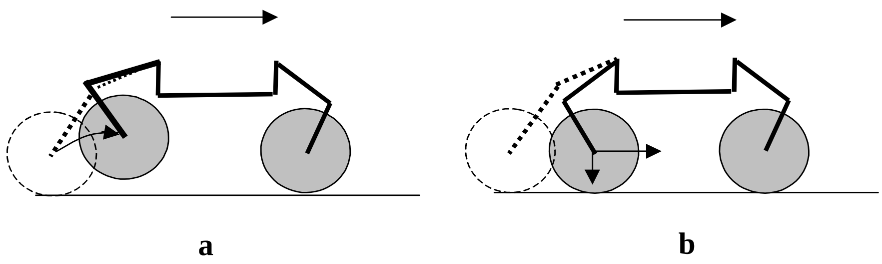


Figure 2.8 Walking vs. rolking.

On a very soft terrain, where wheeled locomotion is difficult or impossible, it has been experimentally observed that rolking motion can improve mobility considerably. This is because of the driving wheel pull is much less than the pull produced by the locked wheel [Bekker, 1969].

Other benefits of the rolking mode compared to normal walking are better speed, stability and weight distribution of the platform. The leg can be moved to supporting phase instantly if needed, which improves reaction responses. Speed is improved because there is no time wasted when lifting or lowering the leg in the walking cycle. Stability will not be easily lost and the weight distribution is more equally divided because the transferring leg supports itself when moving. Standard gait algorithms can also be used. When the gait algorithm commands a transferring leg to the supporting phase, it can be achieved instantly because the leg is already on the ground. This is very effective, especially when free gait algorithms are used, which seems to be the natural choice in this case. In principle, changing between the different locomotion modes is very simple and, in fact, the same program controls them all by only using different parameters. In hybrid motion, the wheel can accelerate the leg in the recovery phase and the acceleration can take place a moment or two before the leg is totally switched to lifting phase. At the end of the recovery phase, deceleration can occur much more slowly due to the rolling wheel, i.e. the foot speed is not zero in relation to the ground. Thus switching between support and recovery phase occurs smoothly.

The only disadvantage of the rolking mode compared to normal walking is that the legs can only be moved in the same direction as that in which the wheels are rolling. The motion direction must be thus controlled as in the wheeled mode. In the case of WorkPartner, steering is performed by using the articulated body.

The WorkPartner-type locomotion system can also be used as a sensor system to measure characteristics of terrain and wheel-soil interaction. Furthermore, an additional feature, active suspension in wheeled locomotion has come along. The wheel-legged robot can divide the load to the wheels equally by producing the desired support force with the leg, which improves locomotion capability on rough terrain compared to the vehicle that has the conventional passive wheel suspension system.

2.2 Control of mobile robot locomotion

A mobile robot requires a sophisticated motion control system in order to locomote cross-country. The motion subsystem consists of the mechatronic locomotion system, which includes the actuating system. The motion control subsystem, which can be referred to as the *piloting system*, controls the motion of the robot. Of course, the robot motion control should utilize sensing information coming from the robot's perception system. Overall motion planning takes place in the motion- and action-planning subsystem, with the help of a navigation subsystem.

The locomotion control of a wheeled robot focuses on the velocity and direction control of the robot, which means velocity control of the wheels and steering angle control of the wheels. The direction control of an articulated wheeled robot is based on the centre pivot steering. Direction control of a tracked robot is carried out by skid control that is controlling the velocity difference between left and right side wheels. In automotive manufacturing, automatic safety features that are based on independent active control of the wheels, like ABS (Antilock Breaking System), ESP (Electronic Stability Program) and TCS (Traction Control Systems) have already been in cross production. ABS, also known as anti-skid brakes, monitors the speed of the wheels and regulates the hydraulic pressure of the brakes accordingly. The aim is to maximize braking power while preventing the wheels from locking and skidding. ESP uses inertial sensors to determine when the car is about to go out of control and can apply individual braking to a wheel to help avoid spinning. ESP will not totally prevent spin, but helps prevent total loss of control. TCS senses differences between the speed of the wheels and determines the slipping wheel or wheels. The brake of the wheel is applied if the wheel begins to slip due to too much power for the grip. These kinds of separate safety automatic features are destined to help the vehicle ride in dynamic situations.

The motion control system of the walking robot is much more complex than the pure velocity and direction control of the wheeled robot. It should take care of the coordinated control of all dofs in real time. It can be divided into the following subsystems:

- Terrain adaptability control
- Attitude and altitude control
- Steering control
- Gait control
- Transfer leg control

A comprehensive study of the subject of controlling a legged robot can be found in [Hartikainen, 1996].

In the rolking motion, the main functions of the overall control system are almost the same as in classical walking. Some new features are, however, needed. The rolking mode could be understood as walking without lifting the legs, but lightening and driving them in the transfer phase. This means that the same types of control strategies as applied in walking can be used in rolking. The gating algorithm, like wave-gate or free-gait algorithms [Salmi and Halme, 1996], can be copied from classical walking.

In traditional walking algorithms, first, the leg that can be lifted to begin the transfer phase is chosen. In rolking mode, this part of the algorithm is similar. Next, the new supporting position where the leg is to be transferred is calculated according to the speed and direction of the machine and the form of the ground. This is also the same in rolking mode.

In the walking algorithms, next the transfer path, which includes the height and shape of the path and the speed of the leg, is planned. This part differs the most in rolking mode. In rolking mode, the shape and the height of the transfer path varies with the ground unevenness and the speed of the transfer leg is calculated according to the speed of the machine. The load of the machine is divided more to the support legs so that the transfer leg wheel moves easily along the ground.

Very little has been written concerning the automatic switching of locomotion modes, i.e. the robot vehicle selects the proper locomotion mode, depending on terrain properties. A reference where this problem has been mentioned is [RST Raumfahrt Systemtechnik AG, 1994], which is a study of Russian locomotion concept analysis for moon exploration performed by Russian and European space engineers. According to this study, Russian space robotics scientists faced this problem in the wheel-walking Moon Rover development; they proposed three solutions with different degrees of automation.

- Mechanics-only solutions
- Pre-programmed solutions
- Autonomous feedback solutions

In the mechanics-only solution, a wheel or a frame is moved by a single motor or a transmission in a mechanically defined way, once this mode of operation (crawling mode, walking mode, etc.) has been switched on. In the pre-programmed solutions, the movement of the frame parts or the wheels can be programmed and executed. The autonomous feedback solutions are based on sensor information and automatic locomotion switching. The degree and the character of movement of frame parts or wheels are controlled autonomously based on feedback from onboard sensors that measure the terrain and soil characteristics. For example, when an obstacle of over-passable size is detected in front of the Rover or when the wheel slippage supersedes a certain value, the LMS (Locomotion System) automatically switches into a dedicated crawling or walking mode. This kind of autonomous solution has not been realized so far; the locomotion mode switching of the Russian space rovers is based on mechanics or pre-programmed solutions.

Another reference where the automatic locomotion mode control has been mentioned is [Ben Amar et al., 2004], which presented the previously mentioned Hylos wheel-legged robot, which has worm-type locomotion mode called *grawling symmetric gait* and also rolling mode. In this reference, they proposed the automatic switching of locomotion mode, which will be based on stereovision and texture analysis, but no reference about implementation was found.

2.3 Mechanics of vehicle-terrain interaction - terramechanics

The locomotion performance of a robot or an all-terrain vehicle depends both on the trafficability of the terrain and on the mobility of the vehicle. The trafficability of terrain is composed of several terrain and soil factors. Terrain can be described by the occurrence of obstacles and the slope gradient or by the terrain profile. The terrain profile is often divided into microprofile, which is relative to the scale of the wheel, and macroprofile, which is relative to the size of the vehicle. Soil factors are used to describe the soil reactions under the wheel load. Typical soil factors widely used are the deformation and compressibility of the soil under pressure and the reactions of soil particles to the horizontal forces, e.g. shear strength or soil strength. The deformation and compressibility of the soil represent the bearing capacity of the soil. The shear strength of the soil represents the traction performance of the wheel.

The mobility of a land vehicle depends on the vehicle dimensions, locomotion principles (walking, wheeled, tracked) and wheel/track/foot characteristics. Mobility in the broad sense refers to the performance of the vehicle in relation to soft terrain, obstacle negotiation and avoidance and ride quality over rough terrain. The study of the performance of an off-road vehicle in relation to its operating environment (the terrain) has now become known as *"terramechanics"* – mechanics of vehicle-terrain interaction [Bekker, 1956], [Bekker, 1969], [Wong, 2001]. The modelling of the vehicle-terrain interaction can be done at two levels: wheel-soil interaction and vehicle-terrain interaction. The aim of terramechanics is to provide a technological base upon which the design and performance of off-road vehicles may be improved.

2.3.1 Methods for modelling wheel-soil interaction

Off-road vehicle performance analysis is a three-dimensional, nonlinear and dynamic problem. Different types of wheel-soil or machine-terrain models have been developed for predicting the performance of the wheel or the vehicle. The simplest approaches are based on empirical 'black box' models developed from empirical data describing the wheel performance in given conditions. These kinds of models are suitable only in the wheel and soil conditions, for which data have been collected, and cannot be extrapolated into other condition types. More general methods for wheel-soil interactions are WES-method [Knight and Rula, 1961], Bekker-method [Bekker, 1969], and the mathematical method based on plasticity theory [Karafiath and Nowatzki, 1978]. Figure 2.9 schematically illustrates these three methods, modified from [Karafiath, 1971].

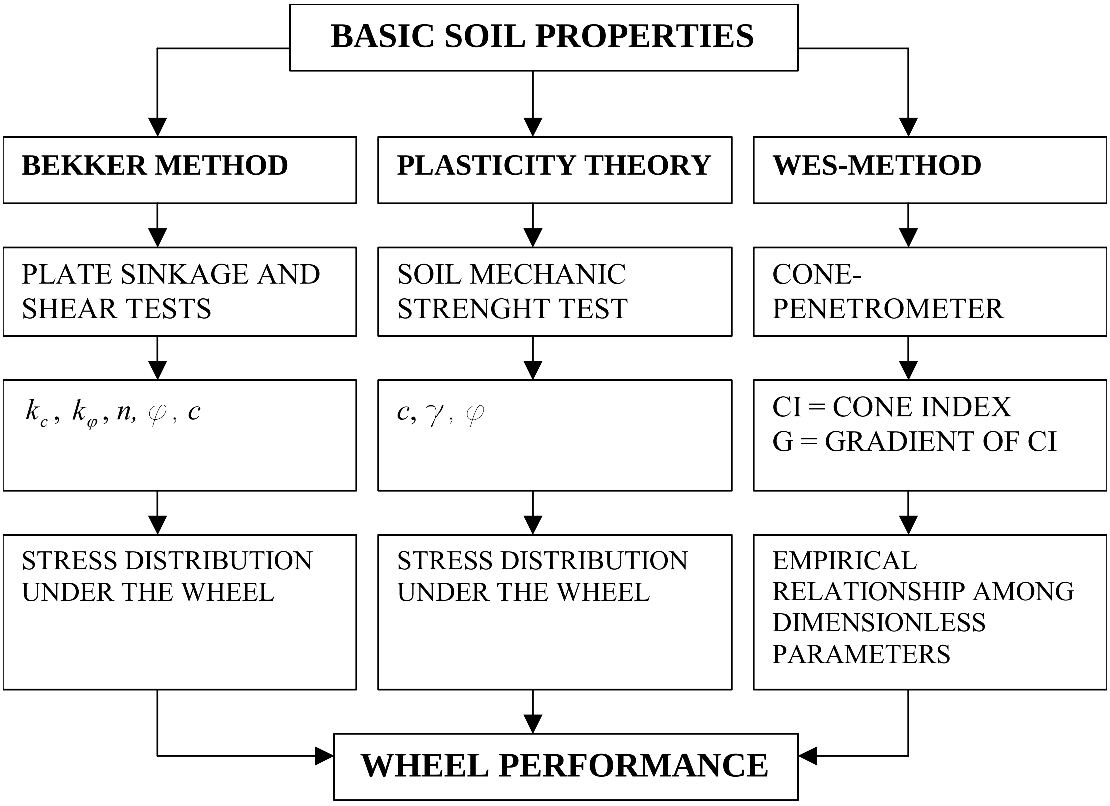


Figure 2.9 Schemes of various approaches to the problem of wheel performance, modified from [Karafiath, 1971]. The soil constants of Bekker method are soil cohesive deformation modulus (k_c), soil frictional deformation modulus (k_φ), and soil deformation exponent (n). Soil mechanical strength parameters are soil cohesion (c), internal friction angle (φ) and weight (γ).

The WES-method on the right side of Figure 2.9 is a semiempirical method based on the use of a penetrometer to evaluate the trafficability of soils, originally developed by the US Army Corps of Engineering research centre, Waterways Experiment Station [Knight and Rula, 1961]. The soil parameter is the penetration resistance of the soil measured using a standard cone and procedure. The soil-bearing capacity is coupled directly to soil penetration. The force per unit cone base area is called the Cone Index (CI). Vehicle performance is then empirically correlated with the cone index or its derivates.

In the Bekker method [Bekker, 1969], the soil parameters are calculated from plate sinkage test results. A vehicle exerts normal and shear loads on the terrain surface. To simulate these, the original bevameter technique comprises two separate sets of tests. One is a set of penetration tests and the other is a set of shear tests. This method uses the concept of sinkage as a description of soil bearing capacity. The soil constants, deformation modulus, deformation exponent, cohesion and internal friction angle of soil can be determined from the load/sinkage and shear stress/shear displacement curves.

The mathematical method in the middle of Figure 2.10 is based on plasticity theory and on soil mechanical strength parameters. Karafiath and Nowatzki modelled soil deformation under the wheel based on theoretical soil mechanics using plasticity theory [Karafiath and Nowatzki, 1978]. They developed a two-dimensional finite difference model of tyre-terrain interaction that simulated the plastic soil deformation under the wheel. Fervers [Fervers, 1997] and [Fervers, 2004] presented a finite element model (FEM) that takes into account interference of vertical and horizontal soil deformation under the wheel. Shoop [Shoop, 2001] developed a three-dimensional finite element model of tyre-terrain interaction that can be used to explore the effects of tyre and terrain variables on vehicle mobility. Such a model can be used for vehicle performance and terrain-damage prediction.

The fundamental parameters commonly used to describe soil for engineering or agricultural purposes are soil type, structure, grain size distribution, moisture content and density. These and other physical properties of soils, as well as how they influence soil strength, are described in [Terzaghi, 1996] and [Karafiath and Nowatzki, 1978]. The strength of soil depends on these basic physical properties.

Each of these methods is based on identification of soil properties, which requires a lot of measurement about soil. In the field, soil is quite often non-homogeneous, which decreases the reliability of soil identification. Vegetation, snow and ice layers also corrupt vehicle performance prediction based on soil mechanical strength parameters.

2.3.2 Modelling of vehicle-terrain interaction

There are two principal methods for modelling vehicle mobility. One is based on empirical correlations between vehicle performance measured in the field and the corresponding terrain conditions identified by simple devices, such as the cone penetrometer. The other is based on the detail analysis of the mechanics of vehicle-terrain interaction. One of the well-known empirical models in use is the NATO Reference Mobility Model (NRMM) [Lessem, 1996], which is the US Army's accredited mobility performance prediction model. NRMM was originally designated AMC-71, since the United States Army Corps of Engineers (USACE) developed it in the early 1970s for the United States Army Materiel Command (AMC). AMC-71 was proposed to NATO in 1978 as its standard mobility model. In 1992, the Tank Automotive Command (TACOM) and Waterways Experiment Station (WES) developed the NATO Reference Mobility Model II (NRMM II) [Birkel, 2003], [Shoop, 2005] to include enhanced mobility algorithms, a better organized modular structure and a more flexible user interface. NRMM II is a comprehensive computer model that predicts vehicle speed performance for operations on roads and cross-country in all weather conditions, including terrain conditions associated with winter, [Shoop, 2006]. The model primarily calculates available traction and motion resistance caused by operation on soft surfaces.

Computer-aided methods based on detailed analyses of the mechanics of vehicle-terrain interaction are playing an important role in the development of off-road vehicles. One of the typical computer simulation models is NWVPM for an off-road wheeled vehicle [Wong, 1994]. It has been developed for the evaluation of the overall performance and design of off-road wheeled vehicles. The NWVPM model takes into account all major design parameters of the vehicle as well as the tyre. The vehicle design parameters considered include vehicle weight, axle load, axle spacing, location of the centre of gravity, axle suspension stiffness, function of axle (driven or non-driven), axle clearance, track of the axle, hull shape and drawbar hitch location. The tyre parameters of the NWVPM model are outside diameter, tread width, section height, lug area/carcass area, lug height, lug width, inflation pressure, average ground contact pressure and tyre construction (radial or bias). Terrain characteristics, including the pressure-sinkage relation, shear strength, rubber-terrain shearing and hull-terrain shearing characteristics, and responses to repetitive normal and shear loadings, are taken into account in the model. The NWVPM model can be used for parametric analysis of the performance and design of off-road wheeled vehicles and also for the selection of tyres for a given operating environment.

To be useful to vehicle development, the simulation models must be comprehensive and realistic and should take into account all major vehicle design features as well as essential terrain characteristics.

Methods for modelling wheel-soil or vehicle-terrain interaction cannot be utilized directly in automatic locomotion mode control, because these methods are based on identification of soil properties, which requires a lot of measurement of soil characteristics beforehand. In addition, these modelling methods require too much computer processing power. The only realistic chance might be to use a cone penetrometer (WES-method) to differentiate a “go” or “not to go” situation in soft soil. If the robotic vehicle has a manipulator in the front of the body, like the WorkPartner robot, it could sense soil characteristics by probing with the penetrometer.

2.3.3 Sensing terrain parameters

3D perception technology is crucial for a mobile robot, which must execute autonomous piloting and navigation in an unstructured environment. To locomote in a correct way, i.e. to use the right locomotion mode, the robot should sense characteristics of the soil and geometry of terrain. This kind of information should be caught in real time in a demanding outdoor environment. There is a great need for sensors that can measure the geometry of terrain and also soil characteristics in a reliable way. The autonomous robots also need a good perception system for path planning.

3D perception technology has been studied in many walking research projects, because obstacle detection and finding suitable footholds are critical for walking machines. Two of typical examples are a terrain scanner of the Adaptive Suspension Vehicle [Pugh et al., 1990] and a binocular ranging system of the OSU Hexapod Vehicle [McGhee et al., 1984]. The terrain scanner of the ASV of the Ohio State University is a three-dimensional range finder using a mechanically scanned, modulated infrared laser as a light source. The terrain elevation map is updated in real time by the scanner data processor so that the ASV can detect obstacles and find suitable footholds. The foothold selection algorithm is quite simple: for a specified x-y location in the terrain map, the algorithm computes slopes from the specified cell to its neighbouring cells. If the computed slope for any pair exceeds a specified threshold, then the selected cell is not a suitable foothold. The indoor semiautomatic ranging system of the OSU Hexapod vehicle consists of two cameras and a handheld pointing laser. The operator of the OSU Hexapod points the desired foothold with the laser and 3D distance information is calculated based on triangulation. The Dante, i.e. the Mount Erebus exploring walking robot developed at Carnegie Mellon University [Wettergreen et al., 1993], has an automatic terrain ranging system. The terrain is sensed by a trinocular stereo system and a laser rangefinder. Nowadays, a lot of research effort is being put into the 3D-perception technology concerning the teleoperated or autonomous UGV (Unmanned Ground Vehicles) development. This type of robot is generally capable of operating outdoors and over a wide variety of terrain. A professional 3D perception system mostly based on laser techniques is essential for UGVs.

Using a vision system or laser-based technology, it is possible to get the geometry of terrain in good environment conditions, but when operating off-road there are a lot of features that dilute ranging reliability. Vegetation, trees, bush and even snow prevent scanning real terrain surfaces. Above all, with vision and a laser-based system, it is hard to discover soil characteristics. To get information about soil characteristics, sensing by touching is needed. Blind people probe the ground with their walking stick in a sophisticated way: they detect obstacles, determine the slope of the ground and even how slippery the ground surface is. Sinha [Sinha et al., 1993] studied the robotic exploration of surfaces with a compliant wrist sensor in manufacturing environments. Their compliant wrist device consists of a passive compliance mechanism with 6-dof compliance that is also capable of measuring the 6-dof deflections within the device. The developed exploratory procedures can recover the penetrability, compliance, and surface roughness characteristics of a surface in laboratory circumstances.

In some walking machines, the pressure sensors in the leg hydraulic system are used to sense the ground contact of the foot as in the ASV [Wong and Orin, 1988] and MECANT [Lehtinen, 1994]. The pressure peak of the leg actuator is detected and the motion control system switches the leg from recovery phase to support phase. The pressure sensor can be utilized for force control of the leg, too. The other way to measure forces acting in the leg is to put separate force sensors in the foot [Adachi et al., 1993], [Klein et al., 1983].

Iagnemma [Iagnemma et al., 2004] has studied online terrain parameter estimation for wheeled mobile robots with application to planetary rovers. They developed a linear least-squares estimator based on a simplified form of classical terramechanics equations for estimating cohesion and internal friction angles. In this method, it was assumed that the vertical load, torque, sinkage, angular speed, and linear speed of the wheel could be measured and estimated. This method can estimate parameters of three different terrain types with good accuracy in laboratory conditions. Results are good, because sinkage is measured with high accuracy using a special terrain characterization testbed. In off-road operations, reliable wheel sinkage sensing is quite hard. Iagnemma [Iagnemma et al., 2003] also studied a vision-based method for measuring wheel sinkage, which is estimated using a body-mounted camera. It is assumed that the wheel rim is visually distinct from the surrounding soil. Again, this kind of assumption is not valid for natural terrain, but it is more likely to be so in planetary exploration, where there is no vegetation.

Savela [Savela, 1998] studied vibration with an accelerometer fixed on the rear axle of a mobile vehicle. Vibration is used to separate different ground surfaces, such as asphalt, sand or gravel. The original source of the vibrations is wheel pattern, which produces cyclic acceleration when driving on hard soil. Savela concluded that the vibration based sensing method works well on hard surfaces, but in soft soil, tyre pattern sinks into the soil and cyclic acceleration is dampened. Brooks and Iagnemma [Brooks and Iagnemma, 2005] also examined vibration to classify terrain. Vibrations are measured using an accelerometer mounted on the rover structure. The classifier is trained using labelled vibration data during an off-line learning phase. They used linear discriminant analysis for on-line identification of terrain classes such as sand, gravel or clay.

The Cold Regions Research and Engineering Laboratory (CRREL) of the US Army has extensively tested and analyzed issues related to vehicle performance in winter [Shoop et al., 2006]. For studying tyre forces at surface interfaces, they have instrumented the Jeep Cherokee vehicle (CIV, CRREL Instrumented Vehicle) with a three-component load cell. When driving in the snow, motion resistance forces can be determined using 3D force measurements [Shoop, 2001].

Ojeda [Ojeda et al., 2005] analyzed terrain trafficability characterization with a mobile robot. They proposed a fully self-contained terrain characterization method for skid-steer mobile robots. In order to develop the classification method, a Pioneer 2-AT skid-steer mobile robot is instrumented with three gyros, accelerometers, and motor current sensors. In extensive tests, data on a variety of different terrains, such as gravel, sand, asphalt, grass and dirt, have been collected. Terrains are characterized by motor current vs. rate of turn curves, which are similar to the strain-stress curves used in terramechanics.

3 THE PROBLEM OF AUTOMATIC LOCOMOTION MODE CONTROL

3.1 Challenge of multifunctional locomotion system

A mobile platform that has a multifunctional locomotion system can move in different ways, driving with wheels, rolking or even walking. To utilize locomotion modes in a smart way, the control system should select the right locomotion mode depending on terrain properties. This study concentrates only on wheeled and rolking locomotion, because rolking offers almost the same advantages as walking, in contrast to wheeled, see Chapter 2.1.3.

Russian space robotics scientists faced this problem in the wheel-walking Moon Rover development [RST Raumfahrt Systemtechnik AG, 1994]. Their Moon Rover could drive with wheels and *wheel-walking*, as they called it. They proposed an autonomous feedback solution in which the Moon Rover should autonomously switch the walking mode based on feedback from onboard sensors characterising the terrain and soil. This kind of autonomous solution has not been realized so far.

There are similar features in the gear shifting of a car that has an automatic transmission. The controller of the automatic gearbox shifts smoothly according to the road slope and driver's demand, i.e. according to how hard the engine is working. Correct shifting is possible because it is possible to sense vehicle and engine speed as well as throttle position or manifold pressure accurately. Of course, engine characteristics are well known. An automatic gearbox downshifts when the driver presses the gas pedal to accelerate. It upshifts when vehicle speed has grown enough or the driver lightens the gas pedal.

The objective of this work is to develop methods for autonomous selection of the optimal mode, wheeled or rolking locomotion, depending on terrain properties, and verify their functioning. What is the optimal mode in a particular situation depends on the definition of the task that the robot is executing. Requirements for the task execution also affect the automatic locomotion mode control, so the control should select the mode that better fulfils these requirements. For example, if time is an important criterion in task execution, then the robot tries to move as fast as possible without taking into account other factors, such as environmental damages.

The differences of locomotion modes are analysed in order to determine essential factors affecting the locomotion mode control.

3.2 Driving with wheels versus rolking

Wheel-soil interaction under an active rotating wheel differs from foot-soil interaction under a pressing foot, especially in soft soil. It has been experimentally proved that it is possible to move in softer conditions more effectively by rolking than driving with wheels [Bogatschev et al., 2000] and [Halme et al., 2000]. The advantage of rolking compared to wheel locomotion in soft conditions or negotiating obstacles is based on the following factors:

- in soft conditions it is possible to achieve greater drawbar force by pulling with a locked wheel
- support legs achieve forward motion of the body without continuous soil compression, which means lower motion resistance
- the transfer leg wheel can roll to a better supporting position unloaded, therefore resisting the body motion only a little

Tests by Von Sybel [Von Sybel and Grosse-Scharman, 1961] have confirmed conclusions based on stress-strain analysis that the drawbar pull of a drive wheel is much less than the pull produced by a locked wheel. Figure 3.1 illustrates simplified ground deformation under both a drive wheel and a locked and pulled wheel. Ground pressure (*p*) is assumed to be equally distributed along the contact area (*l*). Soil deformation (*x*) in Figure 3.1 under the drive wheel increases linearly, while under the locked wheel it remains almost constant. This leads to different shearing stress (τ), which results in the lower pull of the driving wheel and the higher pull of the locked wheel.

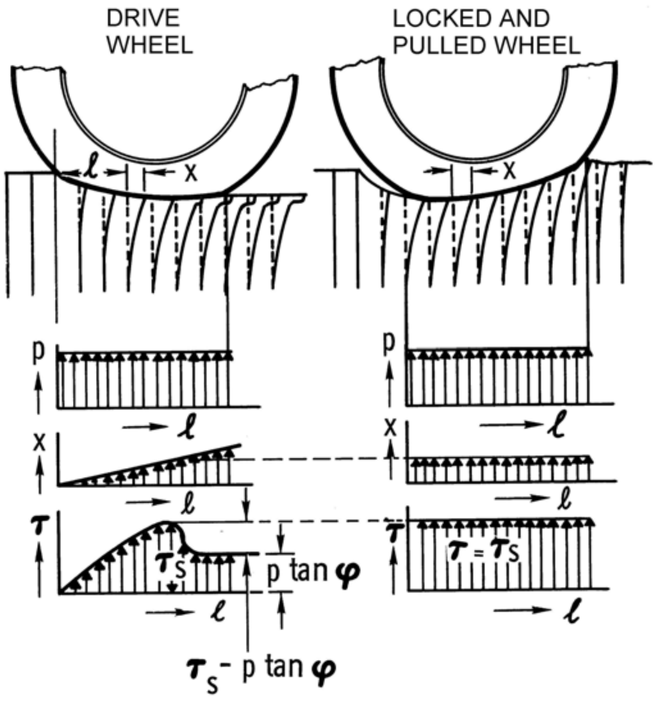


Figure 3.1 Stress-strain of drive and locked-pulled wheels. The ground pressure (p) and angle of soil internal friction (φ) are assumed constant along the contact area. Maximum shear stress (τ_s) depends on strength of soil. Soil deformation (x) increases from zero to maximum at the drive wheel and stays constant at the locked wheel. Shear stress (τ) is therefore different. Modified from [Von Sybel and Grosse-Scharman, 1961].

Shear stress under the drive wheel increases only to the maximum (τ_s), after that it decreases sharply because strength of soil is exceeded. In the case of the locked and pulled wheel, it is possible to strain the soil over the whole contact area with the maximum shear stress.

In rolking, the support legs achieve the body-forward motion without continuous soil compression, as happens in wheel rolling, which means lower motion resistance. Therefore, in soft soil, walking-type locomotion does not need to produce so much drawbar force as wheeled locomotion in order to overcome resistive forces. In soft and slippery conditions, the wheels may sink into soil so that the motion resistance is larger than the drawbar force. This means that a mobile robot is not able to move further with wheels. In this kind of situation, the robot can often move successfully by rolking, because the support legs achieve the body forward motion and the transfer leg's wheel can roll to a better supporting position and be unloaded at the same time. Thus, the better mobility of rolking mode, especially in soft soil or in negotiating obstacles, is based on these three factors.

On the other hand, wheels provide superior speed compared to rolking on hard ground. Figure 3.2 illustrates the preferable use of wheeled and rolking locomotion with respect to terrain trafficability and speed. In this figure, the terrain trafficability parameters are size and occurrence of vertical obstacles and also soil softness. These parameters describe terrain trafficability for wheeled locomotion best. If a robot has to move fast, faster than the maximum speed of rolking, it is clear that it tries to moves with wheels. In addition, wheeled locomotion consumes less energy compared to rolking on hard ground. Therefore, it is economic to drive with wheels in good conditions where the rolling resistance is low. But if soil softness or the occurrence of obstacles is high, rolking provides more mobility and the locomotion mode control should select rolking mode.

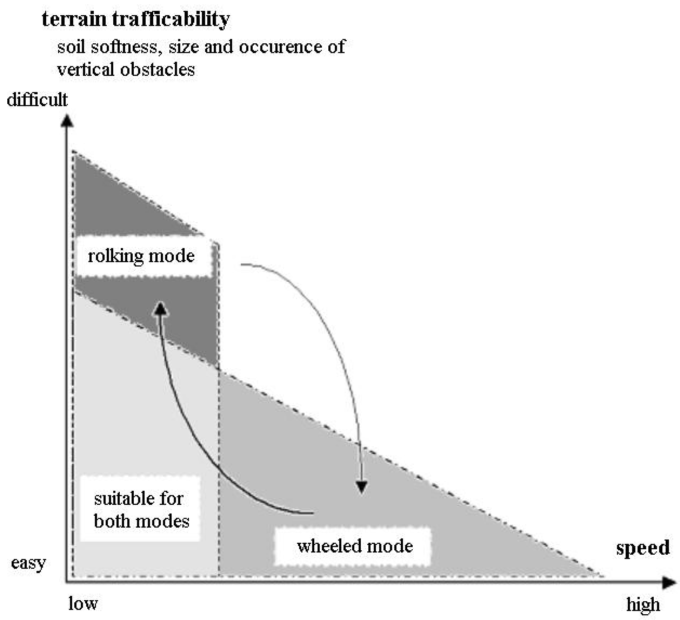


Figure 3.2 Scheme of terrain trafficability versus speed of locomotion in respect of locomotion mode. Terrain trafficability parameters are soil softness and occurrence of vertical obstacles.

There is not always a unique solution for the locomotion mode selection. What is optimal locomotion mode in a particular situation depends on the criteria used in the robot's task execution and the weight of each criterion. Typical criteria for the task execution of a robot are speed, energy consumption and avoidance of environmental damage. For example, if speed is important, a robot tries to drive with wheels as long as possible without considering soil disturbance. On the other hand, if environmental damages should be avoided, the robot should move in soft conditions by rolking, which does not excavate soil.

To determine the essential factors affecting locomotion mode control, vehicle-terrain interaction is analysed below.

3.3 Main characteristics of vehicle-terrain interaction

The locomotion performance of a robot operating off road depends both on the mobility of the vehicle and on the trafficability of the terrain. Mobility of the robot depends on the vehicle dimensions, locomotion principles (walking, wheeled, tracked) and wheel or foot characteristics. Trafficability of the terrain can be determined as the ability of terrain to support the passage of vehicles; it is composed of a set of terrain and soil factors. From the geological point of view, the soil is divided into three basic types: alluvial, moraine and organic soils [Karafiath, 1978]. This distribution is based on the origin and the structure of the soils. In terramechanics, the division is between frictional and cohesive soils, since the typical behaviour under the wheel or the foot load differs.

The function of the wheel is to carry the load and to produce the drawbar force. Keeping in mind this simple rule, it is quite easy to finish listing the main factors of vehicle-terrain interaction. These factors are bearing capacity of soil, traction performance of the wheel and geometry of terrain profile. In the following chapters, these three main characteristics of vehicle-terrain interaction are studied in detail.

3.3.1 Load-carrying capacity of soil

Soil factors, such as deformation and compressibility, are used to describe soil reactions under wheel load. The deformation and compressibility of soil represent the bearing capacity of soil. There are standard methods to measure deformation and compressibility of soil. The next two methods, WES and Bekker, are studied deeply in order to understand wheel-soil interaction. The penetration resistance (kPa) of soil measured by a standard device, the penetrometer, is quite often linked directly to the bearing capacity, as in the WES method [Knight and Rula, 1961]. The Cone Index of the WES-method, i.e. the force per unit cone base area (CI), can be considered as an indicator of bearing capacity. The penetrometer as can be seen in Figure 3.3 is composed of a steel rod fitted with a conical tip and devices to monitor the force and position of the cone. In the measuring procedure, the cone is pushed into the soil at constant velocity and the penetration resistance expressed in kPa is observed. In the WES-method, soil bearing capacity is coupled directly to soil penetration.

Figure 3.3 Cone penetrometer. The standard cone consists of a 30° circular cone with a half-square-inch base area equal to 322,6 mm².

In the Bekker method [Bekker, 1969], the soil parameters are calculated from plate sinkage test results. The bevameter technique has been originally developed by the U.S. Army Tank Automotive Command's Land Locomotion Laboratory. A wheel exerts normal and shear loads on the terrain surface. To simulate these, the original bevameter technique has two separate sets of tests. One is a set of penetration tests and the other is a set of shear tests. The set of penetration tests is coupled to the bearing capacity of soil. The soil constants, the soil deformation modulus (*k*) and soil deformation exponent (*n*), are determined from the load/sinkage curve. The sinkage is

$$z = kp^{1/n}, \qquad (3.1)$$

where

z	sinkage
k	soil deformation modulus
p	load
n	soil deformation exponent.

Because the diameter (*b*) of the plate influences the load/sinkage relation, Bekker adopted the cohesion (k_c) and friction (k_φ) components into the basic sinkage model

$$k = \frac{k_c}{b} + k_\varphi \quad , \qquad (3.2)$$

where

k	soil deformation modulus
k_c	cohesive modulus of soil deformation
k_φ	frictional modulus of soil deformation
b	diameter of the plate.

The cohesion component mainly depends on the soil cohesion that is affected by the soil clay content and moisture. The friction component depends on the compaction degree, particle diameter distribution and form.

Then the Bekker sinkage model is

$$z = \sqrt{\frac{p}{\frac{k_c}{b} + k_\varphi}} \quad , \qquad (3.3)$$

where z, p, k_c , k_φ and b are defined in the same way as that for Equations 3.2 and 3.3. Modelling of the cohesion and friction component requires a large number of standard plate tests before off-road operation, which decreases feasibility.

The bearing capacity of the soil means its capacity to resist the forces generated on it by a rolling wheel or a pressing foot. The locked wheel resembles the pushing foot. When the loaded wheel presses the soil and causes the vertical ground reaction force (F_v), the wheel sinks to certain depth (z), where the wheel load (L_W) and soil reactive forces are equal, as illustrated in Figure 3.4. Rolling resistance (F_{RR}), a force resisting the forward movement of the wheel, is mainly coming from the wheel sinkage. The rolling wheel compresses the soil, thus wasting energy. When the wheel sinkage is significant, a bulldozing resistance is also taken into account in the calculation of the total motion resistance of the wheel. It is important to notice that, in legged locomotion, the compaction of the soil only occurs under the foot in discrete footholds, thus reducing energy losses in soft terrain [Todd, 1985].

If the vehicle is moving at constant low speed, all the consumed energy is lost in compressing and bulldozing soil. Of course, some part of the consumed energy is lost for internal friction of the propulsion system. To compensate for the low bearing capacity of soil such as soft sand, swamp or snow a larger footprint area of a foot or a wheel is used. Footprint area can be grown by increasing the diameter and width of a wheel and using a less inflated rubber tyre. In extreme low bearing capacity soil, a tracked vehicle with a large soil contact area can travel successfully.

3.3.2 Traction performance of the wheel

Traction performance of the wheel is one of the main criteria in the analysis of the vehicle mobility. The drawbar force is needed for driving uphill or pulling a trailer, as well as for acceleration of the vehicle. In Figure 3.4, a simplified wheel-soil interaction model for soft soil is illustrated. When the wheel torque (T_W) generates a turning momentum along the wheel rim, it develops strain in the soil. The integration of longitudinal shear stresses over the entire contact path represents the tractive force (F_T). The traction force can be used to overcome the rolling resistance (F_{RR}) and to generate drawbar pull (F_{DP}). Drawbar pull is the difference between traction and motion resistance, and is the force that is available to pull or push an additional payload until the maximum available traction is reached. Hence drawbar pull is

$$F_{DP} = F_T - F_{RR} \ . \qquad (3.4)$$

In soft conditions, the maximum tractive force depends mainly on the shear strength (τ) of the soil when tyre pattern sinks into the soil. The shear strength of the soil represents the traction performance of the wheel.

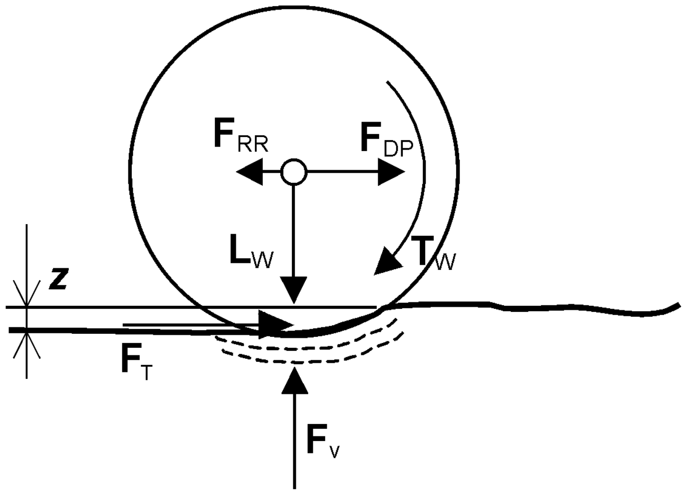


Figure 3.4 Simplified wheel-soil interaction model. The wheel under the load (L_W) sinks to certain depth (z) and causes the vertical ground reaction force (F_V). The wheel torque (T_W) generates shear stress in the contact area of the wheel. The integration of longitudinal shear stresses over the entire contact path represents the tractive force (F_T) that can be used to overcome the rolling resistance (F_{RR}) and to generate pull (F_{DP}).

The bevameter concept of Bekker also includes horizontal soil deformation [Bekker, 1969]. The definition of horizontal stress-strain relationship based on Coulomb's equation is:

$$\tau = c + p \tan \varphi \ , \qquad (3.5)$$

where

τ	shear stress
c	soil cohesion
p	pressure
φ	soil internal friction.

Shear stress τ is related to two soil parameters, cohesion (c) and friction (φ), through ground pressure (p) of the loading area. This means that the traction force of the wheel in pure cohesive soil, such as clay or snow, is

$$F_c = Ac \ , \qquad (3.6)$$

where

A	contact area
c	soil cohesion.

The traction force of the wheel acting on frictional soil like gravel depends on contact pressure and soil internal friction as follows

$$F_f = L_W \tan\varphi, \tag{3.7}$$

where

L_W load of the wheel or the foot
φ soil internal friction.

On hard surfaces, as on roads, the maximum tractive force depends on the friction forces between the wheel and the ground. The friction force between the rubber wheel and the hard road also depends on the wheel load and friction coefficient that can be divided into adhesion and the hysteresis friction coefficient. Now, the friction force of the wheel can be written as follows

$$F_{FR} = F_a + F_h = (\mu_a + \mu_h)L_W = \mu L_W \ , \tag{3.8}$$

where

F_a adhesion force
F_h hysteresis force
μ_a adhesion coefficient
μ_h hysteresis coefficient
μ friction coefficient
L_W wheel load.

In slippery conditions where the friction coefficient between the wheel and the soil is low, the wheel slips, and therefore the traction force is lower. In terramechanics, many studies of the relationship between traction and slip have been carried out. Concerning the rubber tyre, the maximum tractive effort of the wheel involves about 20 % slip [Wong, 2001]. With a larger slip percentage, the traction force is decreased, and therefore a lot of wheel slip should be avoided.

In order to increase grip between the wheel and terrain in slippery conditions, such as on ice, spiked tyres or tyre chains are often used. Then the traction force is dependent on the shear strength of the soil.

3.3.3 Geometry of terrain

In locomotion studies, the geometry of the terrain surface cannot be divorced from vehicle characteristics, because what is rough for a small vehicle, such as a small conventional car, may be smooth for a large off-road vehicle with large wheels. Therefore, the terrain topography is often divided to micro topography that is relative to the scale of a wheel and macro topography that is relative to the size of a vehicle. Micro topography can also be called terrain roughness. Macro topography can be described by variables such as the slope gradient or macroprofile. Terrain also consists of separate surface obstacles, vegetation and seasonal factors, such as ice and snow, which have a great affect on trafficability. *Step down*, *step up*, *ditch* and *embankment* are well-used terms to describe basic surface obstacles.

The ground slope has an effect on trafficability in two ways: the gravitational resistance (R_g) and the manoeuvrability of a wheeled vehicle are dependent on it. In the case of a robot driving up a slope, the gravitational resistance is:

$$R_g = mg \sin \theta_p \ , \tag{3.9}$$

where m mass of the vehicle
g acceleration due to gravity
θ_p a pitch angle of terrain slope.

This means that the propulsion system of the vehicle should produce force enough to overcome the gravitational resistance. Side slope decreases the manoeuvrability, which is the ability to change a robot's heading, avoid obstacles and navigate through cluttered environments. When driving on a side slope, the gravitational force invokes drift of the wheel.

Ground slope also worsens the stability of the vehicle, especially the stability of the classical wheeled vehicle that has no ability to move the centre of gravity to the direction of better stability. Driving on slope terrain, dynamic stability should also be taken into account in order to prevent roll over. In legged locomotion, active balancing is natural with the help of body inclination sensors and the real-time control of foot position.

When a wheeled robot is climbing an obstacle, an additional component of motion resistance is developed at the wheel/obstacle interface due to the change in the normal contact force. In terramechanics, this additional component of motion resistance is called "obstacle resistance". In fact, as the posture of the robot changes due to obstacle climbing, so does the weight distribution over the wheels. This is a similar situation to that of a robot climbing a slope, but in this case, the "grade" is determined by the angle between the line that connects the front/rear wheel contact points and ground level. In legged locomotion, obstacle resistance has a minor effect, because the legged vehicle adapts to the terrain variation by stepping over obstacles and no external vertical propulsion is needed.

Differences of wheeled and rolking mode when negotiating an obstacle that has a height more than the radius of the wheel are presented in Figure 3.5. In wheeled mode, when the wheel enters the obstacle it has to support the body against the gravity with the force (L_W) and to climb over the obstacle at the same time as illustrated at the top of this figure. The other wheels should provide the drawbar force (F_{DP}) needed to press the climbing wheel to the vertical obstacle. Without this extra force that presses the wheel firmly to the vertical obstacle, the wheel cannot climb up and the robot is not able to go forward. The normal force (F_N) of the climbing wheel is a sum of the drawbar forces (F_{DP}) of the other wheels. In rolking mode, the load is divided more to the support leg so that the transfer leg's wheel can drive up easily, as illustrated at the bottom of Figure 3.5. Then the needed drawbar pull of the robot produced by pulling the other locked wheels with the horizontal leg force (F_{x_leg}) is small and the climbing wheel pushes the obstacle less.

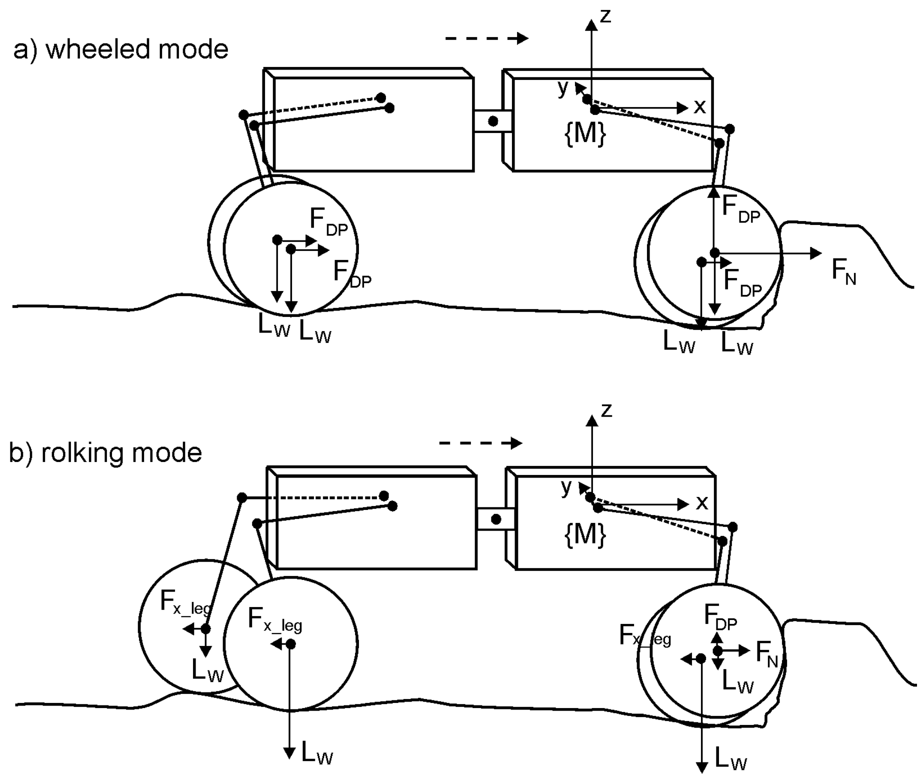


Figure 3.5 The front right wheel is climbing over the obstacle. a) In wheeled mode, the other wheels should provide drawbar force (F_{DP}) enough to press the climbing wheel firmly to the vertical obstacle in order to climb over the obstacle. b) In rolking mode, the load is divided more to the support leg so that the transfer leg's wheel can climb over the obstacle easily. Leg forces are determined in the robot's main coordinate system {M}.

Especially in planetary or moon research, the occurrence of obstacles, such as stones, is used to describe terrain trafficability, because there is no vegetation and the soil is not organic. On Earth, the soil variation is much greater, and quite often the rocky soil is covered with organic material like peat. The size scale and frequency of the obstacles are often used as obstacle parameters.

The seasonal factors, such as snow or ice, shape the terrain geometry and also affect soil strength. Permanent terrain features, such as rivers, lakes or high mountains, are further navigational parameters.

4 SENSING THE CHARACTERISTICS OF VEHICLE-TERRAIN INTERACTION AND TERRAIN FEATURES

A good perception system is important for a mobile robot that must execute autonomous piloting and navigation in an unstructured environment. Perception is also needed for the automatic locomotion mode control of the mobile robot.

Moving over natural terrain and measuring the soil parameters at the same time is complicated, because reliable sensing needs a lot of measurement with the standard device described in Chapter 2.3. Therefore, it is really more practical to sense directly the characteristics of vehicle-terrain interaction, such as traction or rolling resistance of the wheel, in order to switch locomotion mode correctly. This kind of sensing gives more reliable results and it automatically takes into consideration the parameter variation of the soil. For example, changes in moisture content of the soil dramatically affect the strength of the soil. Furthermore, in natural terrain, there are a lot of features that influence wheel-soil interaction. Vegetation, snow and ice layers between the wheel and the basic soil have a significant effect on the traction and rolling resistance of the wheel.

A key issue for automatic locomotion mode control is to sense characteristics of the vehicle-terrain interaction and terrain geometry parameters. In wheeled mode, characteristics of wheel-soil interaction can be used for evaluating how the wheel fulfils two basic requirements, i.e. those of carrying the load and producing drawbar pull. If the wheel cannot fulfil these requirements because terrain trafficability for the wheel is low, then it is time to change to rolking. In rolking mode, it is problematic to measure terrain trafficability for wheeled mode in order to switch wheeled mode on, because rolking strains soil in a way that is different from driving with wheels, as described in Chapter 3.2; rolking more resembles walking. However, it is possible to sense some characteristics of rolking, such as energy consumption, for predicting terrain trafficability for a wheel.

The locomotion system can be used as a sensor system to measure forces and torques affecting the wheel. Force and torque information are needed for sensing characteristics of wheel-soil interaction and rolking. How to measure these essential factors, as well as terrain geometry parameters, using the locomotion system as a sensor system is discussed in the following chapters. In this research, the main emphasis is on on-line measurement algorithms when the robot is moving almost all the time.

4.1 Sensing load-carrying capacity of soil using energy consumption

Sensing soil parameters directly by the robot's sensors is still a complicated problem, as described in Chapter 2.3.3. Wheel sinkage is a good characteristic to describe load-carrying capacity, but unfortunately it cannot be measured in a reliable way in a harsh environment. Iagnemma [Iagnemma et al., 2003] successfully studied a vision-based method for measuring wheel sinkage in laboratory circumstances. It should be mentioned that the professional cross-country driver estimates the load-carrying capacity of the soil by perceiving the wheel sinkage and texture of the ground surface by means of sight. The driver uses the engine's sound to estimate wheel sinkage, i.e. the more the wheel sinks, the more engine power is needed. The driver can also join perceived information to her or his experience in order to determine terrain trafficability.

The load carrying capacity of soil can be estimated indirectly by using the energy consumption of the wheel. When driving with constant speed, the used energy finally converts to deformation of soil and heating of the wheel. In very soft soil, the wheel also looses energy when bulldozing the ground.

The load-carrying capacity of soil can also be measured by separate active probing procedures, such as pressing the wheel into the soil and measuring pressing force and wheel sinkage, imitating standard soil-strength measuring procedures. For this kind of measuring procedure, the robot should stand still and the sinkage of the wheel should be measured accurately. It is better if the robot can drive all the time and sense soil softness without stopping for measuring.

The foot or wheel sinkage reflects soil strength in both wheeled and legged locomotion. Energy consumption of legged locomotion can be thus used to estimate softness of soil. The difference between legged and wheeled locomotion is that the foot does not bulldoze, which means lower energy consumption compared to the wheel in soft soil.

In a fully electrical actuating system, the torque of each wheel can be easily calculated using the current of the electric motor. The power of the wheel is derived from the torque and angular speed of the wheel. If the vehicle has mechanical power transmission, the torque of each wheel can be measured with a separate torque sensor installed in the axle. With hydraulic transmission, the power of the wheel can be calculated using hydraulic flow and pressure meters. The used energy should then be scaled to the travelled distance. In general, the total energy of the propulsion system can be used for acceleration of the robot or driving uphill or in some cases pulling, and, of course, some part of the energy is lost in wheel-soil interaction. To calculate the lost energy correctly, all these essential matters should considered. Ground slope can be derived from the robot attitude and the wheel positions relative to the robot body. In this study, the pitch angle of terrain slope (θ_p) is negative when driving up a slope as described later in Chapter 4.3.1. The longitudinal acceleration of the robot body can be measured by wheel speed and body inertial sensors. Hence the sum of all the wheels' lost energy in wheel-soil interaction per travelled distance, which can also be called *rolling resistance*, is

$$Q_{roll} = \frac{\sum_{j=1}^{n} E_j}{s} + mg\sin\theta_p - ma_x \ , \qquad (4.1)$$

where E_j energy of the wheel j
s travelled distance of the vehicle
m mass of the vehicle
g acceleration due to gravity
θ_p pitch angle of terrain slope
a_x longitudinal acceleration of the vehicle
n an amount of the wheel.

4.1.1 Energy consumption of rolking

The energy consumption of rolking represents the load-carrying capacity of soil, because the support wheel compresses soil more if soil strength is lower. The lost energy of rolking can be estimated using the sum of the energy of all joints and wheels per travelled distance, taking into account gravitation and longitudinal acceleration of the vehicle body at the same time, as follows

$$Q_{rolk} = \frac{\sum_{j=1}^{n} E_j}{s} + mg\sin\theta_p - ma_x \ , \qquad (4.2)$$

where E_j energy of a wheel or the leg joint j
s travelled distance of the vehicle
m weight of the vehicle
g acceleration due to gravity
θ_p pitch angle of terrain slope
a_x longitudinal acceleration of the vehicle
n amount of the wheels and the leg joints.

4.1.2 Motion resistance in static situations

In off-road operation, it can happen that an obstacle or obstacles force the vehicle to stop or the front wheels sink into the soil, thus preventing the vehicle from driving forward. Then the vehicle speed is zero and energy consumption per travelled distance cannot be determined. In this static situation, motion resistance can be estimated by using wheel torque as follows

$$Q_{static} = \sum_{j=1}^{n} \frac{T_j}{r_R} + mg\sin\theta_p \ , \qquad (4.3)$$

where T_j torque of the wheel j
r_R rolling radius of the wheel
m mass of the vehicle
g acceleration due to gravity
θ_p pitch angle of terrain slope.

When the vehicle speed is zero, then the static motion resistance can be used instead of the total lost energy per travelled distance.

4.1.3 Energy consumption of a single wheel in wheel-soil interaction

The wheel generates a drawbar force to the robot body in good conditions. In very soft terrain, a single wheel can produce a resisting force with respect to the body, although the wheel still consumes lot of energy in generating wheel torque. This happens especially when a single wheel sinks into the ground and bulldozes soil. If the pulling or resisting force of the wheel can be measured with the help of forces measurement in the suspension system of the wheel, and if the wheel power is known, it is possible to estimate the lost energy in each wheel-soil interaction. The energy that the wheel consumes in wheel-soil interaction per travelled distance is

$$Q_{roll\_w} = \frac{E_w}{s} - F_{DP} \ , \qquad (4.4)$$

where E_w energy of a wheel
s travelled distance of the vehicle
F_{DP} the drawbar pull of the wheel.

If the lost energy of a single wheel is growing too much, even though the other wheels are working with high energy efficiency, it is often useful to switch to rolking mode in order to prevent soil damages. The motion resistance of a single wheel can also be used to localise the problematic ground area under the vehicle, which enables more sophisticated locomotion mode control.

In a static situation, when the vehicle speed is zero, the motion resistance of a wheel can be estimated by using the wheel's torque as follows

$$Q_{static\_w} = \frac{T_W}{r_W} - F_{DP} \ , \qquad (4.5)$$

where T torque of the wheel
r_W rolling radius of the wheel
F_{DP} the drawbar pull of the wheel.

When vehicle speed is zero, the motion resistance can be used instead of the total lost energy of a single wheel in wheel-soil interaction per travelled distance.

4.1.4 Motion resistance of the transfer leg's wheel

In rolking mode, the transfer leg's wheel drives to the next support position unloaded. Then the transfer leg's wheel does not strain soil and the real load carrying capacity of soil remains unknown. However, with the unloaded driving wheel, it is possible to recognise very soft soil that resists the driving wheel. In addition, with the unloaded driving wheel, it is possible to sense terrain obstacles that also resist the wheel. In the transfer phase, the wheel is under speed control and the transfer leg moves the wheel to the next position. Thus, the motion resistance of the transfer leg's wheel is a sum of the wheel force generated by wheel torque and the leg pushing force as determined in Equation 4.5.

Motion resistance of the rolking leg's wheel in the transfer phase can be used as an indicator of terrain-surface properties. If the rolling resistance is low, it is time to try to continue with the wheels.

4.2 Sensing drawbar force of the wheel

Traction performance of the wheel is one of the main criteria in the analysis of the vehicle mobility. The wheel's tractive force is dependent on soil parameters, cohesion (c) and friction (φ) component, as determined in the Bekker's classical theory [Bekker, 1969]. If the drawbar pull produced by the wheel with respect to the robot's body can be measured directly, it describes wheel-soil interaction and there is no need to use a method based on soil parameters. The robot drives with speed (v) in Figure 4.1 and the wheel torque (T_W) generates the tractive force (F_T). If the motion resistance (F_{RR}) of the wheel is lower than the generated tractive force as in the case of the back wheel in this figure, the wheel pulls the robot's body. Otherwise, the wheel resists the robot. The drawbar force of the wheel is determined according to Equation 3.4 presented in Chapter 3.3.2. The pulling or resisting force (F_{DP}) generated by the wheel can be calculated using force measurement in the suspension system of the wheel. In the case of the wheeled leg, the force affecting in the fixing point of the body can be derived using the leg joint's torques (T_T, T_K). The ground vertical support force (F_V) affects the body through the leg with the force (F_z), as well as the drawbar force of the wheel with the force (F_x). The driving wheel generates the horizontal reactive force (F_H) in the ground.

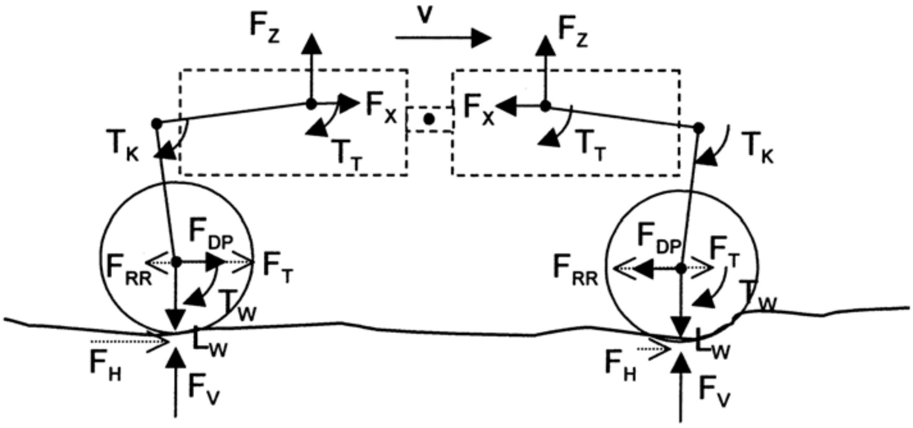


Figure 4.1 Forces and torques in the propulsion system of the wheel-legged robot. The front wheel is resisting the robot body although it is trying to generate drawbar force by the wheel torque. The back wheel is pushing the robot body forward because the wheel-soil interaction produces more drawbar force.

Terrain slope, terrain pitch (θ_p) and terrain roll (θ_r), should be taken into account in calculating the resisting force of the wheel. Terrain roll generates the sideways force (F_{y_leg}) in the leg, as illustrated in Figure 4.2a, and terrain pitch the longitudinal force (F_{x_leg}), as illustrated in Figure 4.2b. Thus, the resisting force originating from the wheel-soil interaction can be estimated

$$F_{resist} = F_{x\_leg} - \tan\theta_p \sqrt{F_{y\_leg}^{\;2} + F_{z\_leg}^{\;2}}\,, \qquad (4.6)$$

where
- F_{resist} the resisting force of wheel-soil interaction
- F_{x_leg} the x-component of the leg force in the robot main coordinate system {M}
- F_{y_leg} the y-component of the leg force in the robot main coordinate system {M}
- F_{z_leg} the z-component of the leg force in the robot main coordinate system {M}
- θ_p the terrain pitch.

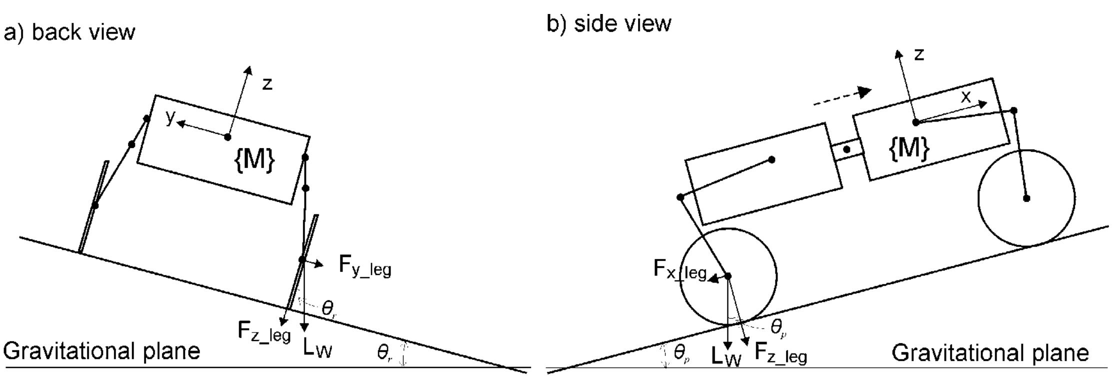


Figure 4.2 Leg forces when the robot is on a slope. a) Terrain roll (θr) and b) terrain pitch (θ_p).

Using direct force measurements, it is possible to sense how a wheel produces drawbar force for accelerating the robot, driving uphill or pulling something. If the single wheel resists the body motion a lot, i.e. the drawbar force measurement is negative, it may then be optimal to switch to rolking mode.

4.2.1 Slipping of the wheel

In slippery conditions where the friction coefficient between the wheel and the soil is low or the shear strength of the soil is limited, the wheel slips and therefore the traction force is lower. The longitudinal slip of the wheel, when a driving torque is applied, is usually defined by the equation

$$S = \left(\frac{r_R\omega - v}{r_R\omega}\right) * 100\%, \qquad (4.7)$$

where

S	slip
r_R	rolling radius
ω	angular velocity of the wheel
v	forward velocity of the vehicle.

When a driving torque is applied to the pneumatic tire, the speed calculated using the angular velocity of the wheel is higher than the speed of the vehicle and a positive value for slip results. If the wheel is rotating at a certain angular speed but the speed of the vehicle is zero, the slip will be 100% according to the Equation 4.7.

The alternative definition for slip is the ratio of the longitudinal slip velocity to the spin velocity of the straight free-rolling wheel (velocity of the vehicle) [SAE J670e, 1978]. Then slip is defined by

$$S' = \left(\frac{r_R\omega - v}{v}\right) * 100\%, \qquad (4.8)$$

where r_R, ω and v are defined in the same way as in Equation 4.7. Both the slip definitions are suitable for the automatic locomotion mode control; in this study the slip definition *S'* has been used.

The angular velocity of the wheel can be measured reliably by an encoder. For the automatic locomotion mode control, the speed of the vehicle can be estimated using the average of the wheel speeds so that the most slipping wheel is eliminated. But problems occur if all wheels slip at the same time. Then the velocity of the vehicle cannot be determined with pure wheel speed sensor information. In the four-wheel locomotion system, it is possible to use one wheel as a sensor wheel for estimating the vehicle speed. Then a sensor wheel rolls freely and measures vehicle speed and odometry. Unfortunately, the drawbar pull of this sensor wheel is lost, which can be critical in low frictional conditions. In very slippery conditions, vehicle inertia sensors with GPS (Global Positioning System) navigation are needed for estimating vehicle speed and odometry. The other way is to use a separate sensor wheel in bad conditions. A vision-based sensing method for estimating the speed of a vehicle is still under research, but might help in the future. It is good to notice that the professional cross-country driver estimates the slip by comparing the motor and vehicle speed. Motor speed is estimated by hearing, vehicle speed by sight.

Slip of the wheel can be utilized for changing the locomotion mode from wheeled mode to rolking mode.

4.3 Sensing the geometry of terrain

There are two basic principles that underlie the sensing of terrain geometry. The first sensing method is based on touching the ground and the second is based on contactless range measurements. With the contactless measuring system, it is possible to model the terrain along a greater distance than sensing by touching the ground. A terrain range scanner, based on laser or vision technology, is crucial for autonomous mobile robots, because the terrain information is needed for path planning and obstacle avoidance. In good conditions (without snow or vegetation), it is possible to use scanned terrain surface information for the automatic locomotion mode control. For example, a deep ditch probably means that the front wheel will lock and the only way to go on is walking or rolking.

The main emphasis in this research is put on sensing the geometry of the terrain surface by touching, because the actual terrain surface under snow or vegetation can be detected with the loaded wheel reliably. A negative aspect of the touching method is that it limits the robot's velocity, because it is possible to sense only terrain that is under the robot. Terrain slope and roughness are the main characteristics that express the geometry of terrain.

4.3.1 Sensing terrain slope

The terrain slope angles, terrain pitch (θ_p) and terrain roll (θ_r), express the inclination of the terrain according to the gravitational vector (g). Terrain slope can be derived from the robot's body inclination and wheel positions utilizing the robot coordinate systems that are shown in Figure 4.3. The main coordinate system of the robot marked {M} in this figure is fixed to the front robot body in the middle of the bases of the front legs, the x-axis pointing forward and the y-axis pointing sideways. The path coordinate system marked {P} in this figure describes the attitude of the vehicle with respect to the gravitational vector. The origin of the path coordinate system is the same as the origin of the main coordinate system. The terrain coordinate system marked {T} is fixed onto the estimated support plane so that the z-axis is parallel to the support plane normal, while intersecting the origin of the body frame. Now the x-axis points forward. The y-axis of the terrain coordinate system is formed according to the *right hand rule*. The path and terrain coordinate systems are fixed at every motion planning cycle.

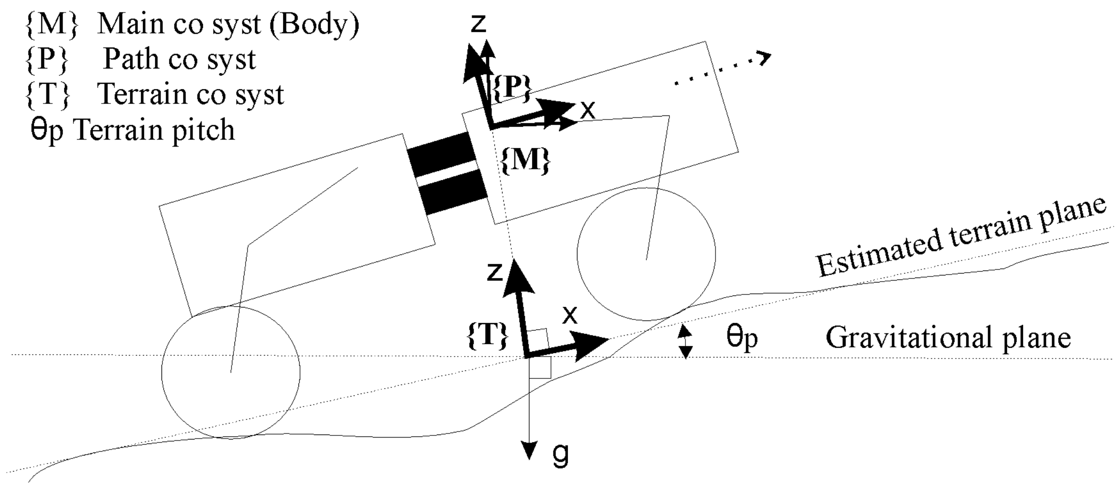


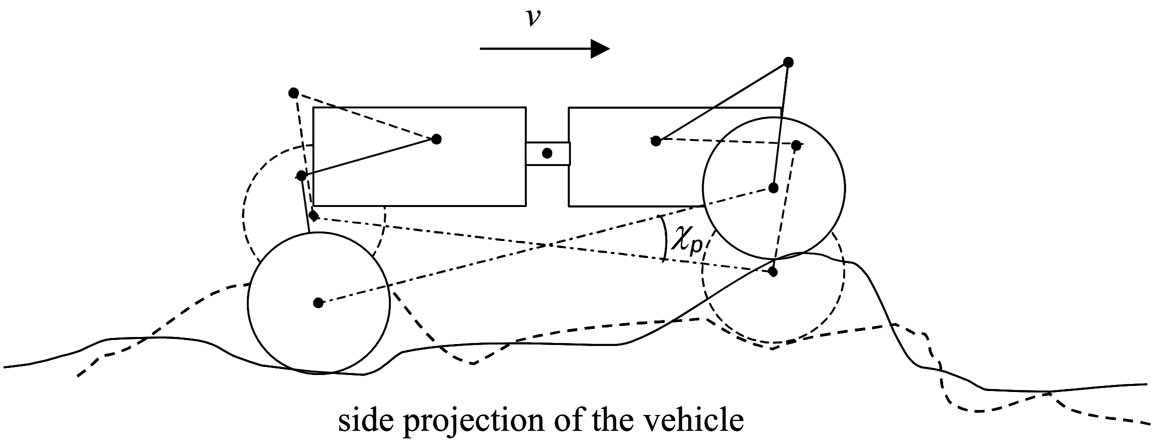
Figure 4.3 Relation of the coordinate systems of the wheel-legged robot and terrain pitch.

The estimated support plane is derived from the wheel positions in the main coordinate system. It can be obtained by using linear regression in fitting a plane into the set of the position coordinates. The pose of the main coordinate system with respect to the gravitational vector can be measured by inclination sensors. Using this information, the terrain pitch and roll angles with respect to the gravitational vector can be estimated. In this study, the terrain pitch angle is negative when driving up a slope.

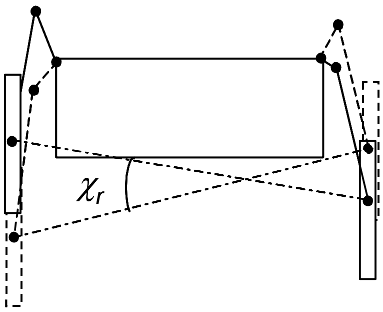
4.3.2 Sensing terrain roughness

There is no good and standard way to model terrain roughness, because natural terrain is composed of an unlimited number of features. Typical often-used separate features in modelling terrain are ditch, step, ramp or a separate obstacle with basic parameters, such as height and width. Modelling of the terrain with standard features can be achieved, but collecting enough geometrical information in real operating conditions can be very difficult. When driving at high speed, the vibration of the body informs of terrain surface roughness, but this kind of information is not good for locomotion mode control. It only tells about the ground surface pattern. In addition, soft soil dampens the vibration effectively. At low speed, the suspension system of the vehicle filters the unevenness of terrain.

The wheeled vehicle with a suspension system will align itself according to terrain. If the wheel positions with respect to the vehicle body are known, it is possible to use the sum of the wheel position distances to estimate the support plane as an indicator of terrain roughness. Because this terrain roughness indicator does not take the vehicle size into account, another way to estimate terrain roughness is proposed. This method is based on using the virtual axles that connect the wheel centres as illustrated in Figure 4.4. At the top of Figure 4.4 is a side projection of the vehicle with the virtual axles. The difference angle (χ) between the virtual axles represents terrain roughness. The same type of projection can be performed from the front of the vehicle, as shown at the bottom of Figure 4.4. The terrain roughness indicator (χ) is the sum of the two angles (χ_p, χ_r) between the virtual axles.



side projection of the vehicle



front projection of the vehicle

Figure 4.4 Terrain roughness indicator based on the virtual axles and their difference angles in the side and front projection.

This terrain roughness indicator takes the vehicle size, i.e. wheelbase and wheel distance, into account automatically. This indicator cannot be used as reliable information for changing the mode correctly, because it does not indicate vertical surface parts that are problematic for the wheel. On the other hand, if the value of this indicator is high, it is likely that terrain consists of more vertical surface parts that are problematic for the wheel and need more drawbar force. In wheeled mode, there is another limitation using this method for sensing terrain roughness: if the front or back wheels, or even all the wheels, encounter a hump (or ditch) at the same time, the value of this roughness indicator remains small although the terrain will be difficult for the wheel to negotiate. In rolking, this kind of limitation only exists when using a worm-type gait in which each pair of wheels in the frontal plane moves only when the other one is firmly braked to the ground.

5 A GENERIC METHOD FOR AUTOMATIC LOCOMOTION MODE CONTROL

The automatic locomotion mode control decides the proper locomotion mode under current terrain conditions. The optimal mode control should let the vehicle drive with wheels on flat and even ground and force the vehicle to rolk on terrain that is problematic for wheels, such as soft terrain or when negotiating obstacles. When the difficult terrain is behind the vehicle, the mode control should switch back to wheeled mode.

The proposed automatic locomotion mode control is based on a sensing method that evaluates the functioning of the wheels in wheeled mode and terrain trafficability in rolking mode. This approach has been selected because it is practical and reliable in sensing the characteristics of the vehicle-terrain interaction directly, such as traction or rolling resistance of the wheel, using the locomotion system as a sensor system. In wheeled mode, it is possible to correctly decide the right moment for mode change by sensing the functioning of the wheels, but in rolking mode, the decision is more problematic, because rolking strains soil differently from driving with wheels. However, it is possible to sense some characteristics of rolking, such as energy consumption of rolking or motion resistance of the transfer leg’s wheel, for predicting terrain trafficability for a wheel.

The characteristics of vehicle-terrain interaction can be used as ***criteria*** for indicating the functioning of a wheel in wheeled mode and terrain trafficability in rolking mode. These criteria are used to determine if a mode change is required. The criteria can be used one by one, which actually means that a single criterion invokes the mode change when its value is over a predetermined threshold during a predetermined time window. The other way to evaluate the right moment for mode change is to use a ***sum of criteria,*** as described in detail in Chapter 5.4. The values of several criteria should be over the predetermined thresholds at the same time in order to invoke the mode change in this method.

5.1 Criteria for locomotion mode control

The criteria for the locomotion mode control are selected on the basis of terramechanics. Different criteria are mainly used in wheeled mode and rolking mode, because the modes differ with respect to vehicle-terrain interaction. The terrain roughness criterion is only used in both locomotion modes as described in the following chapters.

5.1.1 Criteria of wheeled mode

In wheeled mode, the criteria indicate the functioning of a wheel, i.e. how a wheel fulfils two basic requirements: carrying the load and producing drawbar pull. This kind of information can be reached by sensing energy consumption, slipping and drawbar force of a wheel utilizing the locomotion system as a sensor system as described in Chapter 4. The functioning of a wheel decreases when energy consumption or slipping increases, or drawbar pull decreases. Using these basic principles, the criteria for wheeled mode have been selected and collected in Table 5.1.

Table 5.1 Criteria for locomotion mode control.

WHEELED	**MODE CRITERIA**		
Criteria	**Description**	**Sensor information**	**Unit**
C_{roll}, $v \neq 0$	Energy consumption of the wheels per travelled distance	Wheel power, vehicle speed, odometry, terrain pitch	J/m
C_{static}, $v=0$	Static motion resistance when the vehicle speed is zero	Torque of the wheels, terrain pitch	N
C_{roll_w} for each wheel, $v \neq 0$	Energy consumption of a single wheel per travelled distance	Wheel power, odometry, the force in the wheel hub	J/m
C_{static_w} for each wheel, $v=0$	Static motion resistance of a wheel when the vehicle speed is zero	Torque of the wheel, the force in the wheel hub	N
C_{resist} for each wheel	Resisting force of the wheel	Force in the wheel hub, terrain pitch, active braking torque of the wheel	N
C_S for each wheel	Slipping of the wheel	Wheel speed, the vehicle speed	%
C_χ	Terrain roughness	Position of the wheels in the body coordinate system	°
ROLKING	**MODE CRITERIA**		
Criteria	**Description**	**Sensor information**	**Unit**
C_{rolk}	Energy consumption of the leg joints and the wheels per travelled distance	Wheel power, torque of the leg joints, odometry, terrain pitch	J/m
$C_{transfer}$ for each transfer leg's wheel	Motion resistance of a transfer leg's wheel	Torque of the wheel, the force in the wheel hub	N
C_χ	Terrain roughness	Position of the wheels in the body coordinate system	°

A purpose of using several criteria is to cover all the problematic situations that a robot enters in off-road operations. Detailed description of the sensing algorithms of the criteria can be found in Chapter 4.

The first wheeled-mode criterion in Table 5.1, the sum of the lost energy of all the wheels in wheel-soil interaction per travelled distance (C_{roll}), can be used as a criterion to switch the locomotion mode from wheeled mode to the more nature-friendly rolking mode in soft soil. When the energy consumption is growing too high, it is time to continue with rolking. The threshold value depends on the definition of the task that the robot is fulfilling. When the vehicle speed is zero, the energy consumption per travelled distance cannot be determined, but the second criterion in Table 5.1, the static motion resistance (C_{static}), can be used instead. The unit of energy consumption is *J/m,* which is actually same as *N*.

The following four criteria in Table 5.1, energy consumption of a single wheel per travelled distance (C_{roll_w}), static motion resistance of the wheel (C_{static_w}), resisting force of wheel-soil interaction (C_{resist}) and slipping of the wheel (C_S) are calculated for each wheel. In static situations, when the vehicle speed is zero, the energy consumption per travelled distance cannot be determined, but static motion resistance of the wheel can be used instead. The resisting force of the wheel criterion indicates especially vertical obstacles that the wheel may encounter. When a wheel collides with a vertical obstacle, such as a step or stone, it resists body motion and may force the robot to stop. The slipping of a wheel indicates low frictional ground, where rolking might produce more drawbar pull.

The last wheeled-mode criterion, terrain roughness (C_χ), represents terrain geometry information. This criterion partly predicts terrain trafficability, but does not indicate vertical obstacles, which are the most problematic for a wheel. However, if terrain roughness is large, then it is more likely that vertical obstacles exist and need more drawbar force. On the other hand, the wheels often start to slip in rough terrain, which is sensed by the slipping criterion.

The terrain slope information is not used as a criterion for locomotion mode control, but it has been used indirectly to estimate the energy needed to drive uphill. This is because in high frictional conditions, the wheel can produce a large drawbar force and the robot can drive up a steep hill successfully. If the wheel looses grip in driving uphill, it starts to spin and the drawbar force decreases, which can be detected by sensing drawbar force or slipping of the wheel.

5.1.2 Criteria of rolking

In rolking mode, the criteria should predict terrain trafficability for wheeled locomotion reliably in order to change to wheeled mode correctly. This is more problematic, because rolking strains the soil differently from driving with wheels. Therefore, in rolking mode it is difficult to sense terrain and predict how a wheel will work. However, there are some characteristics of rolking that indicate terrain trafficability, and that can be used as criteria to change to wheeled mode. These criteria are presented at the bottom of Table 5.1. The first rolking mode criterion in this table, energy consumption of rolking per travelled distance (C_{rolk}), indicates soil softness and also terrain roughness. The motion resistance of a transfer leg's wheel ($C_{transfer}$) can also be used for indicating soil softness and obstacles in rolking mode. This criterion is only used for a transfer leg's wheel that rolls to the next supporting position. The last rolking mode criterion in Table 5.1, terrain roughness (C_{χ}), predicts partly terrain trafficability as described in the previous chapter.

5.2 Structure of automatic locomotion mode control

The overall control diagram of the proposed automatic locomotion mode control is presented in Figure 5.1. The inner loop controls the locomotion, i.e. walking, rolking or driving with wheels. It uses information as to the internal state of the robot for locomotion control. The external loop controls locomotion mode. The inputs of the locomotion mode control are the sensor signals that are also used for the locomotion control, whereas the output of the mode control is a simple state change. So, minimal or no additional sensors are needed. Because a robot moving on uneven terrain involves a very dynamic process, the sensor information should be filtered. In this study, the main emphasis has been put on utilizing the sensors for observing the internal state of the robot, because perceiving terrain with range sensors or a vision system is troublesome in bad conditions. Terrain geometry information is mainly used in the locomotion mode control in an indirect way.

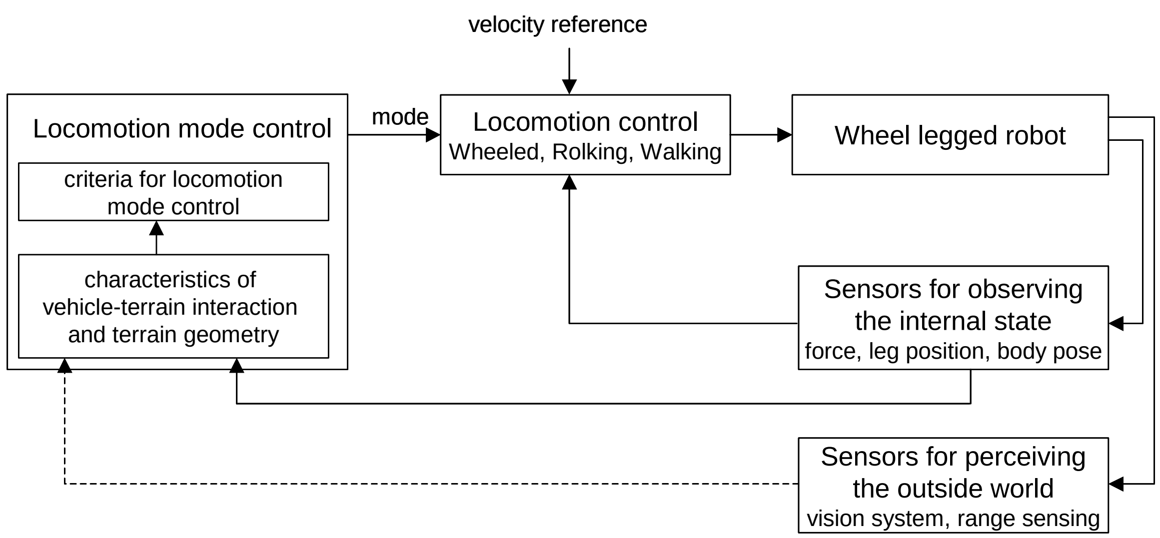


Figure 5.1 Overall control structure of locomotion mode control.

The proposed automatic locomotion mode control works as follows. The locomotion mode control block calculates the criteria by utilizing sensors for observing the internal state. Then the decision when it is time to drive with wheels or to rolk is made using the selected criteria. After that, the locomotion control takes care of the switching. In wheeled mode, the robot is allowed to change right back to rolking mode without moving further, because the terrain might be too difficult for wheels. In rolking mode, the robot has to move at least one rolking cycle in order to collect enough terrain information.

The proposed automatic locomotion mode control does not do path planning or obstacle avoidance, although the selected criteria can also be utilized in these planning processes. The sensors for observing the outside world as well as the results of wheel-soil interaction analysis can also be used for soil-property analysis, which is another research subject.

5.3 Automatic locomotion mode control based on individual criteria

The simplest solution for automatic locomotion mode control is based on using criteria individually, which actually means that a single criterion may invoke the mode change. This means that every criterion should indicate the need for mode change in a reliable way, so that the mode is changed when really needed, but not changed unnecessarily. When driving with wheels, each criterion indicates some problematic terrain conditions. The criteria used in rolking should also work in the same way. If the robot changes too early to wheeled mode, it cannot move forward, and then it has to change back to rolking mode.

The mode changing from wheeled mode to rolking and from rolking to wheeled are separate logic deductions, and are described in the following chapters.

5.3.1 Changing from wheeled to rolking mode

In wheeled mode, the automatic locomotion mode control based on individual criteria can be formulated as follows:

> for each $i = 1 \ldots m$, if any $C_i \geq L_i$ for a time t_i, then change mode to rolking, otherwise keep wheeled mode,

where C_i the wheeled-mode criterion i
L_i the threshold value of the criterion i
m the number of wheeled-mode criteria used
t_i the time window of the criterion i.

A time window is needed for preventing unnecessary mode change. A robot driving with wheels on rough terrain involves a very dynamic process, which also affects values of criteria. Values of criteria may briefly exceed thresholds at times and lead to unnecessary mode change. Therefore, values of criteria should keep over a certain threshold a certain time before mode change is allowed, as illustrated in Figure 5.2. The size of the time window depends on the dynamics and mechanics of the robot, and must be determined experimentally.

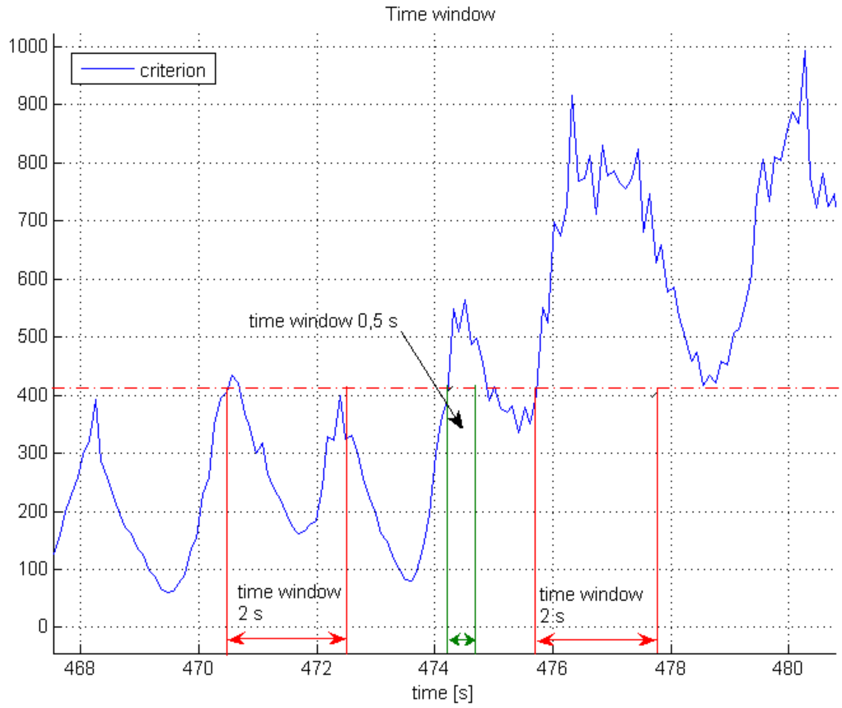


Figure 5.2 Use of time window. Value of a criterion should keep over a threshold for a certain time before mode change is allowed. The time window 2 s does not invoke the mode change at time 472,5 seconds, but later at time 477,7 seconds. If a shorter time window, like 0,5 s, is used, then the mode change occurs at time 475 seconds.

The threshold values (L_i) of the criteria are determined beforehand according to optimisation motives for locomotion of the robot. This is described in detail later in Chapter 5.5. Hysteresis of threshold is needed only if the same criterion is used in the both mode changes, changing to rolking mode and back.

5.3.2 Changing from rolking to wheeled mode

Instead of using a time window, it is reasonable to use a travelled distance window in rolking, because the robot has to collect enough terrain information. Values of rolking criteria should keep below a threshold for a certain travelled distance before mode change is allowed.

Thus, in rolking mode, the automatic mode control based on individual criteria can be formulated as follows:

for each $j = 1 \ldots n$, if any $C_j \le L_j$ for a travelled distance s_j, then change mode, otherwise keep rolking mode,

where C_j the rolking mode criterion j
L_j the threshold value of the criterion j
n the number of rolking mode criteria used
s_j the travelled distance window of the criterion j.

A practical travelled distance (s_j) is one rolking cycle, during which all the legs have performed the transfer phase and therefore collected terrain information.

The threshold values (L_j) of the criteria are determined beforehand according to optimisation motives for locomotion of the robot. This is described in detail later in Chapter 5.5.

5.3.3 Utilizing wheeled-mode criteria for predicting the mode change

Because sensing terrain trafficability for wheel is problematic in rolking, another approach for changing to wheeled mode is studied. This approach is only based on wheeled-mode criteria, especially utilizing single wheel criteria. In wheeled mode, when a certain single wheel criterion causes mode change then it is likely that the most problematic terrain area is under that wheel. If the problematic terrain area is under the front wheels, the robot will rolk a distance that is the length of the robot and then try to continue by wheels. If it is under the rear wheels, the rolking distance can be shorter, perhaps half the robot's length, because rolking is so slow compared to driving by wheels it is reasonable to rolk as little as possible. If the criterion that causes the mode change is based on all the wheels, then the most problematic terrain area can be determined using sums of front-wheel criteria and back-wheel criteria. A larger sum means worse terrain area. The most problematic terrain area can be determined in that way and this information can be used to decide the rolking distance if no other criteria are used in changing from the rolking to the wheeled-mode decision process. When sensing-based rolking criteria are also used, then the predicted rolking distance can be used as a "maximum" rolking distance. Thus, if the robot has not changed mode to wheel before it has travelled a maximum rolking distance, the "distance" criterion will force the mode change. In the case of a large difficult terrain area, this approach leads to the robot rolking a short distance and then trying to continue with wheels, unsuccessfully, and then rolking again. So, mode changes occur more frequently.

5.4 Using a sum of criteria in locomotion mode control

An alternative method using criteria in the automatic locomotion mode switching process is referred to as the ***sum of criteria*** method. Using a sum of the criteria, it is possible to prevent wrong decisions that originate from a single criterion that indicates wrongly in some terrain conditions. The state change occurs only if a weighted sum of the criteria is large enough. In that way, the meaning of a single criterion is less. A time window is not needed because of the use of several criteria at the same time improves the reliability of the mode change. Thus, using a sum of the criteria for preventing wrong decisions requires the use of several criteria, and therefore it can be only utilized in wheeled mode. The sum criterion can be formulated in a following way if $K_1R_1 + K_2R_2 + K_3R_3 + ... + K_mR_m > L_s$, then change to rolking mode, otherwise keep wheeled mode,

where R_i has the value 1, if $C_i > L_i$, and 0 otherwise.

Where C_i the wheeled-mode criterion *i*
L_i the threshold value of the criterion *i*
L_s the threshold value of the sum of criteria
K_i the weight coefficient for the criterion *i*
m the number of criteria used
R_i the threshold-reached flag for criterion *i*.

The threshold values (L_i) of the criteria are determined in the same way when using individual criteria. L_s is the threshold value of the sum of criteria and its value is tuned experimentally by driving in off-road conditions so that the mode is changed when really needed, but not changed unnecessarily.

If a certain criterion is more significant for locomotion control, the weight for that criterion can be increased. Weighting can be changed depending on the task that the robot is performing. For example, if the robot is not allowed to disturb the soil, then any slipping of the wheel is forbidden and therefore the slipping criterion is weighted more.

5.5 Optimisation of automatic locomotion control

The automatic locomotion mode control can be tuned and optimised in different ways by changing the threshold values of the criteria. So, the same vehicle can move with wheels or rolk on the same type of terrain, depending on how the automatic locomotion mode control of the robot has been tuned. Tuning depends on the definition of the task that the robot is fulfilling. The task definition affects not only path planning, navigation and speed of the robot, but also the automatic locomotion mode control. The following are examples of optimisation motives for locomotion of the robot and they also affect the automatic locomotion mode control:

- Avoid environmental damages
- Maximize speed of the robot
- Minimize energy consumption
- Avoid vibration and swinging of the load

The problem in using environmental damage as a motive for optimisation is that there are no standard ways to measure damages. Therefore, the operator has to evaluate environmental damages and estimate threshold values of criteria when the robot drives in real off-road conditions. Environmental damages can be reduced by restricting slipping, pushing and energy consumption of wheels. This can be done by setting the thresholds of these wheeled-mode criteria as low as possible, so that the robot changes to rolking before it has disturbed terrain over a long time. On the other hand, changing to rolking due to a small obstacle is not optimal, because the robot should utilize the faster wheeled mode as much as possible on terrain that is easy for wheels (no big vertical obstacle and soft soil). In rolking mode, the threshold values of the rolking criteria are tuned low so that the rolking criteria invoke mode change only when the terrain is almost flat and easy for wheels. This method, in which the operator evaluates damages and estimates threshold values, has been used in the tuning of threshold values of criteria for WorkPartner as described later in Chapter 6.3.2.

Using the speed of the robot as a main motive for locomotion simplifies tuning of threshold values of criteria because speed demand overdrives other factors, such as energy consumption, environmental damages or strain on the mechanics of the robot. In the extreme case when maximizing only the speed, the robot should drive as much as possible with wheels, because it is a faster mode; only if the speed is under the maximum rolking speed a change to rolking mode is allowed. Then, the robot changes to rolking mode if the speed is distinctly under rolking speed. The threshold values for rolking criteria should be tuned high, which means that terrain may still be difficult for wheels, but wheeled mode should be tried anyway because it may be faster.

When there are many optimisation motives affecting the locomotion of the robot at the same time, tuning the optimal threshold values of criteria is a multidimensional problem that is a separate research subject and should be studied further.

6 EXPERIMENTAL VERIFICATION

The proposed automatic locomotion mode control has been implemented and verified successfully in the WorkPartner service robot, a wheel-legged robot, which has been built at the Automation Technology Laboratory of Helsinki University of Technology [Halme et al., 2003]. The WorkPartner robot possesses a multifunctional locomotion system that can be used, not only for multi mode locomotion, but also as a sensing system to collect information about wheel-soil interaction and terrain surface.

6.1 WorkPartner as a test platform

WorkPartner is a centaur-like service robot with four legged wheels and a human-like upper body with two hands and a head. It can be seen in Figure 6.1. The robot probably closest to WorkPartner's appearance is the Centaur Robonaut designed by NASA JSC for planetary operations [Ambrose, 2000]. Robonaut is also a humanoid robot with a human-like upper body with two hands and a head, but the mobility platform will vary, depending on the application [NASA]. A planetary surface mobility platform concept in which a robot torso with articulating waist is mounted onto a wheeled rover chassis is closest to WorkPartner's appearance.

Figure 6.1 WorkPartner rolking over a snow bank.

The size of WorkPartner is such that it is suited to co-operating with humans. It weighs about 270 kg. The actuation system is fully electrical. The “muscles” of the machine are identical electric linear actuators that consist of a 250W motor, a tailor-made gear and a ball screw. The energy system is hybrid, which carries the energy in the form of fuel and transforms it into electrical power for robot actuation. For this, the system includes a combination of a small lightweight combustion engine with generator and batteries. The operation time is several (4-5) hours with 2 litres of petrol.

WorkPartner is a prototype of a lightweight human-like mobile service robot designed to work interactively with humans in an outdoor environment. The tasks are similar to what a human could do and the robot may replace or work together with him/her. Typical tasks will be guiding, cleaning, transporting and guarding.

6.1.1 Locomotion system

WorkPartner is built on a mobile platform called Hybtor (Hybrid Tractor), which is shown in Figure 6.2. The platform has four legs equipped with wheels and an active body joint. The structure is mostly aluminium for light weight. Some parts of joints are made of steel for greater strength. The Russian company Rover LTD has completed a detailed mechanical design [Halme et al., 2000].

Figure 6.2 CAD model and real Hybtor platform.

The wheeled leg, illustrated in Figure 6.3, consists of a 3-dof mammal-type leg and an active rubber wheel. One leg weighs about 21 kg, including the wheel. It is capable of producing about 70 kg continuous and 100 kg peak force upwards in the nominal driving position. The maximum stride length when rolking is about 0,7 m. The rounded shaped rubber wheel is designed to have two functions: as a foot in the rolking or walking mode and as a wheel in driving mode.

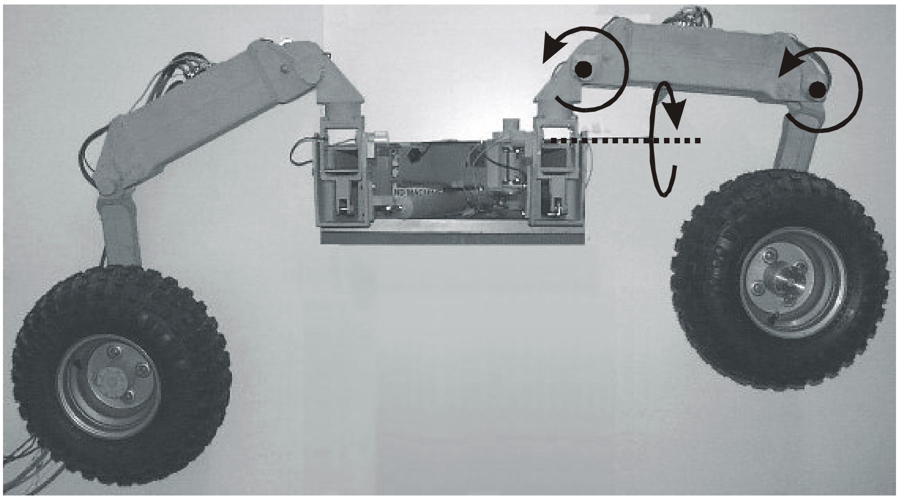


Figure 6.3 Side view of the legs with leg dofs.

The working volume of the leg can be seen in Figure 6.4. The leg-wheel mechanism has been optimised for use as a hybrid propulsion device. Optimal clearance with respect to stride length of rolking is about 0,5 m, as illustrated in Figure 6.4.

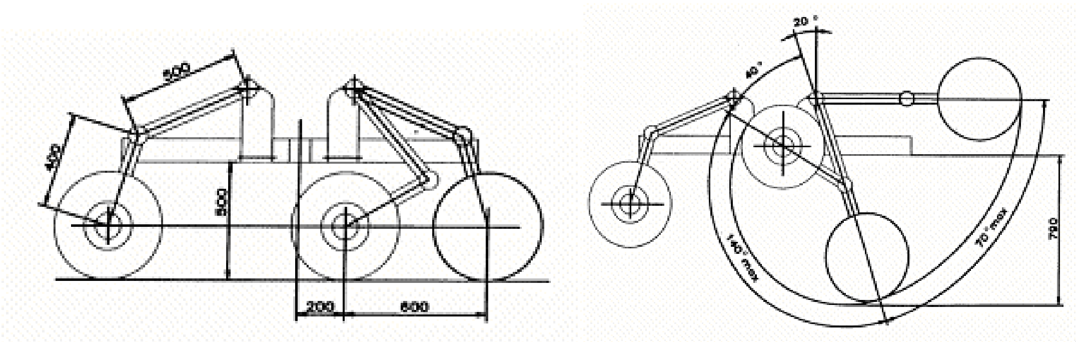


Figure 6.4 Working volume of a wheeled leg.

Parameters of the leg are shown in Table 6.1. It should be noted here that, while the legs have the "hip" joint (longitudinal axis joins the leg to the body) for sideways ankle movement, this joint is not used in locomotion mode control tests. So only the two joints, "thigh" and "knee", are needed in rolking forward, and the wheel is used actively. The wheel is powered by a Maxon EC250W 48V electric motor with a gear with a gear reduction 84,2, which means that the WorkPartner's maximum speed is approximately 2 m/s when the motor is running at 6470 rpm. The power of the used electric motor is too low for heavy off-road tests, where more wheel torque is required. The robot can only produce about 500 N drawbar pull with nominal current 4,7 A and 1000 N drawbar pull with two-times overloading. Nevertheless, the automatic locomotion mode control can be verified successfully with this robot.

Table 6.1 Parameters of a wheeled leg [Leppänen, 2004].

Joint	Angle α [°]	Max. angular velocity ω [°/s]	Max. torque T [Nm]	Max. moment of inertia J [kgm2]	Links l [mm]
Hip (inclination)	±20	28,4	358	3,44	138
Thigh (rotation)	0 - 70	48,9	220	5,76	500
Knee	0 – 140	90,4	112	1,52	400
Wheel	∞	462	27,7	0,162	230 (radius)

The "muscles" of the machine are identical linear actuators, shown in Figure 6.5. Each of them consists of a Maxon EC250W 48V electric motor (the same as in the wheel), a gear tailor-made by Rover LTD and a ball screw from SKF (CCBR32x100). It is possible to mount a tension measuring foil strain gauge inside the rod of the ball screw for measuring forces when the actuator is not actively powered (see Figure 6.5). This direct force sensing by strain gages proved to be accurate [Halme et al., 1999], but, to simplify the sensor system when the robot moves, it uses actively all the joints. Also, it is possible to use the currents of the electric motors for calculating forces. The main performance values of the actuator are presented in Table 6.2.

Table 6.2 Parameters of an actuator.

Weight	2,4 kg
Length of stroke	100 mm
Gear ratio	6,084
Modulus of ball screw	4 mm/revolution
Max velocity (no load speed)	70,90 mm/s
Max force (continuous)	2500N (I=4,6A)
Self-locking force with brake	3042N (0,4 Nm brake)

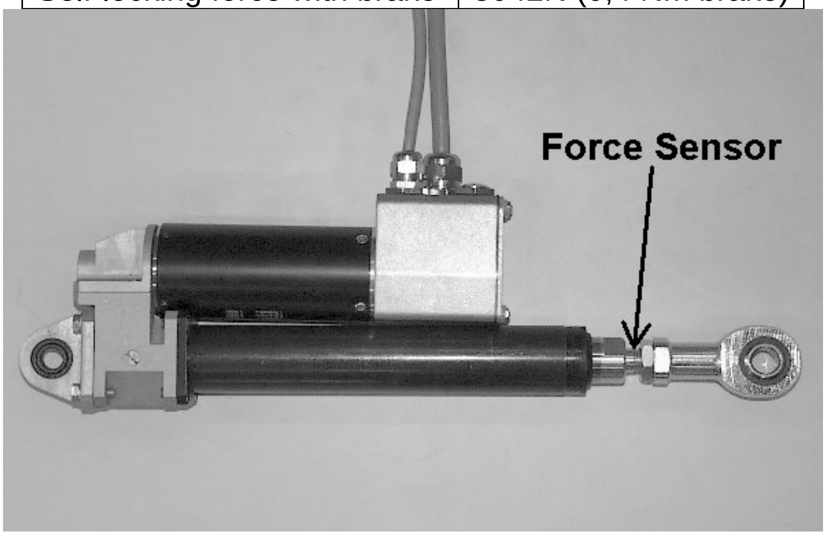


Figure 6.5 Main linear actuator used in the WorkPartner robot.

A reason to develop a new linear actuator was that this specially made actuator has better force and velocity characteristics, as well as a better force-to-weight ratio, than commercial linear actuators found at the time of design. The motors are equipped with brakes that are used when the robot is standing still. This is important because of energy conservation. Active control of joints against gravity consumes electricity and easily drains batteries if in use for a long time.

6.1.2 Control architecture

The computer system of the locomotion platform is distributed around a CAN-bus, as illustrated in Figure 6.6. Each leg has one controller (leg controller) based on a Siemens C167 Micro-controller in a PHYTEC mini-MODULE-167. To connect sensor signals into the micro-controller, a separate sensor interface board has been designed. Servo amplifiers for DC brushless motors are commercial products of ELMO Motion Control. The servo amplifier can power the motor with a 10 A continuous current and 20 A peak current. The middle joint controller is built using the same components. Other nodes, demanding more computing resources – such as those taking care of motion and locomotion control, user interface or perception system devices – are based mainly on PC/104 technology. Also, additional computer power can be used via the wireless local area network, WLAN. The main computer is a 586 PC/104 board running the QNX operating system; this takes care of the automatic locomotion mode control.

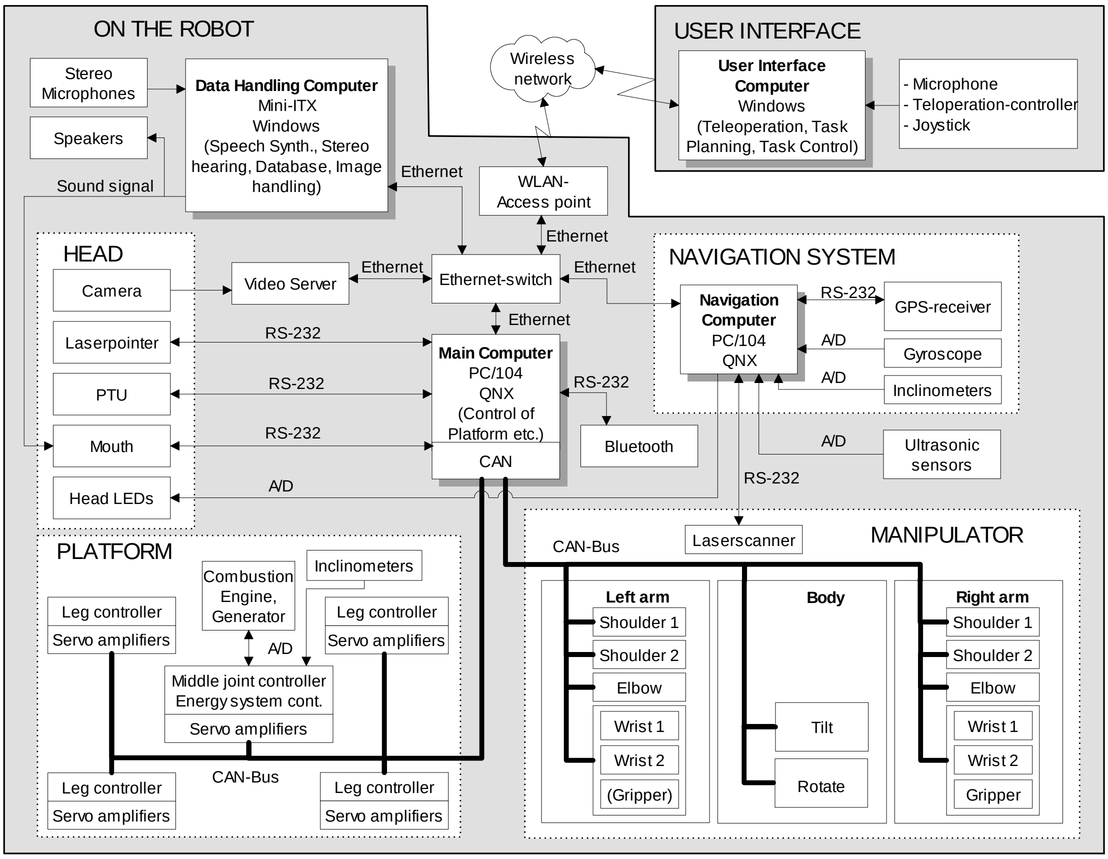


Figure 6.6 System diagram of the WorkPartner hardware.

6.1.3 Sensor system

The WorkParter sensor system includes sensors for observing the internal state of the robot and perceiving the outside world. Only the sensors for the automatic locomotion mode control are described here. A more detailed description of other sensors and sensing algorithms can be found in [Selkäinaho, 2002] and [Halme, 2003].

Joints angles are measured by potentiometers and encoders that are connected to the leg controller. Inclinations of the body are measured using gravity-based inclinometers connected to the middle joint controller that also takes care of the energy system. This sensor information is enough for motion control in most situations, but when force control is needed, force measurement should also be available. Implementing force sensors in every actuator is complicated; therefore, the indirect alternative to measuring the forces through the currents of joint motors was chosen. The joint gears are relatively small, which allows a moderate accuracy in force measurements to be achieved. Kinematic calculations are then used to calculate the forces in the contact points that the robot has with the environment [Ylönen, 2000].

This direct and indirect sensor information is enough for locomotion mode control, as can be seen in the following experiments.

6.1.4 Locomotion modes in the tests

In the verification of the automatic locomotion mode control, the WorkPartner used two modes: it drove with wheels and rolked. Driving with wheels is the faster mode. Although WorkPartner can reach a speed of 2 m/s, the maximum speed was restricted to 0,5 m/s in off-road locomotion mode control tests, because the robot has to negotiate vertical obstacles such as logs lying on the ground, and has to detect that kind of vertical obstacle by a laser- or vision-based system, which is still demanding. If the robot runs into an obstacle at higher speed, it will break down without damping. The position-controlled leg with a soft rubber wheel can absorb impulses, so collisions are not harmful for the mechanics at low speed, i.e. under 0,5 m/s. In wheeled mode, terrain adaptation is based on dividing the load equally to the wheels and controlling the body attitude according to the level of terrain or gravitation [Virekoski and Leppänen, 2007]. Dividing the load is based on measuring forces and controlling the vertical positions of the wheels. Dividing the load to the wheels equally and driving under speed control means better drawbar pull in slippery conditions, less rolling resistance in soft soil and less strain on both robot and terrain.

Rolking is a much slower locomotion mode compared to driving with wheels. In the tests, the robot rolks at about 0,04 m/s. On the other hand, rolking has only been used in bad situations, such as in soft soil or negotiating obstacles. A regular wave gait is used with a duty factor $\beta = 3/4$, which means that three legs support the body and one leg moves to the next position at the same time. This crawl gait has been chosen for off-road locomotion mode control tests, because it is good for negotiating obstacles.

In order to improve obstacle negotiation and reduce rolling resistance of a wheel that is moving to the next supporting position, the load can be divided more between the support legs. How much load is divided to the support legs can be adjusted by sensing the motion resistance of the wheel that is in transfer phase. This simple control strategy helps WorkPartner negotiate obstacles.

The body attitude control of WorkPartner has two modes, "level" and "terrain". In "level" mode, the controller attempts to keep the body perpendicular to gravitation using two inclination sensors. In "terrain" mode, the leg positions are adjusted so that the body follows the terrain profile. Both body attitude control modes function equally well in both driving with wheels and rolking. The automatic locomotion mode control also works regardless of the attitude control mode. The "terrain" mode is used in the locomotion mode control tests.

6.2 Experiment plan

The experiments collected in Table 6.3 are divided to three parts: first, the sensing methods are tested, then the functionality of the criteria is verified separately and, finally, the functionality of the proposed automatic locomotion mode control is verified in an off-road test track.

First, the sensing methods are tested in different real conditions. These experiments consist of energy consumption, pulling and slipping, obstacle resistance, colliding with a high vertical obstacles and terrain roughness tests.

Then the criteria are verified by driving over off-road terrain. Each criteria signal is examined with respect to the terrain conditions. Initial thresholds and time windows are determined roughly for the mode change. These off-road tests are repeated and the criteria values refined by monitoring the behaviour, i.e. how well the robot moves forward and how the mode changes occur. The goal here is to minimize unnecessary changes and make sure the mode is changed to rolking when there is much slipping, large energy consumption or large resisting forces, because WorkPartner has been adjusted to move carefully and avoid environmental damages and strain on the mechanics of the robot. Also, the change back to wheeled mode is observed and the criteria values adjusted so that the change occurs when the criteria indicate the terrain to be again suitable for wheeled drive.

Finally, the functionality of the proposed automatic locomotion mode control is verified in an off-road test track shown in Figure 6.7. The 40 m long test track consists of typical natural terrain features that are problematic for wheels: a slippery 18º slope followed by a 10 cm deep and 50 cm wide ditch; then a 3 m long and 25 cm deep soft snow area, two 19 cm diameter logs lying on the ground, followed by easy and smaller obstacles, i.e. a 1 m long 20 cm deep snow bank and two planks of cross section 5 * 10 cm. Finally, there is an easy and flat terrain area at the end of the test track. The robot drives through the track several times (nine times) to ensure that the locomotion mode control changes the mode equally.

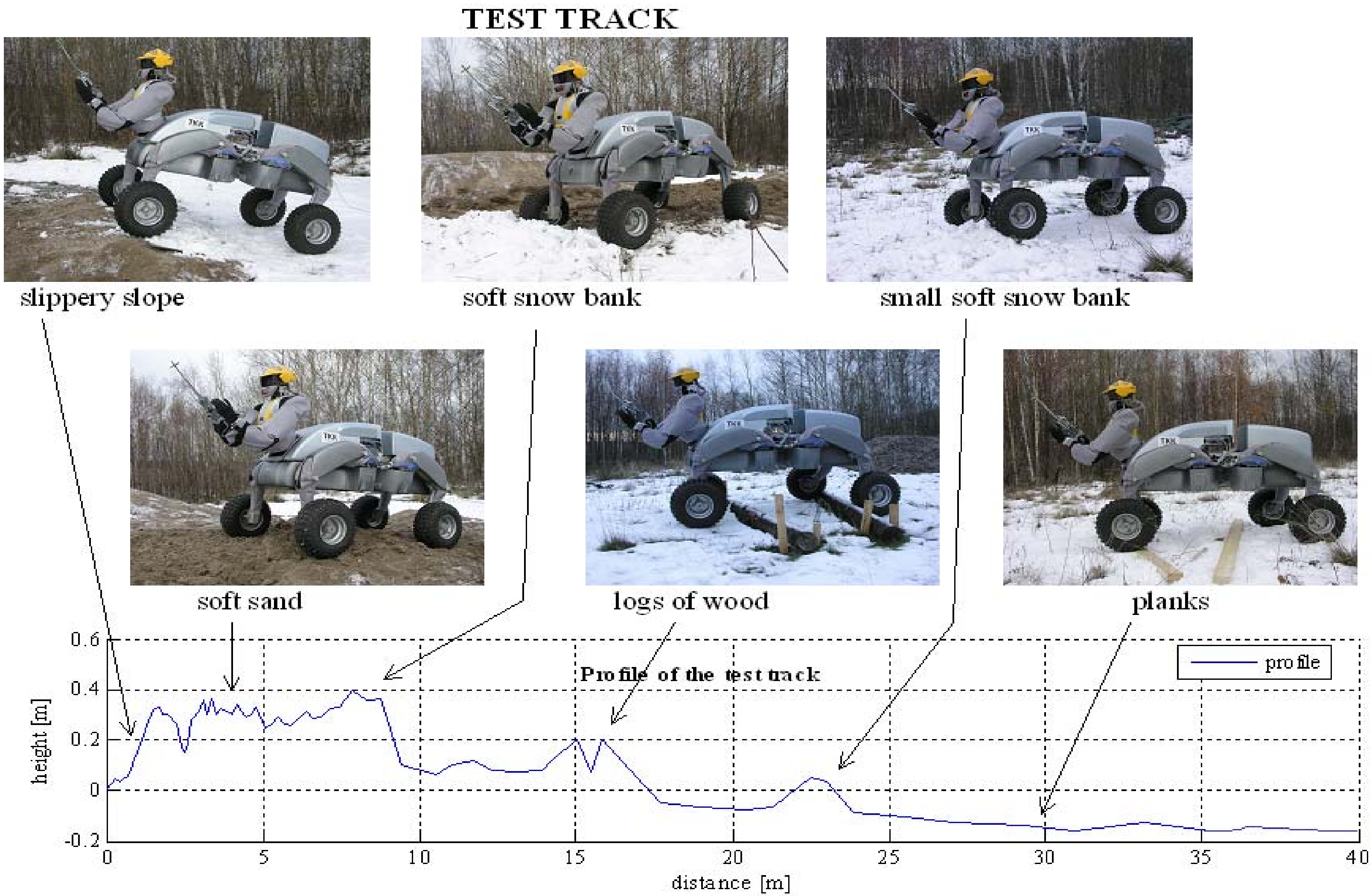


Figure 6.7 Test track for WorkPartner.

In all nine test runs, changing mode to rolking is based on the criteria described in Table 5.1. Changing mode to wheel is tested in three phases. In the first three test runs, changing mode to wheel mode is based on travelling a short predetermined distance (the length of the robot, 2 m) only and no sensing is used. The idea of using a short rolking distance as a “criterion” to change mode is that the robot overcomes the problematic terrain area by rolking a short distance and then tries by wheels. If the terrain is still too difficult (soft or vertical obstacles) for wheels, the robot has to change back to rolking mode.

During the next four test runs, tests 4-7, the automatic locomotion mode control does not use only the three sensing criteria described in Table 5.1 for changing to wheeled mode, but also the predicted rolking distance as described in Chapter 5.3.3. If the robot has not changed mode to wheel before it has travelled a short distance, the distance “criterion” will force the mode change. In these tests (4-7), the predicted rolking distance is 2 m if the most problematic wheel-soil interaction is under the front wheels, and 1 m in the case of the back wheels, as described in Chapter 5.3.3.

In the last two test runs, tests 8 and 9, changing to wheel mode is based only on the three sensing criteria.

Table 6.3 Experiment plan.

PART 1	**TESTING SENSING METHODS**
Test 1	**Energy consumption**
Purpose	Energy consumption of wheeled and rolking mode in different conditions
Test 2	**Pulling and slipping test**
Purpose	Force and drawbar pull sensing in wheel mode, how slipping affects on drawbar pull
Test 3	**Obstacle resistance**
Purpose	Sensing motion resistance of a wheel in driving over a small obstacle (a vertical obstacle, height 0,1 m).
Test 4	**Colliding with a high vertical obstacle**
Purpose	Sensing the horizontal force affecting on a wheel when it collides with a high vertical obstacle, the height of which is more than the radius of a wheel.
Test 5	**Terrain roughness and slope**
Purpose	Sensing terrain parameters, terrain pitch and roll as well as terrain roughness.
PART 2	**VERIFYIENG FUNCTIONALITY OF CRITERIA SEPARATELY**
Purpose	Justify functionality of criteria singly. Determine a proper threshold for each criterion.
Test 1	**Energy consumption of wheel mode**
Test 2	**Energy consumption of rolking**
Test 3	**Motion resistance of a transfer leg in rolking**
Test 4	**Energy consumption of a single wheel**

Test 5	**Resisting force of a wheel**
Test 6	**Slipping of a wheel**
Test 7	**Terrain roughness**
PART 3	**VERIFYING FUNCTIONALITY OF AUTOMATIC LOCOMOTION MODE CONTROL IN A TEST TRACK**
Purpose	Functionality of the automatic locomotion mode control is verified in off-road conditions. The robot drives through the test track nine times with different locomotion mode controls. Changing mode to rolking works in the same way in all nine test runs using sensing-based criteria described in Table 5.1. Changing mode to wheeled mode is tested in three ways as follows.
Tests 1 - 3	**Testing locomotion mode control. In rolking mode without sensing information.**
Purpose	Testing locomotion mode control in a way where changing to wheeled mode is based on travelling a short fixed distance (2 m) without utilizing sensing.
Tests 4 - 7	**Testing locomotion mode control. In rolking mode with sensing information and a rolking distance.**
Purpose	Testing locomotion mode control in a way where changing mode to wheel mode is based on travelling a short predicted distance (1m or 2 m) and also utilizing sensing based criteria.
Tests 8-9	**Testing locomotion mode control. In rolking mode with sensing information only.**
Purpose	Testing locomotion mode control in a way where changing mode to wheel mode utilizes sensing based criteria.

6.3 Experiments

6.3.1 Testing sensing methods

Test 1: Energy consumption

The energy consumption of locomotion is the main parameter for locomotion mode control. The energy consumption of WorkPartner has been measured in several conditions in both locomotion modes. Results have been collected in Table 6.4. Energy consumption of a wheel has been tested in up to 22 cm deep soft snow only, because the robot cannot drive in deeper snow with the present motors. Losses in the gears and the linear actuators are included in energy consumption values.

Table 6.4 Energy consumption of WorkPartner.

Locomotion mode	**Speed [cm/s]**	**Energy consumption [J/m]**	**Terrain**
Wheeled mode	50	130 (only wheels)	Flat hard
Wheeled mode	50	600 (only wheels)	Soft sand
Wheeled mode	50	600 (only wheels)	Soft snow without ice layer 15 cm
Wheeled mode	50	900 (only wheels)	Soft snow without ice layer 22 cm
Rolking, crawling gait	2	2800	Flat hard
Rolking, crawling gait	3	3400	Flat hard
Rolking, crawling gait	2	4500	Soft snow, 25 cm
Rolking, trot	4	3700	Flat hard
Rolking, trot	8	4500	Flat hard
Rolking, worm gait	4	4000	Flat hard

The speed of rolking affects the energy consumption so that higher speed means higher consumption. The energy consumption of rolking, especially in trot gait, is very cyclic, as can be seen in Figure 6.8. This originates from changing the load on the other support pattern and accelerating the transfer legs.

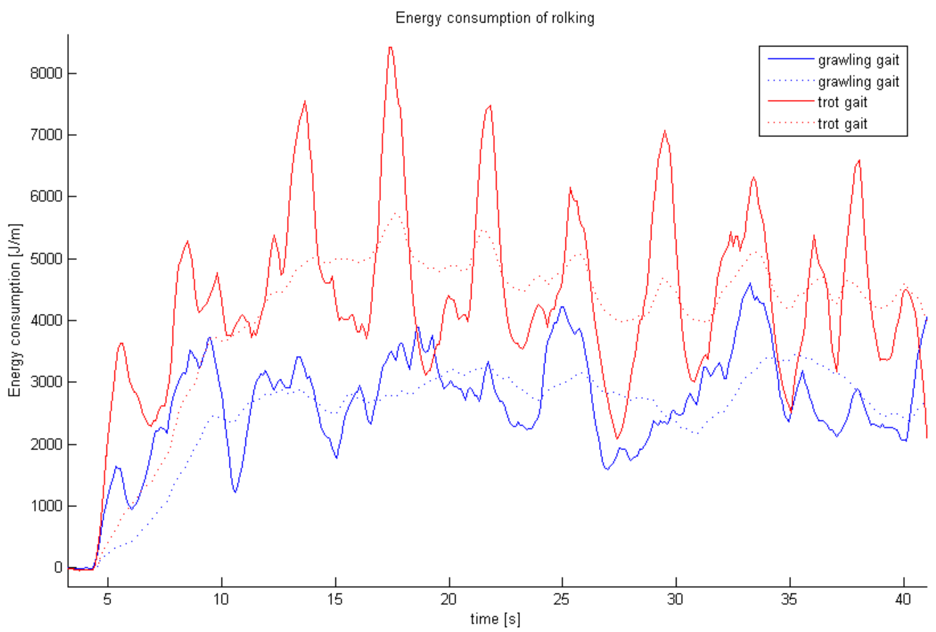


Figure 6.8 Energy consumption of rolking on flat ground. The crawling gait has been tested at 2 cm/s and trot gait at 8 cm/s.

Test 2: Pulling and slipping test

Drawbar pull is needed for driving uphill or pulling a trailer, as well as for acceleration. To verify force and drawbar pull sensing and how slipping affects the drawbar force of the wheel, WorkPartner pulled with constant horizontal force (491 N) at a constant speed of 40 cm/s on even, partly slippery, ground. The test was arranged so that a 50 kg mass was pulled against gravity using a rope and pulley blocks. Test results are presented in Figure 6.9. When the rear left wheel (wheel 3) encountered slippery ground, it started to slip, which affected drawbar force negatively, as can be seen in Figure 6.9 at 16,5 seconds. The drawbar force of wheel 3 decreased significantly, but the other wheels compensated, because WorkPartner drove under speed control. The drawbar force and speed of the robot kept almost constant all the time. Wheel slipping is detected by comparing wheel speeds. The drawbar pull of WorkPartner was calculated using leg forces and proved to be accurate enough using the currents of the electric motors. The calculated drawbar pull of WorkPartner (marked with green in Figure 6.9) is little more than the actual one (491 N) because of friction in the pulley block.

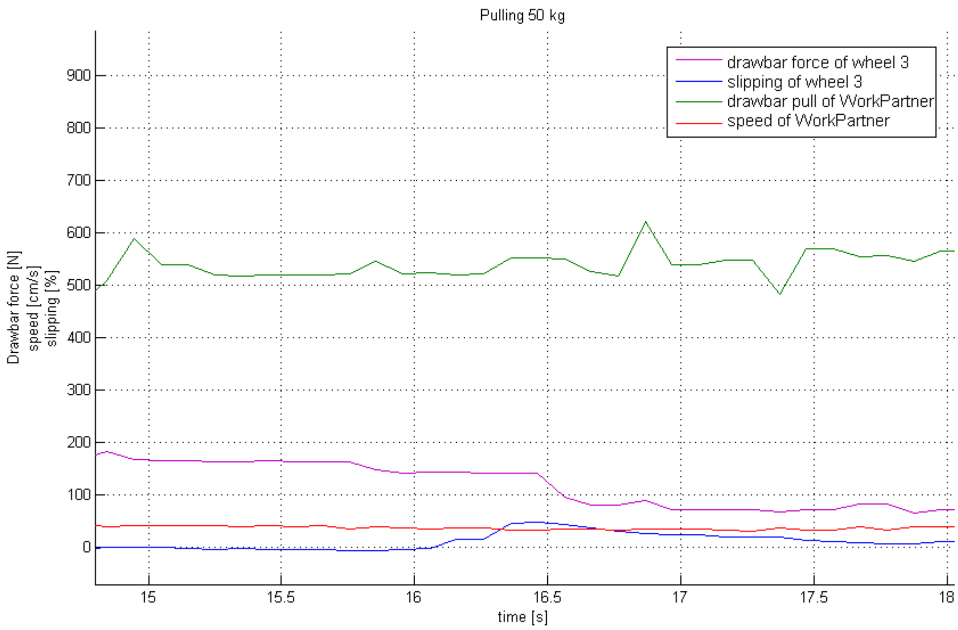


Figure 6.9 Pulling 50 kg on partly slippery ground. Slipping of the wheel affects drawbar pull.

Test 3: Obstacle resistance

Overriding an obstacle is a dynamic process, in which large peak forces appear. It also briefly increases the energy consumption of wheels, as can be seen in Figure 6.10. In this experiment, WorkPartner drove with the left front wheel (wheel 1) over a small obstacle 9 cm high. The drawbar pull of wheel 1 is negative, which means that the wheel cannot produce drawbar pull; it can only resist the robot's motion.

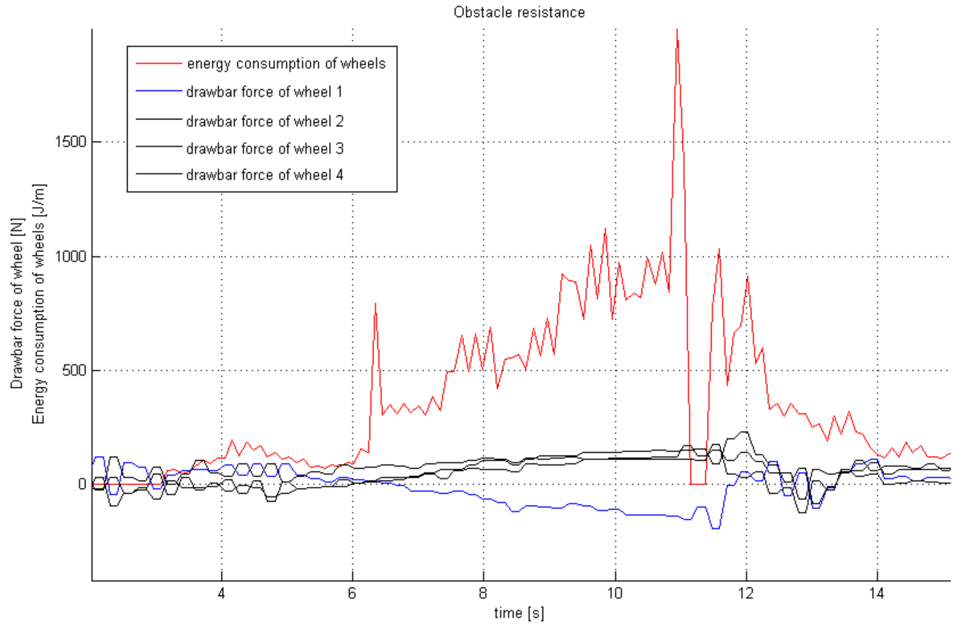


Figure 6.10 Obstacle resistance. WorkPartner drives over a small 9 cm high obstacle with the left front wheel.

Test 4: Colliding with a high vertical obstacle

The developed automatic locomotion mode control does not prevent collision with obstacles. In general, driving at high speed requires terrain scanning to detect an obstacle beforehand; after that, the robot should avoid it. However, if driving at low speed (like below 0,5 m/s in the case of WorkPartner) the collision can be detected using leg forces and wheel torques and the harmful impulse force can be absorbed with the flexible position controlled leg and the soft rubber tire. Collisions have been tested with WorkPartner several times and a test run is shown in Figure 6.11. In this test run, the right front wheel collided with a big obstacle after 13 seconds and the robot could not drive further. The horizontal leg force of the right front wheel (wheel 2) started to increase rather slowly, because the wheel has a rubber tire, the position-controlled leg is flexible and WorkPartner drove slowly. The robot pushed with 150 N at the maximum, before it was commanded to stop moving.

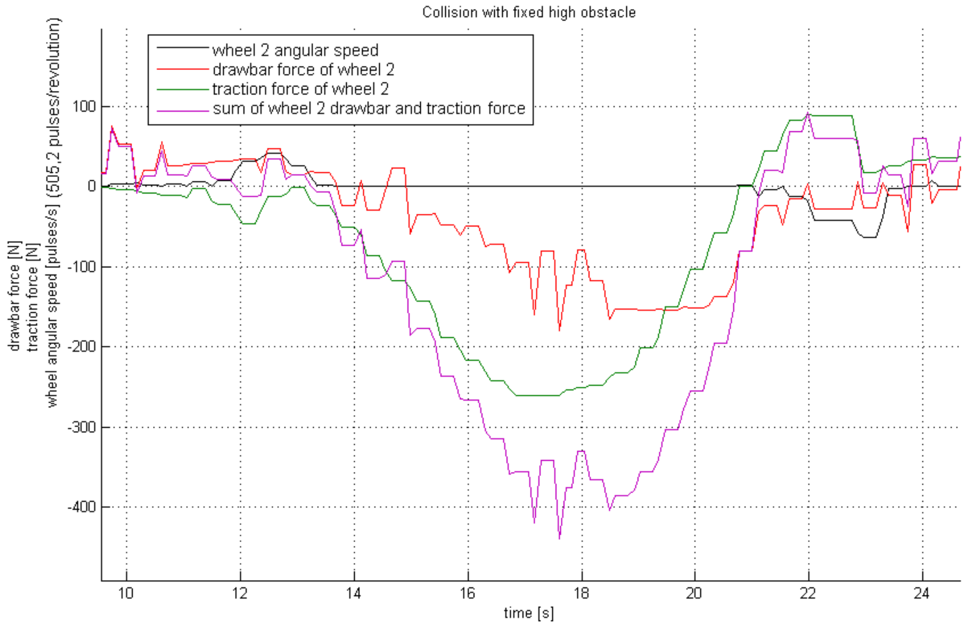


Figure 6.11 Collision with a high vertical obstacle and the right front wheel. WorkPartner could not drive further.

Test 5: Terrain roughness and slope

Terrain slope and roughness are calculated according to algorithms described in Chapter 4.3. To demonstrate the sensing principle, WorkPartner driving in terrain mode climbed over a 30 cm high and 140 cm long ramp with the left side wheels; the results are shown at the bottom of Figure 6.12, while the ramp is shown at the top. The wheels were in the nominal positions so that the wheel base was 1,45 m and sideways distance between the wheels was 1,0 m. The ramp is so short that the left front wheel climbed first up then down and the robot was level for a short time before the rear wheel did the same. The theoretical value for the roughness of this test was 29º, but the roughness indicator (marked red in Figure 6.12) differs with respect to whether the front or rear wheel is on the obstacle. This results from the flexibility of the asymmetric middle joint. If a wheel of WorkPartner is on an obstacle with a height of the radius of the wheel (0,23 m) and the other wheels are in the nominal positions, roughness is about 22 º. If the opposite corner wheels are on the same size obstacle (0,23 m), then the roughness will double (44 º). When driving over a ramp at higher speed, the terrain roughness indicator is over the threshold in a shorter time, which may not generate mode change if a fixed time window is used. Therefore, the time window for the terrain roughness criterion should be scaled according to the driving speed, but this has not been done in the case of WorkPartner because it drives at moderate speed (below 0,5 m/s) all the time. The effect of the speed should be studied further, because it does not only influence locomotion mode change, but it also affects the stability and stress of the robot. On the other hand, driving at higher speed requires obstacle detection for regulating the correct speed, which is another important key issue in mobile robotics.

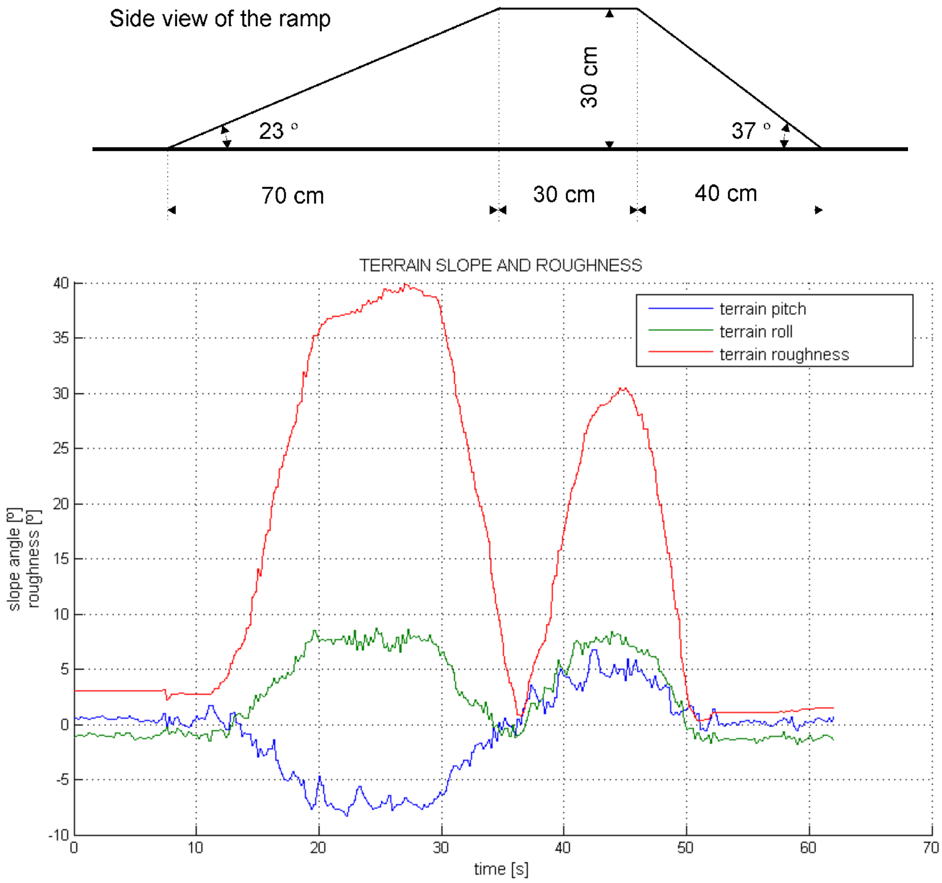


Figure 6.12 Terrain slope and roughness. WorkPartner drives over a 30 cm high and 140 cm long ramp with the left wheels and senses terrain slope and roughness at the same time.

6.3.2 Tuning of locomotion mode control

The automatic locomotion mode control can be tuned and optimised in different ways, depending on the definition of the task that the robot is fulfilling. WorkPartner has been adjusted to move carefully, avoiding environmental damages and strain on mechanics of the robots due to a large amount of slipping or high energy consumption of the wheels or due to pushing an obstacle with a wheel using great force. This adjustment has been made by setting the threshold values of the slipping, energy consumption and resisting force of the wheel as low as possible so that WorkPartner changes to rolking mode before it damages soil a lot, but it still drives by wheels on firm and even ground. If these threshold values are high, then WorkPartner tries to drive with wheels, even though it is pushing with the wheel or excavating soil by slipping. The threshold values of rolking criteria have the affect that, if these values are high, WorkPartner may change to wheeled mode although the terrain is still problematic for wheels; in this case, it then has to change back to rolking. On the other hand, if these values are set at a low level, it may happen that WorkPartner rolks, although the terrain is traversable for wheels.

In Table 6.5, the threshold values for criteria are collected. In wheeled mode, the threshold for energy consumption of wheels has been set to 800 J/m according to the energy consumption tests presented in Table 6.4. On even soil, the energy consumption in wheel-soil interaction is low (100 – 200 J/m), but it increases rapidly in soft soil, for example, 900 J/m in 22 cm deep snow, where the wheels of WorkPartner start to excavate. Therefore, the energy threshold value has been set to a low level. The threshold for the energy consumption of a single wheel in wheel-soil interaction has been set to 300 J/m. This is more than the quarter of the energy consumption of all the wheels, because it is possible that a single wheel can consume more energy in wheel-soil interaction when the other wheels are on good frictional ground and therefore pushing it.

It is possible to control how much WorkPartner pushes obstacles by means of a wheel by tuning the threshold for the force with which the wheel resists the body motion. If a wheel of WorkPartner collides with an obstacle, it resists body motion a lot and the other three wheels should produce drawbar pull to overcome the obstacle, which can be hard in slippery conditions. The threshold for the resisting force has been set to a low level (100 N) in order to prevent environmental damages. If friction allows, one wheel of WorkPartner can produce 120 N drawbar force with nominal current.

The threshold for the slipping of wheels has been set to 100 %, which means that the wheel rotates at a speed two times higher than the speed of the robot. The drawbar pull of a wheel decreases significantly over a 50 % slip, as can be seen in Figure 6.9. The drawbar pull of WorkPartner is good, because load is divided between the wheels equally and the wheels generate torque under speed control.

The threshold for roughness in wheeled mode has been set to 30 º according to the terrain roughness and slope test presented in Figure 6.12. This means, for example, that the vertical position of one wheel differs by about 30 cm from the positions of the other wheels.

To find optimal thresholds for criteria of rolking is problematic, because rolking criteria only represent terrain trafficability. A threshold of 4000 J/m for the energy consumption of rolking has been chosen on the grounds of rolking tests presented in Table 6.4. The energy consumption of rolking is about 2800 J/m in flat terrain and about 4500 J/m in 25 cm deep snow. The other criterion that represents terrain trafficability is the motion resistance of a transfer leg's wheel. Because a transfer leg's wheel rolls under reduced load, it resists soil less; therefore, the threshold should be lower in rolking than in wheeled mode (300 N). Thus, the threshold for motion resistance of a transfer leg's wheel has been chosen as 140 N. In the case of WorkPartner, motion resistance of the transfer leg's wheel does not need to scale with respect to the load of the wheel, because the load stays almost constant (about 15 % of the machine weight, or 400 N) with the help of load distribution control. The third criterion that represents terrain trafficability is roughness. The threshold value for roughness has been set to a low level, 8º, according to the terrain roughness and slope test presented in Figure 6.12, which means that the terrain is almost even. So, in rolking mode, the roughness criterion will only evoke mode change when terrain is flat.

Time windows for wheeled-mode criteria have been set to 2 seconds, except for the resisting force of a wheel, for which it has been set to 1 second in order to prevent environmental damages by pushing. These times were verified in the experiments to be long enough to filter out short peaks and therefore avoid unnecessary mode changes, and short enough to not delay the mode change unnecessary.

A practical distance window for rolking mode criteria is one rolking cycle in which all the legs have performed the transfer phase and therefore collected terrain information. During the rolking cycle, WorkPartner moves about 40 cm.

Table 6.5 Criteria for locomotion mode control of WorkPartner.

WHEELED	**MODE CRITERIA**		
Criteria	**Description**	**Threshold for criterion**	**Time/distance window**
C_{roll}, $v \neq 0$	Energy consumption of the wheels per travelled distance	800 J/m	2 sec
C_{static}, $v=0$	Static motion resistance when the vehicle speed is zero	800 J/m	2 sec
C_{roll_w} for each wheel, $v \neq 0$	Energy consumption of a single wheel per travelled distance	300 J/m	2 sec
C_{static_w} for each wheel, $v=0$	Static motion resistance of a wheel when the vehicle speed is zero	300 J/m	2 sec
C_{resist} for each wheel	Resisting force of the wheel	100 N	1 sec
C_S for each wheel	Slipping of the wheel	100 %	2 sec
C_χ	Terrain roughness	30 º	2 sec
ROLKING	**MODE CRITERIA**		
Criteria	**Description**	**Threshold for criterion**	**Time/distance window**
C_{rolk}	Energy consumption of the leg joints and the wheels per travelled distance	4000 J/m	a rolking cycle, 40 cm
$C_{transfer}$ for each transfer leg's wheel	Motion resistance of a transfer leg's wheel	140 N	a rolking cycle, 40 cm
C_χ	Terrain roughness	8 º	a rolking cycle, 40 cm

6.3.3 Verifying functionality of criteria separately

To verify the functionality of the criteria for the automatic locomotion mode control separately, WorkPartner moved on the off-road test area. There were typical terrain obstacles, like vertical obstacles or a slippery slope, and also soft and flat firm soil on the test. Next, the test results that illustrate typical behaviour of criteria best are presented and described.

Test 1: Energy consumption of wheeled mode

The wheels consume more energy when soil softness increases, which has been proved by an energy consumption test shown in Figure 6.13. The robot tried to drive at a constant speed on terrain that consists of even ground with snow of varying depth. At the time stamp 557 seconds, the depth of snow started to increase, which affected the energy consumption marked with black and the speed of the robot. At the time 568,2 seconds, the robot changed to rolking (marked with green in Figure 6.13) because energy consumption was over the threshold value 800 J/m more than 2 seconds (marked with blue). Energy consumption was briefly over the threshold at 562 seconds, but for less than two seconds, which didn't cause mode change.

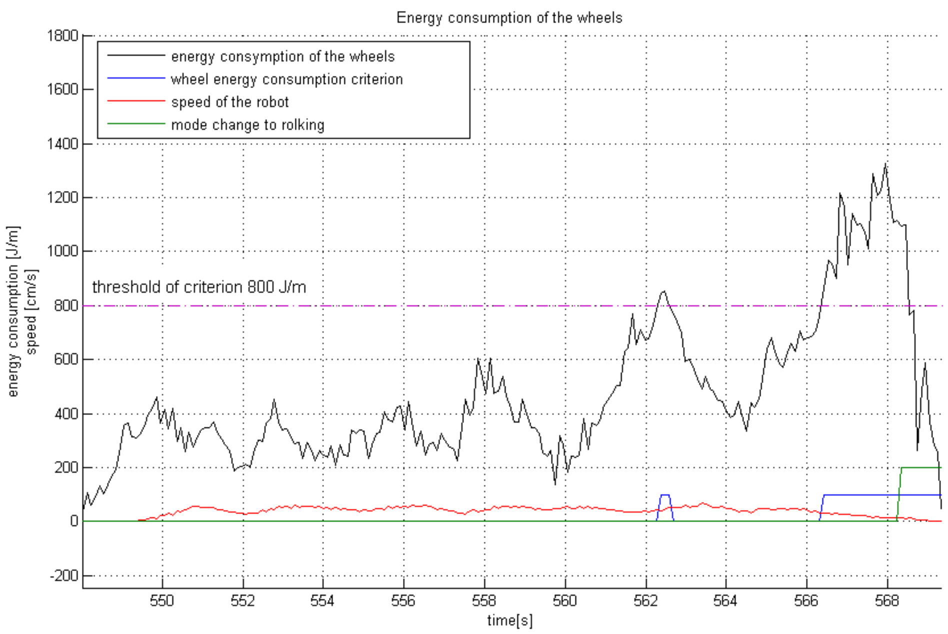


Figure 6.13 Increasing snow depth caused mode change to rolking at 568,2 seconds.

Test 2: Energy consumption of rolking

The energy consumption of rolking as well as walking will increase in softer soil. Slip of the support legs doesn't only affect the speed of the robot, but also the energy consumption, as shown in Figure 6.14. In this experiment, the robot climbed up a slippery 18 º slope successfully. Slip of the support legs causes more internal forces in the robot, which results in increasing energy consumption. When the robot succeeded to move from the slippery slope to more frictional and flat terrain, the energy consumption marked with black in Figure 6.14 decreased and remained below the threshold for a longer time. When this occurred, the energy consumption criterion, marked with blue in the figure, was on respectively.

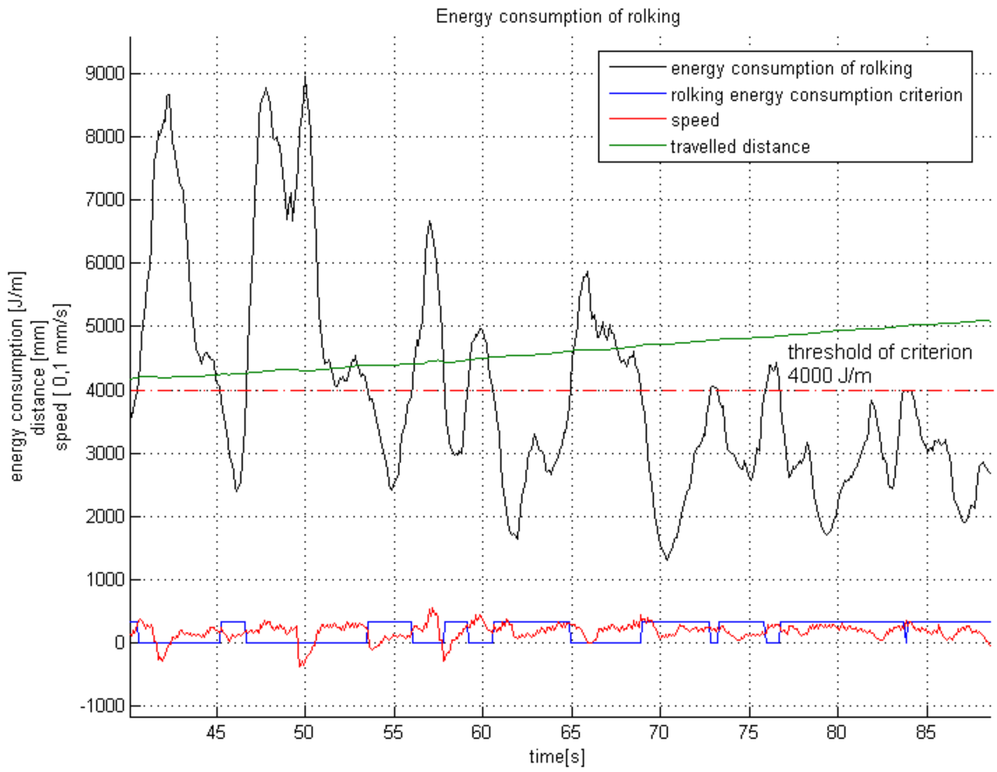


Figure 6.14 The robot climbs up a slippery 18 ° slope that causes slip of the support legs. Energy consumption decreases below the threshold when the robot arrives on flat and level ground.

Test 3: Motion resistance of a transfer leg's wheel in rolking

Terrain trafficability can be estimated with motion resistance of a transfer leg's wheel. When the depth of snow decreases, so does the motion resistance of the transfer leg's wheel also, as can be seen in Figure 6.15. If motion resistance is under the threshold during a particular travelled distance (in this case 40 cm), the robot changes to wheeled mode, as happened at 234 seconds, see Figure 6.15. At the end of this test, WorkPartner moved on firm ground during 214 – 235 seconds, when the average motion resistance of the transfer leg's wheel was about 80 N. The load of the transfer leg's wheel stays almost constant, because the load of WorkPartner is divided so that the support legs carry about 85 % of the robot's weight and the transfer leg only about 15 %.

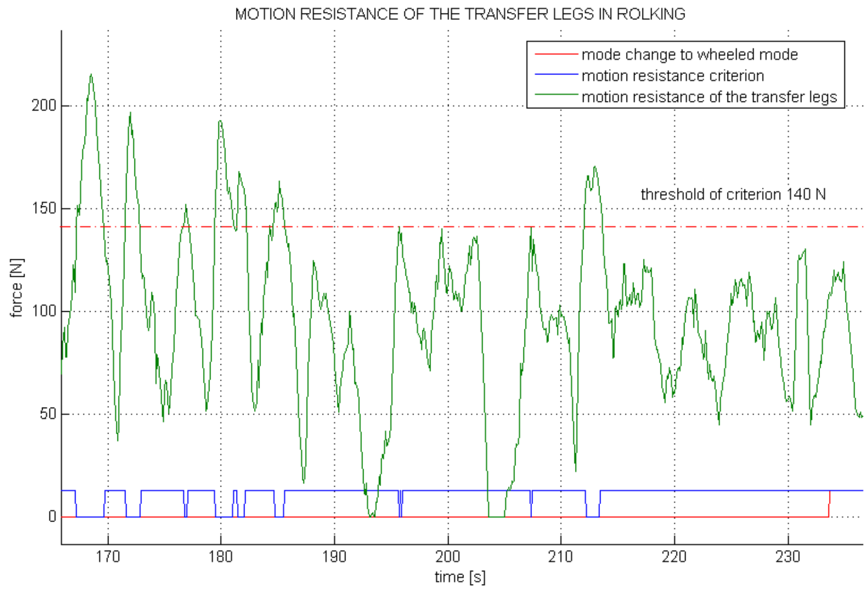


Figure 6.15 WorkPartner rolked from soft snow to firm ground. Motion resistance of the transfer legs decreased and the robot changed to wheeled mode at 234 seconds.

Test 4: Energy consumption of a single wheel

The energy consumption of a wheel per travelled distance increases if the wheel drives on soft soil or slips a lot under low-frictional condition. To illustrate energy consumption, WorkPartner climbed a slippery 18º slope; test results of this climb have been presented in Figure 6.16. The rear left wheel started to slip (marked with green) and the speed of the robot decreased (marked with black).

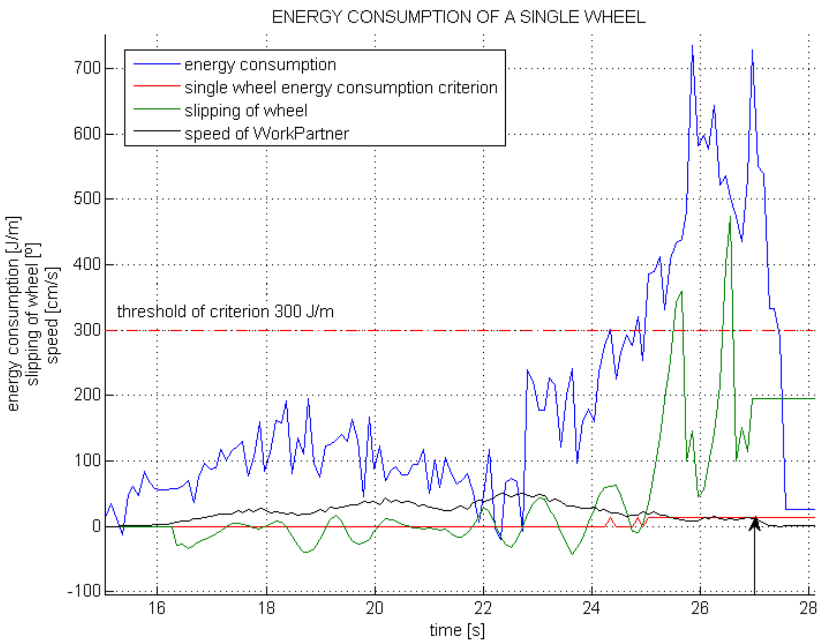


Figure 6.16 WorkPartner tried to climb a slippery 18 º slope with wheels. The rear wheels started to slip, which also increased the energy consumption of the wheel per travelled distance so the robot changed to rolking mode at 27 seconds.

All slipping wastes energy. Energy consumption of the rear left wheel increased over the threshold for more than 2 seconds, which caused mode change to rolking at 27 seconds.

Test 5: Resisting force of a wheel

The direct drawbar force can be used as a criterion to change locomotion mode from wheeled mode to the more propulsive rolking mode when a single wheel resists the body motion a lot, i.e. when the direct drawbar force measurement is negative. This has been demonstrated in the following test where the front left wheel of WorkPartner collided with a vertical obstacle (see Figure 6.17). The left wheel stopped and resisted the robot's motion longer than 1 second with a force of more than 100 N, so the robot changed to rolking mode.

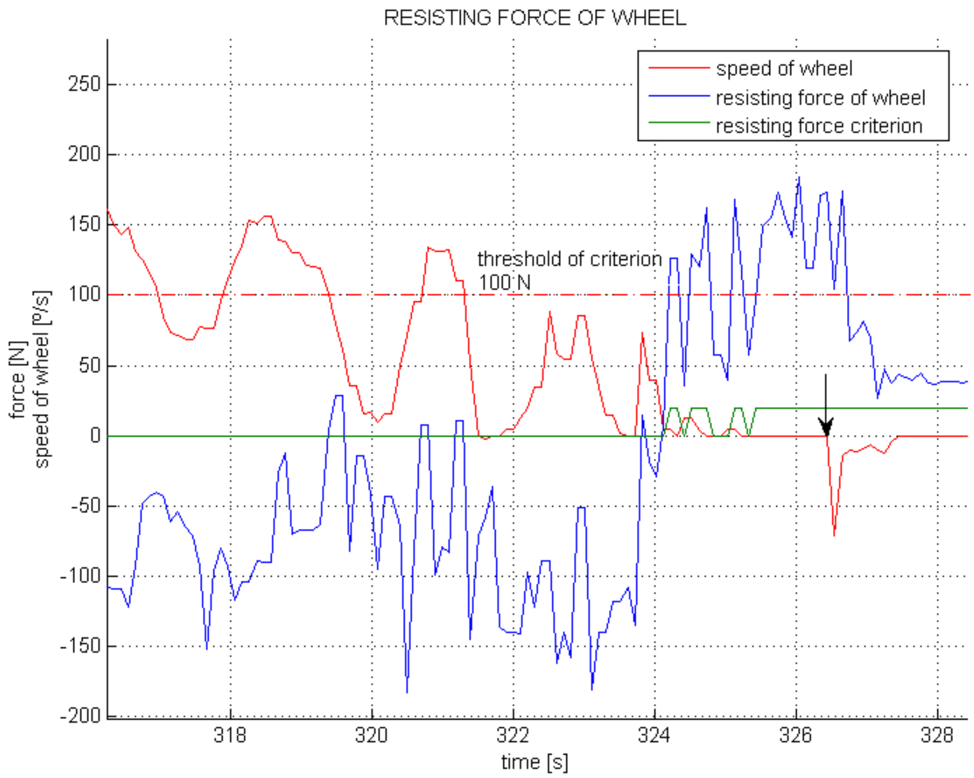


Figure 6.17 WorkPartner collided with a vertical obstacle with the front left wheel at 324 seconds. This wheel stopped and resisted robot motion a lot (more than 100 N in 1 second), which caused a change to rolking mode at 326,5 seconds.

Test 6: Slipping of a wheel

The slipping of a wheel causes a decrease in drawbar pull that might mean a decrease in the speed of the vehicle, as happened in the slipping test illustrated in Figure 6.18. In this test, WorkPartner drove with wheels on a slippery 18 ° slope and the rear left wheel started to slip at 109 seconds. The speed of the robot decreased because the other wheels could not produce more torque with the low-power motors. The slope was so slippery under the rear left wheel that the slip was over 100 % in two seconds, which caused mode change at 113,5 seconds.

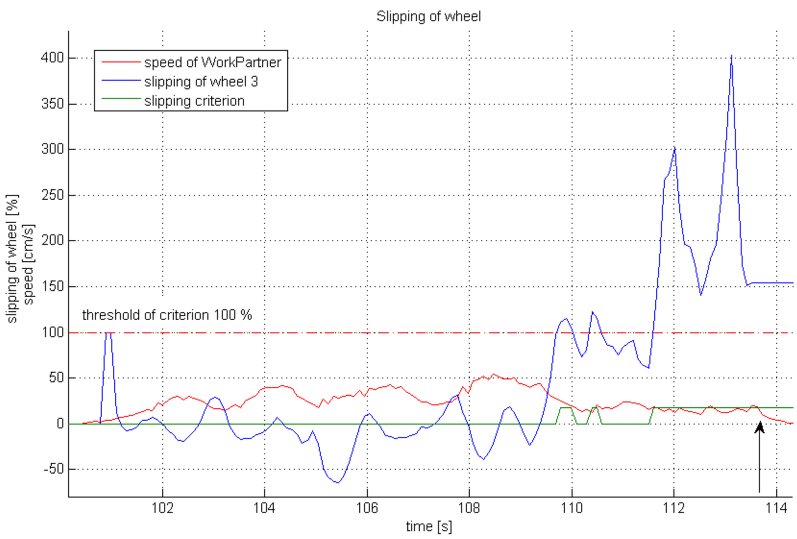


Figure 6.18 WorkPartner drove on a slippery slope. The slip of the rear left wheel caused a decrease in the robot's speed and mode change at 113,5 seconds.

Test 7: Terrain roughness

The terrain roughness indicator that has been described in Chapter 4.3 can be used for switching from rolking to wheeled mode and also back. Figure 6.19 illustrates terrain roughness when WorkPartner rolked over a log of wood with its front legs. The front wheels were over the log at 300 seconds; terrain roughness was about 6 º. Terrain roughness is about 0-6 º on flat terrain, but if a wheel is on a log, roughness is much greater. In rolking mode, the roughness criterion will cause mode change when roughness is below the threshold 8 º. In wheeled mode, mode change will occur when roughness is over 30 º.

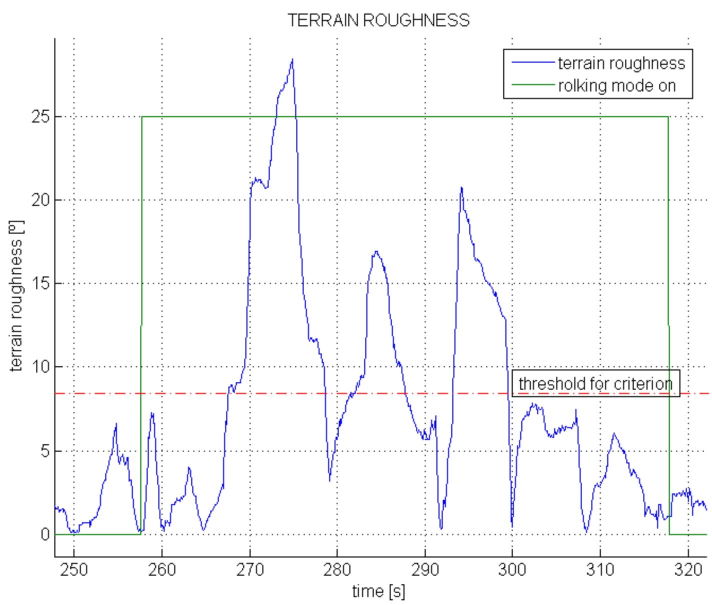


Figure 6.19 WorkPartner rolked over a log of wood with its front wheels. Terrain roughness is significantly greater when a wheel is on a log.

6.3.4 Verifying the functionality of the locomotion mode control

The functionality of the proposed automatic locomotion mode control has been verified in an off-road test track shown in Figure 6.7. Use of rolking and wheeled mode has been presented in Figure 6.20. In all the test runs, changing mode from wheeled to rolking was based on sensing the criteria described in Table 5.1.

In rolking mode, during the first three test runs, the automatic locomotion mode control did not utilize sensing-based criteria for it. This means that WorkPartner rolked a constant distance (2 m) and then tried to continue with wheels, which can be seen clearly in Figure 6.20. During test runs 4-7, especially runs 5-7, more mode changes occurred, because changing to wheeled mode was based on travelling a short predicted distance (1m or 2 m), and also utilizing sensing-based criteria. In rolking mode, use of a predicted short distance as a "criterion" leads to mode change, although the terrain can be still difficult for wheels.

The locomotion mode control has been based on sensing criteria only during the last two runs, 8-9. The results of these runs prove that it is possible to change mode using sensing-based criteria only.

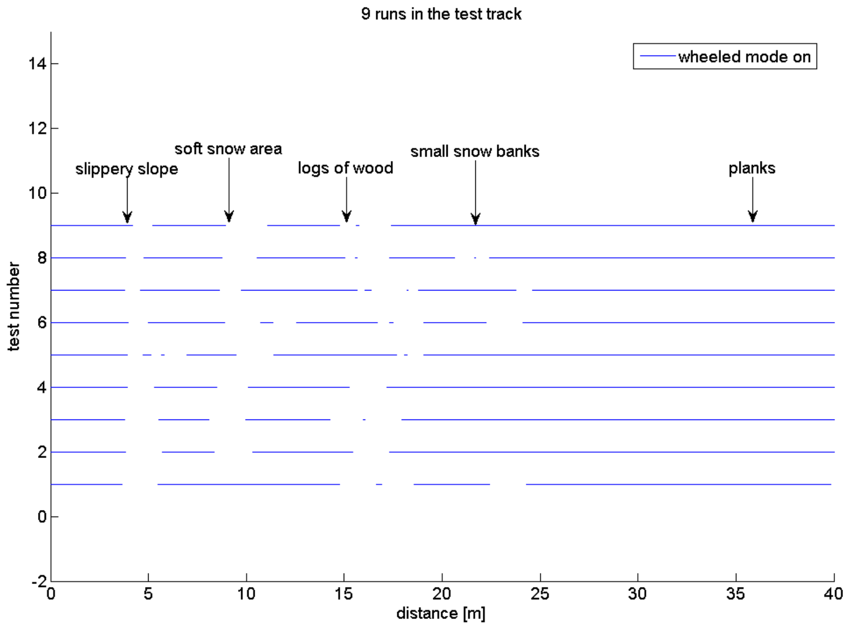


Figure 6.20 Use of locomotion modes in the test track. WorkPartner runs through the test track 9 times. The distances where the mode changes occur vary, because distance has been calculated from the odometry of WorkPartner.

Functionality of the sum of criteria method for the automatic locomotion mode control has been verified in wheeled mode only, because the sum of criteria requires several (more than 3) criteria to change mode properly; therefore, it cannot be verified in rolking mode, which has only three criteria. The same data that was collected during the test runs is presented in Figure 6.20 and has been utilized for verifying the functionality of the sum of criteria. Results calculated afterwards can be seen in Figure 6.21, where mode changes to rolking based on the sum of criteria have been marked with red dots. Mode changes calculated afterwards occurred almost at the same time as real mode changes based on using a single criterion, which proved that the sum of criteria could be utilized in mode change control successfully. An advantage of using the sum of criteria is that it invokes the mode change immediately, because the time window is not utilized in this method.

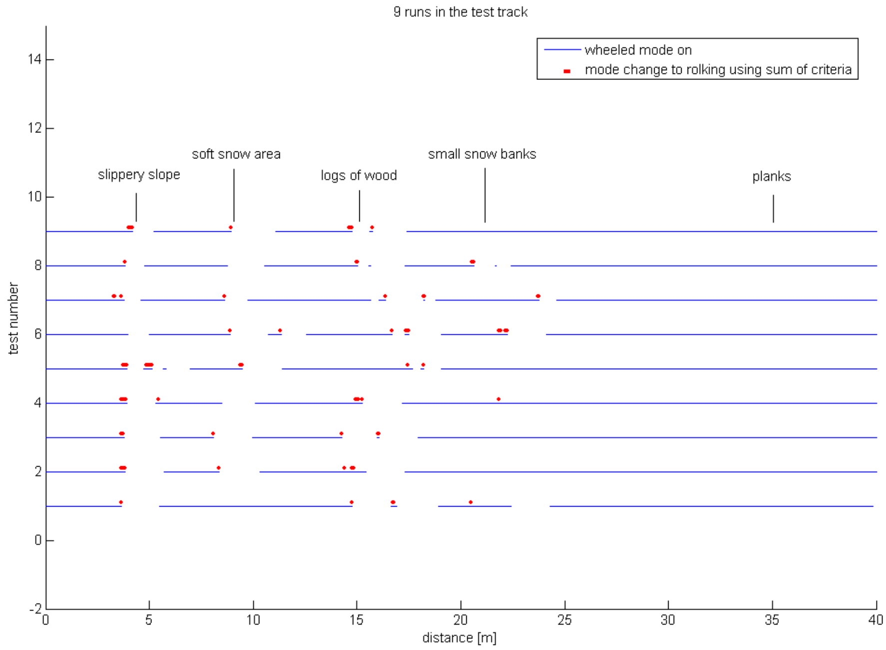


Figure 6.21 Locomotion mode changes using the sum of criteria. Mode changes marked with red dots have been calculated afterwards using data accumulated in test runs shown in Figure 6.20.

The sum of criteria of test run 9 is presented in detail in Figure 6.22. The value of the sum of criteria is higher when the terrain is difficult for wheels and lower when it is flat and firm.

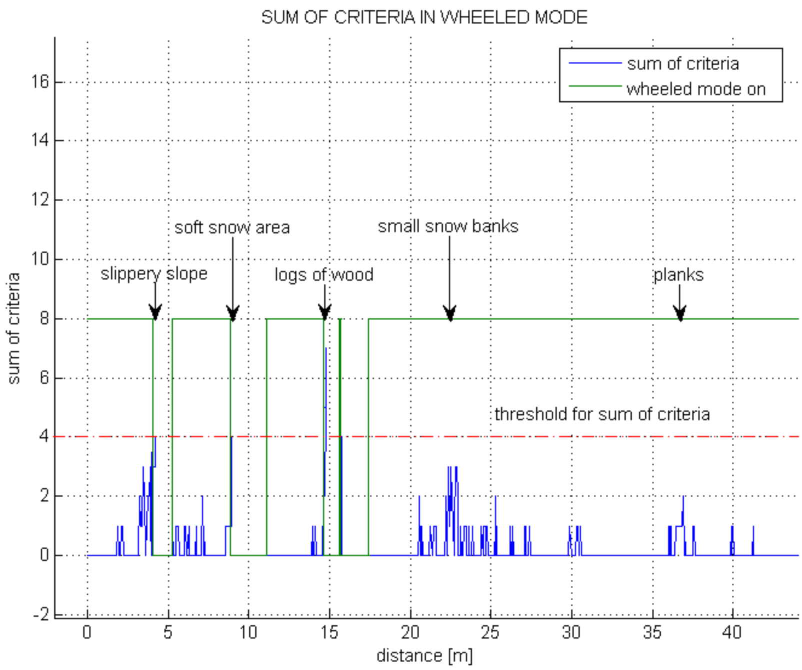


Figure 6.22 Sums of criteria have been calculated using data of test run 9. Sum of criteria is large when the terrain is difficult for wheels.

In wheeled mode, when a certain single wheel criterion causes mode change, then it is likely that the most problematic terrain area is under that wheel. If the criterion that causes the mode change is based on all the wheels, then the most problematic terrain area can be determined using sums of front-wheel criteria and back-wheel criteria. Utilization of the sum of criteria for evaluating the most problematic terrain area is illustrated in Figure 6.23; a larger sum means worse terrain. During test runs 4-7, the most problematic terrain area can be sensed in that way; the rolking distance (1 m or 2 m) will have already been decided.

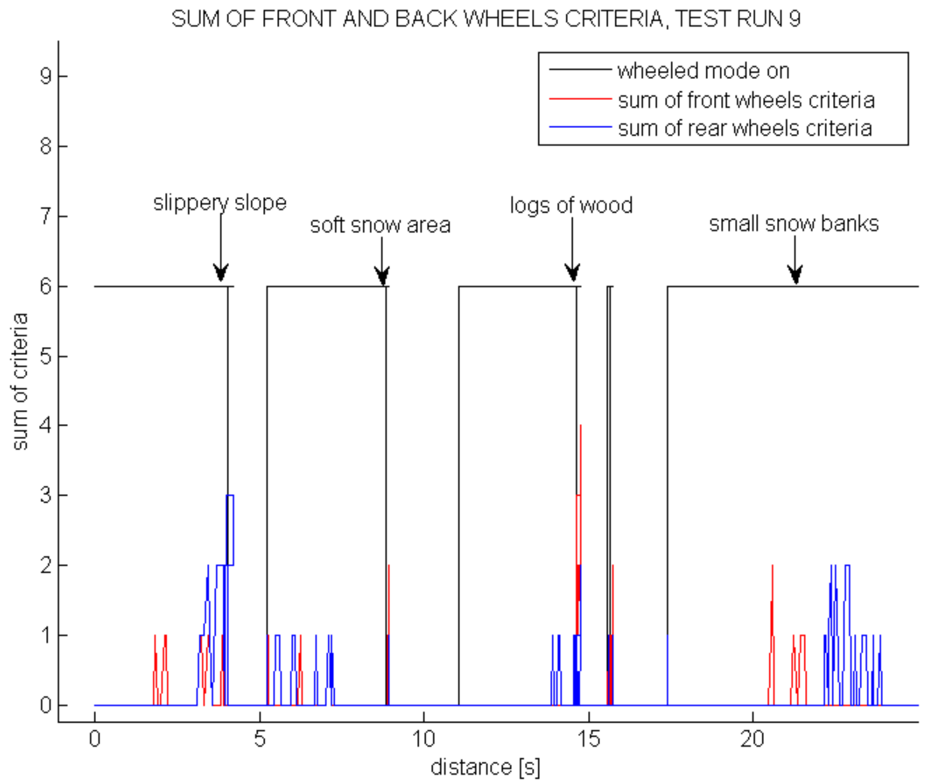


Figure 6.23 Sums of front-wheel criteria and back-wheel criteria. The sum of criteria is calculated using data of test run 9 shown in Figure 6.20. A larger sum means worse terrain area.

6.4 Results of experiments

The results of the experiments prove that it is possible to sense characteristics of vehicle-terrain interaction and some terrain geometry parameters using sensors for observing the internal state of the robot. Characteristics of vehicle-terrain interaction that can be used as criteria for automatic locomotion mode control are energy consumption, slipping of a wheel, motion resistance of a wheel and resisting force of a wheel. Terrain parameters are slope angle and roughness.

The results of Part 1 of the experiments prove that it is possible to measure reliably the forces through the currents of joint motors. Force and torque measurements have been used for evaluating the functionality of the wheel and also estimating terrain trafficability.

Threshold values of criteria were tuned using real data collected by moving through greatly varying terrain. WorkPartner was tuned to move carefully to avoid disturbing soil. The results of the test runs prove that automatic locomotion mode control can change mode correctly, depending on the terrain the use of sensing-based criteria. The mode changes to rolking occurred at the right moment when WorkPartner encountered vertical obstacles, when the wheel started to slip a lot or energy consumption increased due to soft soil. The mode changes happened before WorkPartner damaged the soil a lot. It also changed to wheeled mode when the terrain was traversable for wheels; furthermore, only a very small amount of needless mode change occurred. Thus, WorkPartner moved in an optimal way by driving with wheels as much as possible and rolking over obstacles or on soft soil only.

7 CONCLUSIONS

7.1 Main results

A locomotion system makes a robotic vehicle move, negotiate terrain and reach its goals during the execution of its task. Good locomotion capability is critical to the successful execution of a mobile robot's tasks. The locomotion should also be as autonomous as possible without the operator guiding the robot all the time.

In this work, an automatic locomotion mode control for the wheel-legged robot has been developed. This kind of robot can move using different locomotion modes; it can drive with the wheels, rolk (using wheels and legs at the same time) or even walk. The automatic locomotion mode control uses a mode that is optimal for current terrain. The proposed generic solution is valid for all types of wheeled locomotion systems with a 2-dof active suspension system for the wheel. The main principle in the development work has been good functionality in very varied conditions.

A key issue for locomotion mode control is the ability to sense characteristics of vehicle-terrain interaction, especially wheel-soil interaction, and the geometry of terrain. With the current range of sensing systems based on laser or vision technology, it is quite hard to discover the soil parameters needed for automatic locomotion mode control. Therefore, sensing is based on the wheels contacting the ground all the time. The locomotion mode control utilizes the same sensor system that the motion control system uses in the controlling of the multi-dof robotic platform; a minimal number of additional sensors are needed, if any. In low frictional soft conditions, body-speed sensing is challenging and an additional sensor, such as a sensor wheel, is required.

In this research, algorithms for sensing characteristics of vehicle-terrain interaction, such as energy consumption, slipping and drawbar force of a wheel and terrain parameters, such as terrain slope and roughness, in real time have been developed. The characteristics of vehicle-terrain interaction and terrain parameters are used as criteria for indicating the functioning of a wheel in wheeled mode and terrain trafficability in rolking mode. The criteria for the logic-based locomotion mode control have been selected on the basis of terramechanics. These criteria are used to determine whether a mode change is required. The criteria are mainly based on sensing forces and energy consumption.

The locomotion mode control can be tuned according to the definition of the task that the robot is carrying out. Typical optimisation motives for locomotion of the robot are avoiding environmental damages, maximizing speed of the robot or minimizing energy consumption; these also affect automatic locomotion mode control. So, the same vehicle can behave differently on the same terrain. For example, if time is critical, then the robot tries to locomote as fast as possible with the wheels, without taking into account whether the wheels are slipping or pushing obstacles with great force.

The proposed automatic locomotion mode control has been implemented and verified in the wheel-legged service robot, WorkPartner, successfully. After testing on a real field track, it can correctly be claimed that the WorkPartner drives with wheels over flat firm ground and automatically changes to rolking in order to negotiate obstacles. It also uses rolking mode on soft terrain automatically. Because of low-power wheel motors, the locomotion mode control of WorkPartner is tuned to operate in a sensitive way to avoid disturbing the soil. If more wheel power is available, the WorkPartner can be tuned differently.

7.2 Future work

As is usually the case with empirical research, the knowledge gained raises more questions than it answers. The effect of driving speed on the automatic locomotion mode control should be studied further. A time window is needed for preventing unnecessary mode change, because values of criteria may briefly exceed thresholds at times and lead to unnecessary mode change. Scaling the time window with respect to the speed of the robot should be studied further in wheeled mode. On the other hand, driving at higher speed requires a terrain scanner for the detection of obstacles. In addition, the speed of the robot also affects the stability and stress of the robot.

In this study, two alternative methods for utilizing wheeled-mode criteria have been developed and verified separately. The first is based on individual criteria and the second on the sum of criteria. These alternative methods could also be used at the same time in order to increase the reliability of the mode change. How to utilize both methods at the same time should be studied further.

In the future, the developed sensing methods will also be able to be used in developing new locomotion modes, such as free gait-based movement, in which the motion control switches a single wheel to a different mode, depending on terrain properties. An example of a new locomotion mode is halfrolk, where the wheels on one side work as wheels and on the other side as legs propulsing the body with more force in soft soil. The developed sensing system can also be utilized in collecting terrain information for path planning for later use.

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