California AHMCT Program University of California at Davis California Department of Transportation

DEVELOPMENT OF A HUMAN-ASSIST NON-STATIONARY DEVICE FOR LIFTING

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Abstract

The Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center has been developing robotic equipment and machinery for highway maintenance and construction operations. It is a cooperative venture between the University of California at Davis and the California Department of Transportation (Caltrans). The research and development projects have the goal of increasing safety and efficiency of roadwork operations through the appropriate application of automation solutions.

In this report, the development of a human-assist non-stationary device for lifting (HANDL) is presented. The device is designed to handle payloads at or just beyond the threshold of safe human manipulation, such as crates, barrels, guard-rail sections, and sacks of building materials. The machinery consists of two main components: an omnidirectional mobile platform and a grasp and lift manipulator. The former is developed here at the AHMCT Center and the latter is developed in collaboration with Steven's Institute of Technology Department of Mechanical Engineering. An omnidirectional platform allows the operator to drive the vehicle in any direction, instantly. This includes: moving laterally from rest, rotating in place, as well as simultaneous translation and rotation. Key research areas for the development of the platform are: testing the performance limits of the traction drive system and developing a torque-regulated control system. The grasp and lift manipulator is designed to grasp a variety of objects without damage. That is, the goal of the sensors and control system is to maintain contact without crushing the payload. Secondly, the system includes slip detection to sense if the payload is slipping the jaws during transport. To date the two components have been built and tested separately in the laboratory.

Executive Summary

According to the 2002 Liberty Mutual Workplace Safety Index, overexertion accounts for 26.2% of workplace injuries and has cost employers \$13.2 Billion in medical care and worker compensation, as presented by Croasmun 2004. Overexertion is defined as injuries caused by excessive lifting, pushing, pulling, holding, carrying, or throwing of an object. This classification implies that such objects are at or below the threshold for human manipulation. One can imagine a situation where a worker may opt to manually lift and carry a heavy box or bag of concrete rather than using a cart or hand-truck.

Manual handling of heavy objects is one of the most common tasks found in highway maintenance and construction operations and causes many injuries. The California Department of Transportation (Caltrans) reports that over 16% of all injuries during the period 1994 through 1999 were incurred during lifting tasks. Caltrans paid over \$16 million during the 1990's for back strain injuries which are often caused by lifting tasks. Corresponding to this requirement, a mobile lifting device, which is referred to as HANDL (Human-Assisted Nonstationary Device for Lifting) is developed by the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center in collaboration with the Stevens Institute of Technology. The device consists of an omnidirectional mobile platform and a force-controlled grasp and lift manipulator. The proofs-of-concept for the mobile platform and the manipulator have been fabricated and tested and demonstrated to Caltrans personnel in the winter of 2004.

The mobile platform demonstrated its maneuverability and intuitive operation as each of the Caltrans representatives drove the platform around the lab. The novelty of the design was that the platform could climb over an obstacle in any direction and from any initial orientation relative to the obstacle. A multimedia presentation was used to demonstrate the grasp and lift manipulator, which is being tested at Stevens Institute of Technology. The video demonstrates the ability of the gripper system to adjust for load variations.

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DISCLAIMER / DISCLOSURE

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Program, within the Department of Mechanical and Aeronautical Engineering at the University of California, Davis and the New Technology and Research Program of the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, state and federal governments and universities.

The contents of this report reflect the view of the author(s) who is (are) responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the STATE OF CALIFORNIA or the FEDERAL HIGHWAY ADMINISTRATION and the UNIVERSITY OF CALIFORNIA. This report does not constitute a standard, specification, or regulation.

1 Introduction

According to the 2002 Liberty Mutual Workplace Safety Index, overexertion accounts for 26.2% of workplace injuries and has cost employers \$13.2 Billion in medical care and worker compensation, as presented by Croasmun 2004. Overexertion is defined as injuries caused by excessive lifting, pushing, pulling, holding, carrying, or throwing of an object. This classification implies that such objects are at or below the threshold for human manipulation. One can imagine a situation where a worker may opt to manually lift and carry a heavy box or bag of concrete rather than using a cart or hand-truck. However, even maneuvering rolling payloads can lead to injury. This is called "inertia management" by Wannasuphoprasit et al. 1998 and has lead to extensive research on such topics as virtual walls and force feedback control. According to the author, steady, linear motion is relatively safe, since the operator need only supply longitudinal propulsion to overcome the rolling resistance. However, there is considerable difficulty in accelerating and decelerating the payload as well as in turning corners or avoiding obstacles. The latter is characterized by abrupt changes in direction or speed, generating appreciable forces on the operator.

Manual handling of heavy objects is one of the most common tasks found in highway maintenance and construction operations and causes many injuries. The California Department of Transportation (Caltrans) reports that over 16% of all injuries during the period 1994 through 1999 were incurred during lifting tasks. Caltrans paid over \$16 million during the 1990's for back strain injuries which are often caused by lifting tasks. Therefore, there is a definite need to develop a mobile lifting device for on-site material handling in highway work zones.

Corresponding to this requirement, a mobile lifting device, which is referred to as HANDL (Human-Assisted Nonstationary Device for Lifting) will be developed by the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center in collaboration with the Stevens Institute of Technology. HANDL consists of two subparts; a mobile platform, which will be developed by the AHMCT Research Center, and a manipulator. Such a device will address material handling tasks that are at the threshold of manual manipulation but with spatial constraints that prohibit the use of larger equipment, such as forklifts or cranes. The omnidirectional platform will be developed here at the University of California at Davis Advanced Highway Maintenance and Construction Technology (AHMCT)

Research Center, headed by Professor Velinsky. The lifting manipulator will be completed in collaboration with Professor Chung of Steven's Institute of Technology. Deliverables to Caltrans include laboratory demonstration of an omnidirectional platform and documentation describing the design and fabrication of the device. The platform must demonstrate the enhanced mobility as well as a sufficient degree of robustness, with the latter consisting of towing loads and overcoming obstacles representative of a work environment.

Although legged platforms have more accessibility to rough terrain than Wheeled Mobile Platforms (WMPs), WMPs have been previously studied and developed for all-terrain locomotion Cherif 1999, Fiorini 2000. This is because "Wheels are simple to control, pose fewer stability problems, use less energy per unit distance of motion, and can go faster than legs" Mekerrow 1991.

2 Problem Statement

To develop this prototype as an effective option for vehicle applications it is necessary to characterize the mechanics of the ball wheel mechanism. This characterization will lead to specifications on performance limitations of the traction drive system and to the formulation of an empirical or semi-empirical model, analogous to tire models in vehicle dynamics. However, for this dynamic characterization, and for motion tracking in general, accurate velocity feedback is necessary. The intuitive approach involves encoder-equipped contact rollers positioned along the equator of the ball wheel, analogous to the trackball PC mouse. This approach proves cumbersome since each wheel must be retractable to avoid interaction with the sphere rotation axis. The sensing problem is further complicated by the presence of spin (rotation about an axis normal to the ground plane), which introduces transverse slip at the rollers. Consequently, the development of the ball wheel mechanism will require a means of tracking three-dimensional rotation of the sphere without contact and with suitable robustness for non-ideal environments.

Navigation is a basic capability required of a mobile robot, and it remains a research issue Salichs and Moreno 2000. Navigation may be divided into four parts: path planning, localization, motion control, and obstacle avoidance. Path planning involves arranging a trajectory that allows the mobile robot to reach a goal position with minimum cost (e.g. time, energy, etc.) by using knowledge about its environment and the goal position. Localization provides the answer for where the mobile robot is in the environment, and motion control makes the mobile robot follow a given trajectory. Obstacle avoidance is a re-planning processes when the mobile robot's path interferes with unexpected obstacles.

A highway work zone is a temporary area, which means that knowledge of the environment is usually unknown to a mobile robot. For autonomous path planning, a mobile robot should explore a work zone for a while to gather information, and build a map of that area. This task is time consuming and a mobile robot may enter into an unsafe zone during exploration. Thus, autonomous path planning is not practical and is abandoned due to safety reasons. However, a desired trajectory and a field map around a desired trajectory can be built by manual maneuvering. Once a desired trajectory and a map is built, a mobile robot could travel along the desired trajectory autonomously, which requires localization, motion control, and obstacle avoidance.

Since the HANDL will typically involve the loading and unloading of an unknown object, both its dynamic and kinematic parameters will change due to deformation of the ball wheels. According to the literature survey, using incorrect values of these parameters increases the dead reckoning position error. An adaptive computed-torque controller Lewis et al. 2004 cannot estimate kinematic parameters alone, because they cannot be separated as a linear form. Kinematic parameters are used in the Jacobian matrix, which are transformed from desired state values in task space into desired state values in joint space. If the Jacobian matrix is not correct, a desired trajectory in task space does not correctly map to joint space. As a result, errors in task space will occur, even if a mobile robot is ideally controlled to trace a desired trajectory in joint space. Therefore, these parameters should be compensated, especially in the HANDL application due to its varying load distribution.

3 Contribution

The primary contribution of this thesis is the development of the ball wheel mechanism as a viable option for robust, omnidirectional locomotion in vehicle systems. This development consists of three elements: dynamic characterization of the ball-wheel traction drive system, a means of non-contact, three-dimensional angular motion tracking, and an adaptive control system. A prototype robust omnidirectional platform based on the ball wheel mechanism has been developed and successfully demonstrated to Caltrans personnel. The prototype is developed around a 12-inch diameter pneumatic sphere, composed of highly abrasion resistant polyurethane. Drive wheels, in contact with the sphere surface, actuate the sphere to rotate about an arbitrary axis. The novelty of this design, in contrast to other designs found in the literature, is active control over the contact pressure between the drive wheels and the sphere.

The non-contacting, three-dimensional angular motion sensor has been developed but has not been implemented in the current design. The enabling technology is based on a straightforward magnetometry scheme that tracks the field of cylindrically-symmetric ferromagnet embedded at the center of the sphere. The sensor configuration provides a direct measurement of the orientation of the magnet axis. Then, an approach based on vectororthogonality is used to derive the angular velocity vector of the rotating sphere from the sampled orientation data.

A motion controller for an Omnidirectional WMP with two ball wheels (OWMP) has also been developed. The proposed controller estimates not only uncertain dynamic parameters, but also uncertain kinematic parameters, and uses the estimated parameters in the control input computation and the Jacobian matrix. Therefore, traction position errors are significantly reduced. The previous work on adaptive controllers, which estimate both parameters, do not consider unequal wheel diameters, and they require an accurate absolute position and orientation. However, kinematic parameters estimation method on the proposed controller does not depend on absolute position and orientation feedback, and it estimates each wheel diameter separately. Therefore, the proposed controller is more practically applicable.

Its kinematic and dynamic models are derived, and a robust adaptive motion controller with kinematic parameters compensation is presented. A knowledge based kinematic parameters compensation method is proposed. The proposed controller was simulated with different trajectories to show feasibility and efficacy.

A localization method for the OWMP will be studied. This method will be used to compensate nonsystematic errors cooperating with the presented controller. It is anticipated that this work will result in a new kinematic parameters compensation method based on localization, which does not depend on the desired trajectory.

4 Omnidirectional Platform Design

4.1 Literature Review

Omnidirectional WMPs have three degrees-of-freedom of motion in the plane. Thus they are also known as holonomic mobile platforms. There are two types of omnidirectional WMPs. One type consists of WMPs with special wheels, and the other type includes WMPs with regular wheels. Special wheels, which have been mostly studied for the omnidirectional mobile platform, have an active tracking direction and a passive moving direction. Regular wheels can be broken into two types, caster wheels and steering wheels.



Figure 4.1.1 Mecanum Wheel OWMP Uranus by Muir and Neuman 1987

In the Mecanum wheel Ilon 1975, as shown in Figure 4.1.1, passive rollers are oriented at a 45° angle against the wheel shaft and four independently driven wheels are positioned with opposite orientations. Dickerson and Lapin 1991 presented the benefits of a vehicle with Mecanum wheels relative to an all wheel steered vehicle. Muir and Neuman 1987 introduced the kinematic model and developed an algorithm for feedback control of Uranus, which consists of four Mecanum wheels. WMPs with Mecanum wheels have some shortcomings. According to Nagatani et al. 2000, the vehicle with Mecanum wheels is susceptible to slippage, and as a result, with the same amount of wheel rotation, lateral traveling distance is different from longitudinal traveling distance. In addition, the ratio of longitudinal traveling distance over lateral traveling distance with the same amount of wheel rotation, changes with ground condition. The second

drawback is that the contact point between the wheel and the ground moves along a line parallel to the wheel axis, even though the wheel is always in contact with the ground. The lateral movement produce horizontal vibrations. The last drawback is that its ability to overcome obstacles is not independent of travel direction. This will be referred to as surmount capability from here on in this document, and nonisotropic surmount capability means directional dependence of the wheel's ability to overcome obstacles.



Figure 4.1.2 Orthogonal Wheel OWMP

Byun et al. 2002

In the orthogonal wheel Bluumrich 1974, as shown in Figure 2, passive rollers are oriented at a 90° angle against the wheel shaft. Since the classic orthogonal wheel has a gap between successive passive rollers, it produces discontinuous contact with the ground, which causes vertical vibration. To reduce the gap between passive rollers, several orthogonal wheels have been devised. Killough and Pin Killough and Pin 1992, Pin and Killough 1994 developed a new orthogonal wheel using two original orthogonal wheels overlapped. But, due to the changing contact point from one wheel to the other wheel, horizontal vibrations are generated. Byun et al. 2001, Byun et al. 2002, Byun and Song 2003 designed the continuous alternate wheels, which eliminates gaps between passive rollers. Hirose and Amano Hirose and Amano 1993 developed the Vuton Crawler which is a caterpillar track with free rollers. A

vehicle with four Vuton Crawlers performs omnidirectional movement. Damoto et al. Damoto et al. 2001 introduced the Omni-Disc, which consists of several free rollers arranged in a disc. However, all types of orthogonal wheels have nonisotropic surmount capability, which depends on the diameter of the wheel or the passive roller.



Figure 4.1.3 Spherical Wheel OWMP

(a) Ball wheel Wada and Asada 1999 (b) ROLLMOBS Ferriere and Raucent 1998

Spherical wheels, as shown in Figure 3, can make continuous contact with the ground and have isotropic surmount capability. Therefore, the spherical wheel based platforms demonstrate good omnidirectional mobility. West and Asada West and Asada 1997 designed a ball wheel which is comprised of a spherical wheel and closing rollers. This wheel was applied to a reconfiguable mobile bed Mascaro et al. 1997 and a wheel chair Wada and Asada 1999. Tahboub and Asada Tahboub and Asada 2002 presented kinematic and dynamic analysis of the vehicle with four ball wheels. Ferrière et al. Ferriere et al. 2001 introduced ROLLMOBS, which is a spherical wheel driven by an orthogonal wheel. However, the traction force by each spherical wheel is not usually along the heading direction of the platform. Accordingly, the traction force is affected by the friction coefficient between the wheels and the ground. The friction coefficient can change significantly due to irregular ground conditions. Therefore, this type of the WMP can only be usable on a well controlled floor.

An actuated caster wheel, which is a caster wheel with actuators for steering and driving, as shown in Figure 4, was conceptually described by Muir and Neuman Muir and Neuman 1987,

and was demonstrated by Wada and Mori Wada and Mori 1996. Holmberg and Khatib Holmberg and Khatib 2000 presented a dynamic model of this vehicle and designed a control algorithm. In order to reduce scrubbing force during steering, Yu et al Yu et al. 2000 introduce an Active Split Offset Caster. One drawback of these vehicles with caster wheels is that small vehicle motions require large motion of the wheels. According to Holmberg and Khatib Holmberg and Khatib 2000, significant disturbances occurred when a vehicle changes its moving direction 180 degrees.



Figure 4.1.4 Active Caster Wheel OWMP

Holmberg and Khatib 2000

4.2 Ball Wheel Designs

The ball wheel designs presented above have been demonstrated successfully in the laboratory, achieving omnidirectionality with a minimum number of actuators. However, a rolling element with a passive and an active axis may be problematic in an unstructured environment with uncertain, inconsistent traction. Since the velocity vector of each wheel cannot be independently regulated, it is uncertain whether these platforms can compensate for the traction inconsistencies. For example, consider motion of the platform mass-center, purely in the \hat{j}_2 direction. The sum of the components of the velocity vectors \underline{v}_B and \underline{v}_C in the \hat{j}_2 direction must be equivalent to the magnitude of \underline{v}_A . Furthermore, the components of the

velocity vectors \underline{v}_B and \underline{v}_C in the \hat{j}_1 direction must be sum to zero. If these constraints are not satisfied, the actual trajectory of the platform becomes uncertain.



Figure 4.2.1 Ball Wheel Kinematics

(a) Diagram of ROLLMOBS (b) Diagram of ROLLMOBS wheel kinematics

Ostrovskaya and Angeles present a slightly different approach. Their conceptual model describes a platform in which each sphere is driven about a single axis, as in the designs above, but each sphere and drive train assembly is mounted in a carrier that is actively rotated. The carriers rotate about an axis normal to the plane, passing through the sphere center. Their platform consists of three such carriers for a total of six actuators. Since the authors have yet to develop a proof of concept, the effectiveness of this design remains to be seen. However, in their formulation, there are several instances where no-slip conditions are assumed. For a robust mobile platform designed for high-load applications, dynamic modeling may be inevitable. As a result, slip must be present to generate traction forces for longitudinal motion and direction changes.



Figure 4.2.2 Ball Wheel Mechanism Drive System

Diagram of bench-top proof of concept drive system

The novelty of the proposed ball wheel mechanism, in contrast to designs found in the literature, is two-fold: driving a single sphere about multiple axes and active control over the contact pressure between the drive wheel and the sphere. These variations on the designs currently found in the literature are necessary for high-load applications in unstructured environments.

Generally, a sphere rolling on a plane can rotate about any axis passing through its center with complete isotropy. For the moment, assume zero spin (rotation about the plane-normal axis, passing through the sphere center) and let the two-dimensional angular velocity vector be decomposed to two orthogonal components. By regulating these two components, the net angular velocity vector of the sphere can assume any, arbitrary orientation in the equatorial plane. Practically, the two orthogonal rotation components are controlled via drive wheels in friction contact with the sphere along its equator. In a rigid-body, kinematic model without spin, the velocity vector of a point on the sphere surface, along its equator, is normal to the plane at all times. As a result, no transverse or lateral slip exists between the drive wheels and the sphere. It is the non-holonomic nature of the drive wheels that restrict spin and actively set the axis of rotation of the sphere. While the mechanism is not truly omnidirectional (rotation or orientation is not defined nor actuated), its position is unconstrained on the plane. Full omnidirectionality is achieved by combining two such mechanisms. Unlike the ball wheels used by West and Asada and Ferriere and Raucent, the two-dimensional velocity vector of each sphere in this mechanism can be completely defined. As a result, each ball wheel mechanism can compensate for wheel slip attributed to inconsistent traction or eccentric loading of the platform.



Figure 4.2.3 Bench-top Proof of Concept

Photo of bench-top proof of concept of robust ball wheel mechanism

The bench-top proof of concept of the robust ball wheel mechanism is based on a 12-inch diameter, pneumatic sphere composed of highly abrasion resistant polyurethane. Four polyurethane contact wheels are equally spaced along the equator of the sphere. Two adjacent

wheels are actuated by servo motors through a precision gear head. Opposite each drive wheel is a passive wheel equipped with a high resolution optical encoder. The contact pressure between the wheels and the sphere is generated with pneumatic cylinders. Currently, the cylinder pressure is set manually with a mechanical regulator and actuated with solenoid valves. The sphere is supported by three spherical casters oriented symmetrically about the vertical axis. The axis of rotation and angular speed of the sphere is completely defined by setting the velocity ratio of the two drive wheels. This ratio is determined by a relatively simple trigonometric function of the desired heading direction and the desired speed.

The proof of concept provides empirical data that quantifies the accuracy of the kinematic model, which neglects the inertial and material affects. Moreover, the relationship between the sphere velocity and drive wheel velocities is based on a kinematic model with point contacts in pure rolling. In the experiment, the drive wheels are regulated such that the axis of rotation of the sphere cycles through 360°. The experiments show that, in the absence of a ground load, the kinematic model produces the desired motion, through the majority of the operating range.

However, tracking errors occur whenever the axis of rotation of the sphere enters a drive wheel contact region. These errors are primarily attributed to material effects of the sphere and the drive wheels. As the drive wheels are pressed against the sphere, the relatively soft polymers deform, generating a finite contact area or patch, which is necessary for traction. The magnitude of this area is a function of the contact pressure, material properties, as well as geometry. While the exact nature of the material interaction is complex, the net effect is slip, between the sphere and drive wheels, due to velocity variation across the contact patch. Moreover, the existence of a finite contact patch undermines the assumption of point contacts in pure rolling.



Figure 4.2.4 Ball Wheel Motion Tracking Results

Omnidirectional motion tracking data for (a) motor A and (b) motor B

Slip occurs throughout the range of motion but is a maximum when the axis of rotation of the sphere enters the contact patch. Conceptually, the axis of rotation is fixed relative to the vehicle as is a point on the sphere surface along this axis, herein called the zero-velocity point. However, the velocity of material points about the zero-velocity point is finite and grows with distance. When the sphere axis of rotation is orthogonal to the axis of rotation of a drive or passive encoder wheel, that particular wheel is not rotating. With point contacts, there would be no relative velocity between the zero-velocity point and the non-rotating wheel. However, with a finite contact patch, the sphere material adjacent to the zero-velocity will slip about the non-rotating wheel.

This slip generates shear forces that act as a disturbance moment on the dynamics of the sphere. As a result, the complimentary drive wheel must compensate for the disturbance by generating more torque. The cost of maintaining contact in this configuration is power dissipation and excessive wear on both the sphere and the drive wheel. Active control of the contact pressure allows the drive wheel to be retracted from the sphere in this situation, thereby eliminating the disturbance moment. However, once a drive wheel is retracted, controllability of the sphere is lost.

A solution to this problem involves using three drive assemblies oriented 120° apart. With this configuration, only two of the three drive wheels engage the sphere at any given moment. Preprogrammed geometric conditions are used to determine wheels are to be engaged based the desired trajectory. For certain trajectories, all three drives can be engaged for additional torque.



Figure 4.2.5 Redundant Drive System

Diagram of mobile proof of concept of robust ball wheel mechanism with redundant drive system

While not instrumented for feedback, a mobile platform was developed to demonstrate the enhanced maneuverability and robustness of the ball wheel mechanism. More specifically, the mobile platform is an alternative to more rigorous testing with a dynamometer, which would require additional machine design and instrumentation. Robustness is demonstrated by climbing steps, with a net height of four inches, as well as climbing over, and maneuvering around, other obstacles representative of a worksite, e.g. cables, tools, etc. Configured for human-in-the-loop operation, the operator provides the feedback and compensation at the joystick to generate the desired trajectory. The operator also provides the balance and orientation control of the platform-similar to handling a wheel barrow. During testing the ball wheel mechanism effectively demonstrates the desired maneuverability and climbing tasks. Traction force was tested with a spring scale and the drive wheels began slipping on the sphere at 60 lbs. In practice, the device was able to tow a rolling payload in excess of 200 lbs.



Figure 4.2.6 Mobile Proof of Concept

Photo of mobile proof of concept of robust ball wheel mechanism

4.3 Vehicle Systems Modeling

For modeling vehicle systems, a key distinction is a kinematic versus a dynamic model. In a kinematic model the motion of the body is defined without regards to forces while in a dynamic model the ensuing motion is a result of applied and inertial forces. As a result, a dynamic model is generally more complex. Relatively small, wheeled mobile robots (WMR) often rely on kinematics for vehicle tracking, known as dead reckoning. In which, measured wheel rotations are fed into a kinematic model to calculate the vehicle trajectory. However, according to Balakrishna and Ghosal 1995, and Williams et al. 2002, tracking WMRs with dead-reckoning and pure rolling constraints lead to substantial error. As a result, both authors resort to dynamic models with linear and non-linear variants of the Coulomb friction model to account for wheel slip.

When WMRs are used for construction or material handling, load demands are higher and, as a result, have significant affect on the vehicle motion. Boyden and Velinsky Boyden and Velinsky 1994 compare kinematic and dynamic models for WMRs in high load applications through simulation. Experimental verification of this work followed in Hong et al. 1999 by Hong, Velinsky, and Feng. This research determined that for a given control algorithm for tracking a reference path, using a kinematic model for the system plant lead to substantially more error than with a dynamic model. Aside from inertial and externally applied forces, a dynamic model requires consideration of forces and moments generated by the tires. The field of tire mechanics involves the study of constitutive laws that relate the tire outputs: longitudinal force, lateral force and aligning moment, to the tire inputs: normal load, side slip angle, and longitudinal slip.

Two supplements to the journal Vehicle System Dynamics compile key papers on tire analysis, see Pacejka 1991, Bohm and Willumeit 1997. In Pacejka and Bakker 1993 Pacejka presents the latest version of the Magic Tyre Formula which is an empirical model that accurately describes the steady-state tire force and moment characteristics in terms of the side slip angle and the longitudinal slip. A drawback with Pacejka's model is the large number of parameters from empirical data that are necessary to formulate the relationships. Another prevalent model is by Dugoff Dugoff et al. 1970 which is based on idealized tire/road contact geometry and stresses arising from elastic deformation. There are also several examples of simplified tire models based on the more complex models described above, see for example Shim and Margolis Shim and Margolis 2000 and Guntur and Sankar Guntur and Sankar 1980. These simplified models reduce the number of necessary parameters and facilitate numerical simulations and controls implementation.

Of particular interest to this project is related work by Bernard and Clover Bernard and Clover 1995 who address tire modeling in low speed applications. Historically, there has been little interest on low-speed tire modeling because vehicle dynamacists are more concerned with the limits of lateral tire forces at high speeds. Furthermore low-speeds lead to numerical difficulties because expressions for slip are inversely proportional to the longitudinal speed. Motivation for this work stems from the need for a model with a seamless transition from low to high speeds; the primary application being vehicle simulators. For omnidirectional mobility in high load applications a model that can handle low-speeds and transients is desirable because of the propensity for abrupt direction changes.

5 Non-Contact Motion Sensing

5.1 Literature Review

For single-axis, rotating devices there are many non-contact motion sensing options: for example, optical encoders, tachometers, and magnetic pick-up coils. The sensing problem is more involved when the body has multiple rotational degrees of freedom. Optical and vision sensing techniques measure surface displacement, which can be used to derive the tangential surface velocity at a given location. Current image-processing techniques used in optical mouse technology limits the tangential speed to 1 ft/s and require a relatively small sensor-to-surface gap, on the order of millimeters Agilent 2001. More sophisticated vision techniques are based on edge or contrast detection which requires a surface grid or pattern Garner et al. 2001. Both the surface-to-gap constraint and the surface pattern requirement are problematic in harsh environments. In the absence of spin, two, non-collinear tangential velocity measurements are sufficient to extract the angular velocity of the sphere. However, for three-dimensional rotation the inverse problem becomes ill-conditioned according to Verstraete and Soutas-Little 1990. That is, the matrix relating the three-dimensional angular velocity vector and the threedimensional tangential velocity vector is skew-symmetric and its inverse is undefined. To overcome this, Verstraete uses a least squares approach from a multitude of position measurements to estimate the angular velocity and angular acceleration of limb segments.

Magnetometry based motion tracking has applications in the biomedical field for noninvasive gastrointestinal transit studies, as well as in geo-physics, vehicle detection, and detection of buried ordnance, such as mines and artillery shells. For example, consider Prakash and Spelman 1997 and Weitschies et al. 1994. In this research a grid of magnetometers are used to localize a magnetic marker. Data reduction for localization involves an iterative least squares approach, the accuracy of which is sensitive to the orientation of the magnetic marker. For motion tracking in robust vehicle applications, much of the literature implements magnetometry with active field sources. Jacobs and Nelson 2001 has developed magnetic sensor schemes for abdominal-cavity motion detection in crash test dummies and helmet tracking in aircraft cockpits. This research addresses key difficulties in motion tracking of dynamic systems, namely harsh environments, short response times and signal distortion from ambient fields. Jacobs, along with Raab et al. 1979, use tri-axial, active sources fixed to the body to generate time-varying magnetic fields. By using different frequencies for each source coil, it is possible to demodulate the three, orthogonal fields. These multi-directional fields are necessary to track through singularities as well as to differentiate the signal field from ambient fields.

With sensor development key specifications are accuracy, resolution and bandwidth. The sensing requirements are primarily defined by the response time of the system or plant, but may also depend on the mode of operation. For this project, a principal mode of operation is humanin-the-loop control or teleoperation. As a result, the response time of the vehicle is limited by the response time of human sensory input and neuromuscular output. In Brooks 1990 Brooks presents a survey on telerobotic response requirements. In summary, human input bandwidth is about 320 Hz and human output bandwidth is about 10 Hz. This information provides insight that bounds vehicle response for safe human interaction. These bounds can be used to size actuators and define the necessary bandwidth and resolution of the feedback sensors.

5.2 Magnetometry Scheme



Figure 5.2.1 Magnetic Dipole Field

Schematic of field lines from magnetic dipole

The proposed magnetometry scheme is based on tracking the magnetic flux density vector of a cylindrically-symmetric ferromagnet, which will be modeled as a magnetic dipole. Generally, the theoretical field equations are a function of six configuration variables and physical properties of the magnet. For this analysis it will be assumed that the sphere and the magnet are both fixed in translation and both are perfectly centered at the origin of an inertial reference frame.

Consider the planar case as shown in Fig. 5.2.1. The magnet is located at origin O_m and the sensor is located at point O_s . Unit vector \hat{p} defines the magnet axis, \underline{r} is the position vector from O_m to O_s , and θ is the relative orientation between \hat{p} and \underline{r} . The magnetic flux density vector \underline{B} is decomposed into radial and tangential components B_r and B_t , and are, respectively,

$$\begin{cases} B_r = \frac{\mu_0 M}{2\pi r^3} \cos \theta \\ B_t = \frac{\mu_0 M}{4\pi r^3} \sin \theta \end{cases}.$$
(5.2.1)

The relationship between the field components and the configuration variables can be found in most texts on electromagnetic fields, such as Shadowitz 1975. For the threedimensional case, the expressions in Eq. 5.2.1 can be used in the plane defined by vectors \hat{p} and \underline{r} . It remains, then, to find the relationship between the radial and tangential field components and the three-dimensional, measured field components. A diagram of the configuration is shown in Fig. 5.2.2.



Figure 5.2.2 Sensor Configuration

The magnetometer is positioned along the x-axis of the inertial reference frame. This significantly simplifies the geometry of the problem. {Bx,By,Bz} are the orthogonal field

components from the magnetometer and $\{1,m,n\}$ are the direction cosines used to parameterize the magnet axis \hat{p} . Next, orthogonal triad $\{\hat{e}_r, \hat{e}_n, \hat{e}_t\}$ is positioned at O_s and defined as,

$$\left\{ \hat{e}_r = \frac{\underline{r}}{\|r\|}, \, \hat{e}_n = \frac{\hat{e}_r \times \hat{p}}{\|\hat{e}_r \times \hat{p}\|}, \, \hat{e}_t = \hat{e}_r \times \hat{e}_n \right\}.$$
(5.2.2)

Unit vector \hat{e}_r is directed along the radial vector, \hat{e}_n is a unit vector normal to the plane defined by \hat{p} and \underline{r} , and \hat{e}_t is the tangential unit vector in the \hat{e}_n -plane, orthogonal to \hat{e}_r . Moreover, the trigonometric functions in Eq. 5.2.1 can be expressed as a function of the direction cosines of \hat{p} ; as such,

$$\begin{cases} \cos \theta = l \\ \sin \theta = \sqrt{m^2 + n^2} \end{cases}.$$
 (5.2.3)

For an arbitrary orientation of \hat{p} , the theoretical magnetic flux density vector can be expressed as,

$$\underline{B}_{TH} = B_r \hat{e}_r + B_t \hat{e}_t. \tag{5.2.4}$$

Eq. 5.2.2 and Eq. 5.2.3 provide the proper sign conventions through the transformations. Substituting Eq. 5.2.1-5.2.3 into Eq. 5.2.4 results in the following expression:

$$\underline{B}_{M} = \begin{bmatrix} B_{x} \\ B_{y} \\ B_{z} \end{bmatrix}_{M} \cong \underline{B}_{TH} = \begin{bmatrix} \frac{M}{2\pi R^{3}} l \\ -\frac{M}{4\pi R^{3}} m \\ -\frac{M}{2\pi R^{3}} n \end{bmatrix}.$$
(5.2.5)

Eq. 5.2.5 states that the direction cosines of \hat{p} are linearly proportional to the measured field components. Assuming a fixed sphere radius, the sampled data can be used to calculate the aboslute position of a point on the sphere surface throughout the angular motion.

Another important issue occurs when the axis of the cylindrical magnet is perfectly aligned with one of the coordinate axes. Due to the assumed cylindrical symmetry of the magnet, there will be no field variation in this configuration. An approach that could address this problem is multiple, active fields. This involves the installation of two active coil elements, orthogonally oriented, at the sphere center. Each coil will generate cylindrically symmetric magnetic fields, analogous to the permanent magnet, but these fields will have distinct frequencies. The measured field at each sensor will be a superposition of these signals. However, through demodulation the fields can be demodulated into distinct signals. Then the formulation presented in this proposal can be carried out with each signal. Since these active fields are orthogonal, it is certain that only one of the two can ever be in a singular orientation. Practically, this scheme provides a redundant measurement.

5.3 Velocity Estimation

With the exception of Doppler techniques and certain inductive techniques used in tachometers, very few sensors provide velocity data directly. Often velocity is estimated from position and acceleration data, which are more commonly sensed quantities. There are essentially two methods for velocity estimation: numerical differentiation and state observers, or state estimators. Numerical differentiation estimates the velocity from current and previous values of position; the simplest scheme being the backward difference. Generally, observers estimate unavailable states from available states and a dynamic model of the system. For example Yang and Ke 2000 show that a state observer based on position and motor current data is superior to a backward difference scheme in estimating the motor velocity. The benefits include: a reduction of errors due to quantization and improved accuracy at low velocities.

However, many non-linear observers require numerical differentiation for state estimation; see Diop et al. 2001 for example. Furthermore, when a dynamic model is not available, the observer approach is not an option. In general, while numerical differentiation is considered an ill-posed or ill-conditioned problem, its applications in control theory and in the differentiation of non-linear functions have led to many advances in the art. Kahn and Ohba Khan and Ohba 2000 present new finite difference approximations for differentiation that match the accuracy of interpolating polynomials, with superior performance in high frequency oscillatory functions. Diop et al. in Braci and Diop 2003 compare the performance of a linear differentiation filter, a backward finite difference differentiation scheme, and the Savitsky-Golay differentiation scheme for differentiating on-line sampled data.

For this preliminary feasibility test the raw data will run through a second order Butterworth filter and a simple discrete differentiator in Simulink will be used to carry out the differentiations. Since the magnetometry data is sinusoidal for pure rotation of the magnet the signal is well-behaved.



Figure 5.3.1 Magnetic Sensor Data

Differentiation and filtering of magnetometry data

5.4 Kinematics of a Rigid Body

With the position data successfully acquired and the data satisfactorily differentiated, the remaining task involves deriving the rigid-body angular motion of the sphere from the given information. From the perspective of spatial kinematics the forward problem of extracting the trajectory of a point on a rigid body, given the axis of rotation and the rotation angle about this axis, is a relatively straight forward matter. Methods for representing such motion include: rotation tensors, exponential mapping in the form of the Rodrigues formula, Quaternions, Euler angles, and screw displacements. Fundamental descriptions of these methods can be found in Chapter 2 of Murray et al. 1994. Even with a large number of joints, the forward problem essentially consists of a series of linear transformations based on knowledge of the rotation axis and the angle or rotation of each joint. A standard in robotics is the Denavit-Hartenberg parameters Murray et al. 1994, which is a set of rules for specifying the position and orientation of frames attached to each successive link of the system. Regardless of the representation, the inverse kinematics of a system with more than one axis of rotation is significantly more involved. Conceptually, the goal is to calculate the joint angles for a given displacement of an

endpoint or orientation of an end-effector. Several techniques are shown in Chapter 3 of Murray et al. 1994 and some numerical approaches are presented in Angeles 1985. Generally, the analytical approach involves matrix inversion or pseudo-inversion to extract the joint angles.

The material presented above involves kinematic analysis where the orientation of the rotation axes of a multilink system are known and each joint is assumed to rotate about a single axis. For example, spherical wrists in robotics consist of three revolute joints all orthogonally oriented. These three joints provide the three degrees of freedom for spherical motion. Rico-Martinez and Gallardo-Alvarado claim that up until the last decade, there appeared to be no results relating a representation of a spherical motion and its angular velocity and acceleration Rico-Martinez and Gallardo-Alvarado 2000. According to the authors, works related to this topic are limited to Peres 1980, Nikravesh et al. 1985, Angeles 1988. In Angeles 1988, Angeles presents a treatment of the rotation of a rigid body about a fixed point based on a set parameters called natural invariants, which consists of a unit vector defining the axis of rotation and a scalar rotation angle. This formulation applies to systems where the axis of rotation is not fixed in orientation but remains a known quantity.

A different approach is provided by Halvorsen et al. 1999 for estimating the axis of rotation, or the center of rotation, in biomechanics studies. Like Angeles, Halvorsen considers invariants in rotational motion. More specifically, the axis of rotation is the intersection of two planes normal to each of the displacements and going through the midpoint of each displacement. Formally, this is cast as: the axis of rotation is normal to the plane spanned by all the displacements. Halvorsen formulates this approach by finding the unit vector that minimizes the sum of squares of scalar products of the displacements with the unit vector representing the rotation axis.

5.5 Determination of Angular Velocity Vector

Spherical motion is defined as motion of a rigid body about a fixed point O. The inverse problem, of calculating the angular displacement given the axis of rotation and the trajectory of a point on the body, is a straightforward matter; several techniques are shown in Murray et al. 1994. However, determining the orientation of the rotation axis and the angular displacement, given only the trajectory of a point, is not well established. A method for estimating these values can be found in the biomechanics literature for limb motion tracking. In an approach by

Halvorsen et al. 1999, two displacements are used to locate the axis of rotation. More specifically, each of these displacement vectors represent a plane; the axis of rotation is the intersection of these planes. Halvorsen's method involves a quadratic optimization problem and is developed for post-processing.

For applications in vehicle tracking, a real-time method is necessary. The scheme presented below is based on Halvorsen's concept of vector orthogonality but results from a direct calculation of the on-line sampled data.



Figure 5.4.1 Kinematics of Spherical Motion

Diagram for (a) general system kinematics and (b) planar sub-problem

Fig. 5.5.1(a) is a diagram for the problem formulation. The position vector $\underline{\mathbf{r}}$ of point p on sphere S is parameterized by the direction cosines {1,m,n}. As S rotates with angular velocity $\underline{\omega}$, point p follows the circular arc C. Fig. 5.5.1(b) illustrates the vector relations of this motion; $(\underline{\mathbf{r}} \cdot \hat{e})\hat{e}$ is the projection of position vector $\underline{\mathbf{r}}$ along the axis of rotation, which is denoted by unit vector \hat{e} and $\underline{\mathbf{r}}_{Perp}$ is another projection of $\underline{\mathbf{r}}$ and is related the other configuration variables by:

$$\underline{\mathbf{r}}_{Perp} \times \underline{\mathbf{r}}'_{Perp} = \left| \underline{\mathbf{r}}_{Perp} \right| \left| \underline{\mathbf{r}}'_{Perp} \right| \sin \alpha \ \hat{e} \ . \tag{5.5.1}$$

All the variables in Eq. 5.5.1 are unknown since the projections cannot be made until the axis of rotation is determined. However, following Halvorsen's work, $\underline{\mathbf{r}}_{Perp}$ can be replaced with a vector $\hat{\mathbf{u}}$ which is a unit vector representing the instantaneous heading of the position vector.
Computationally, \hat{u} is the instantaneous tangential velocity of point p, normalized by the velocity magnitude, and requires numerical differentiation of the position vector data; as such,

$$\hat{\mathbf{u}} = \frac{\underline{\mathbf{V}}_{\mathrm{p}}}{\left|\underline{\mathbf{v}}_{\mathrm{p}}\right|} = \frac{\dot{\underline{\mathbf{r}}}}{\left|\underline{\dot{\mathbf{r}}}\right|}.$$
(5.5.2)

Substituting \hat{u} for \underline{r}_{Perp} and making a small angle approximation, Eq. 5.5.1 becomes,

$$\hat{\mathbf{u}} \times \hat{\mathbf{u}}' = \alpha \,\hat{\mathbf{e}} \,. \tag{5.5.3}$$

Eq. 5.5.3 is often denoted the rotation vector. The numerical expression of Eq. 5.5.3 for an approximation of the angular velocity is

$$\frac{\hat{\mathbf{u}}(\mathbf{t}-\mathbf{T}) \times \hat{\mathbf{u}}(\mathbf{t})}{\mathbf{T}} = \frac{\alpha(t)}{\mathbf{T}} \,\hat{\mathbf{e}} \approx \omega(t) \,. \tag{5.5.4}$$

5.6 Simulation

In the analysis outlined above, the inputs are the direction cosines of the magnet axis relative to the inertial reference frame and the outputs are the magnitude and direction of the sphere angular velocity vector. To verify this technique direction cosine data is generated based on an assumed initial orientation of the magnet, a defined axis of rotation, and a defined angular speed. The details of this derivation will described shortly, but the final relationship is

$$\begin{bmatrix} l\\m\\n \end{bmatrix} = \begin{bmatrix} \frac{R_h}{R} \cos q_1 + \frac{R_v}{R} \sin q_1 \sin \Omega t\\ \frac{R_h}{R} \sin q_1 - \frac{R_v}{R} \cos q_1 \sin \Omega t\\ \frac{R_v}{R} \cos \Omega t \end{bmatrix}$$
(5.6.1)

The objective then is to extract the angular speed Ω and the orientation of the rotation axis, which is parameterized by the configuration coordinate q_1 , from the sampled direction cosines $\{l,m,n\}$. It is apparent from Eq. 5.6.1 that the system of equations is non-linear, making inversion non-trivial; this is why the proposed approach was adopted. Furthermore, the large radian values and volume of rotations prohibit linearization. In the absence of noise the algorithm exactly reproduces the input angular speed and the defined axis of rotation. There is significant noise amplification in the calculations, for the addition of random noise leaves the results indiscernible. However, a second order Butterworth filter, or the more sophisticated Savitsky-Golay filter, effectively attenuates the noise and recaptures the signal. This exercise imparts sufficient confidence in the sensor scheme to carry-on with experimental verification.



Figure 5.6.1 System Configuration for Simulation System configuration for simulating direction cosine data

The configuration for simulating the direction cosine data is shown in Fig. 5.6.1. Let sphere S rotate about the \hat{e}_1 -axis with angular rate Ω . Before motion ensues, let <u>r</u> be contained in the $\{\hat{e}_1, \hat{e}_3\}$ -plane at an angle of $q_2(0)$ relative to the \hat{e}_3 -axis. The horizontal and vertical components <u>r</u> in the *E* frame are respectively,

$$\begin{cases} R_h = R \sin(q_2(0)) \\ R_v = R \cos(q_2(0)) \end{cases}$$
(5.6.2)

These quantities are invariant for a given initial configuration $q_2(0)$ and a given axis of rotation \hat{e}_1 . If \underline{r} is not initially contained in the $\{\hat{e}_1, \hat{e}_3\}$ -plane then the trigonometric functions must be replaced with their corresponding vector or scalar product; as such,

$$\begin{cases} R_h = \underline{r} \cdot \hat{e}_1 \\ R_v = |\underline{r} \times \hat{e}_1| \end{cases}$$
(5.6.3)

In the *E* frame the vector \underline{r} is expressed as,

$$\underline{r} = R_h \hat{e}_1 + R_v \hat{e}_3 \,. \tag{5.6.4}$$

As S rotates, point p(t-T) moves to point p(t) over one sampling period. The displacement of p can be represented in two manners: variation in the three direction cosines representing vector \underline{r} in N or as pure rotation of Ωt about the \hat{e}_1 -axis. These expressions are written respectively as,

$$\underline{r}_{N} = Rl\,\hat{i} + Rm\,\hat{j} + Rn\,\hat{k} \tag{5.6.5}$$

and

$$\underline{r}_{D} = R_{h}\hat{e}_{1} - R_{v}\sin(\Omega t)\hat{e}_{2} + R_{v}\cos(\Omega t)\hat{e}_{3}.$$
(5.6.6)

Resolving Eq.5.6.6 into the N frame yields,

$$\underline{r}_{D} = D_{1}\hat{i} + D_{2}\hat{j} + D_{3}\hat{k}$$
(5.5.7)

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} R_h \cos q_1 + R_v \sin q_1 \sin \Omega t \\ R_h \sin q_1 - R_v \cos q_1 \sin \Omega t \\ R_v \cos \Omega t \end{bmatrix}$$
(5.6.8)

Equating components of Eq. 5.6.8 with the components of Eq. 5.6.5 and solving for the direction cosines results in the following relationship,

$$\begin{bmatrix} l\\m\\n \end{bmatrix} = \begin{vmatrix} \frac{R_h}{R} \cos q_1 + \frac{R_v}{R} \sin q_1 \sin \Omega t\\ \frac{R_h}{R} \sin q_1 - \frac{R_v}{R} \cos q_1 \sin \Omega t\\ \frac{R_v}{R} \cos \Omega t \end{vmatrix}.$$
 (5.6.9)

In Eq. 5.6.9 the direction cosine time histories are a function of a given axis of rotation parameterized by the generalized coordinates q_1 and $q_2(0)$, and a given angular speed Ω .



Figure 5.6.2 Simulated Direction Cosine Data



Fig. 5.6.2 shows the simulated direction cosine histories with band-limited white noise from Simulink with a power of 0.0001, defined as,

$$x_{Noise} = x + Noise \tag{5.6.10}$$

At this point the actual characteristics of the noise are unknown. The purpose of this exercise is a qualitatively study of the relative noise amplification as the analysis is carried out. It is known that differentiation is a highly sensitive operator, where small perturbations in the

input cause large fluctuations in the output. Fig. 5.6.3 shows the calculated velocity data from a backward-difference numerical differentiation scheme. Fig. 5.6.4 shows the extent of the noise amplification at each step of the algorithm in terms of the standard deviation between the clean signal and noisy signal. Note that the standard deviation in the angular velocity signal includes a cross product and a Euclidean norm. However, a second order Butterworth filter or a more sophisticated Savitsky-Golay filter can effectively attenuate this noise and recapture the signal, see Fig. 5.6.5. These results show that the proposed scheme is viable for calculating the angular velocity of the sphere.



Figure 5.6.3 Numerical Differentiation of Noisy Data

Calculated velocity from noisy position data



Figure 5.6.4 Noise Amplification





Figure 5.6.5 Filtered Angular Velocity Data

Comparison of filters on the calculated angular velocity data

5.7 Experimental Verification



Figure 5.7.1 Set-up for Experimental Verification

The approach has been tested with real data using an Applied Physics System (APS) 535 Tri-axial Fluxgate Magnetometer. Fig. 5.7.1 illustrates the set-up for the experimental verification. For the data presented below the angle q_1 was set to zero and the magnet was spun using an electric motor. As a result the angular velocity vector is aligned with the \hat{j} axis. The speed was varied throughout the test and the three-component data was collected using a digital oscilloscope with a sample period of 0.01 seconds. An electric motor spins the magnet with angular velocity $\underline{\omega}$. A tri-axial fluxgate magnetometer positioned at O_s measures the threedimensional flux density field of the magnet centered at O_M . For the experiment, the configuration coordinate q_1 is set to zero and as a result the rotation axis is parallel to the \hat{j} axis. The motor spinning the magnet is stepped through a series of speeds and the field components are measured and stored on a digital oscilloscope with a sampling period of 0.01 seconds.

For a given test the generalized coordinate angle q_1 will be constant and the magnet axis, represented by p, will rotate according to the angular velocity vector $\underline{\omega}$. With the vector analysis approach the direction cosines are simply scalar multiples of the measured flux density components; as such,

$$\begin{bmatrix} B_X \\ B_Y \\ B_Z \end{bmatrix}_{Measured} = \begin{bmatrix} 2B_0 l \\ -B_0 m \\ -B_0 n \end{bmatrix}$$
(5.7.1)

The data is generally very clean with the noise band several orders of magnitude larger than the desired signal bands. A second order Butterworth filter was used before and after the discrete differentiation scheme to attenuate noise amplification through the calculation. The results were generally promising. Fig. 5.7.2 illustrates the Simulink block diagram used to carry out the differentiation.



Figure 5.7.2 Data Reduction of Magetometry Data

Direction cosine data is filtered and differentiated with discrete differentiator in Simulink

Figure A4. While the drive motor was not instrumented for velocity feedback, examining the frequency content of the flux density signal provides a rough approximation. Fig. 5.7.3 is a FFT of the B_X signal (\hat{i} -component of the flux density vector). Note that the steady state angular speeds correspond to the frequencies of the principal harmonics in the FFT.



Figure 5.7.3 FFT of Magnetometry Data

Fig. 5.7.4(a) shows the raw and filtered direction cosine data. Note the lag introduced by the Butterworth filter. Fig. 5.7.4(b) illustrates the velocity data from differentiating the position data. The experiment was a rough proof of concept so the rotation axis and magnet position were not rigidly fixed. As a result some deviation is expected. But generally, the data illustrates the expected results.



FFT of the magnetometry data provides approximation of actual magnet rotation speed

Figure 5.7.4 Processing of Actual Magetometer Data

(b)

(a) Raw and filtered direction cosine data (b) differentiated data

Carrying on with the analysis, the velocity data is normalized to generate the unit tangent vectors and the cross products of successive unit tangent vectors were calculated to generate the components of the rotation vector. Fig. 5.7.5(a) shows the rotation vector components. As expected the plot illustrates the magnet has rotated primarily about the \hat{j} axis. Fig. 5.7.5(b) illustrates the magnitude of the rotation vector, which results in the scalar angular speed. The algorithm clearly captures the stepped increase of the input angular speed.



Figure 5.7.5 Calculated Angular Velocity

(a) net angular speed (b) Components of rotation vector

Fig. 5.7.6 shows the corresponding plots when the axis of rotation is oriented relative to the sensor axes. This illustrates how the sensor scheme picks up the three-dimensional rotation data.



Figure 5.7.6 Results for Oriented Rotation Axis

6. Control System Design

6.1 Introduction

Navigation is a basic capability required of a mobile robot, and it remains a research issue according to Salichs and Moreno 2000. Navigation may be divided into four parts: path planning, localization, motion control, and obstacle avoidance. Path planning involves arranging a trajectory that allows the mobile robot to reach a goal position with minimum cost (e.g. time, energy, etc.) by using knowledge about its environment and the goal position. Localization provides the answer for where the mobile robot is in the environment, and motion control makes the mobile robot follow a given trajectory. Obstacle avoidance is a re-planning processes when the mobile robot's path interferes with unexpected obstacles.

A highway work zone is a temporary area, which means that knowledge of the environment is usually unknown to a mobile robot. For autonomous path planning, a mobile robot should explore a work zone for a while to gather information, and build a map of that area. This task is time consuming and a mobile robot may enter into an unsafe zone during exploration. Thus, autonomous path planning is not practical and is abandoned due to safety reasons. However, a desired trajectory and a field map around a desired trajectory can be built by manual maneuvering. Once a desired trajectory and a map is built, a mobile robot could travel along the desired trajectory autonomously, which requires localization, motion control, and obstacle avoidance.

Since the HANDL will typically involve the loading and unloading of an unknown object, both its dynamic and kinematic parameters will change due to deformation of the ball wheels. According to the literature survey, using incorrect values of these parameters increases the dead reckoning position error. An adaptive computed-torque controller Lewis et al. 2004 cannot estimate kinematic parameters alone, because they cannot be separated as a linear form. Kinematic parameters are used in the Jacobian matrix, which are transformed from desired state values in task space into desired state values in joint space. If the Jacobian matrix is not correct, a desired trajectory in task space does not correctly map to joint space. As a result, errors in task space will occur, even if a mobile robot is ideally controlled to trace a desired trajectory in joint space. Therefore, these parameters should be compensated, especially in the HANDL application due to its varying load distribution.

6.2 Literature Review

In the last two decades, the position control of nonholonomic WMPs has received great research attention due to the challenging theoretical nature of the problem Kanayama et al. 1990, Fierro and Lewis 1995, Fierro and Lewis 1995, Dixon et al. 2000, Fukao et al. 2000, Jiang et al. 2001, Zhang et al. 2003, Do et al. 2004, Do et al. 2004. The position control of nonholonomic WMPs may be divided into two problems: stabilizing the position and orientation of the WMPs to an arbitrary setpoint, and tracking a time-varying reference trajectory Dixon et al. 2000. It is well known that a nonholonomic system cannot be made asymptotically stable to a rest configuration by smooth time-invariant state-feedback control laws, due to Brockett's theorem Brockett 1983. A variety of controllers have been proposed to solve this problem, including discontinuous control laws, piecewise continuous control laws, smooth time-varying control laws, and hybrid control laws (M'Closkey and Murray 1997, Dixon et al. 2000, and the references therein). However, most tracking controllers do not solve the stabilization problem. Recently, a single controller that is able to solve both stabilization and tracking for nonholonomic WMPs was proposed in Dixon et al. 2000, Morin and Samson 2002, Do et al. 2004, Lee et al. 2004. Nevertheless, their results show that controllers have poor convergence behavior or that nonholonomic WMPs do not exactly follow the desired trajectory before stopping.

Since holonomic WMPs are fully actuated and have full degrees of freedom on the plane, stabilization and tracking are not separate problems, and any kind of control law can be used for position control. In the literature, the control of holonomic WMPs was usually designed only using kinematic models. One of the reasons is that most of the holonomic WMPs are designed with passive rollers, which are discontinuously used and their motions cannot be sensed, so that the dynamics of these elements cannot be accounted for Holmberg and Khatib 2000. However, since the holonomic WMP with ball wheels does not consist of passive rollers, designing the controller for the holonomic WMP with ball wheels could be extended easily using a dynamic model.

Another difficulty of position control of WMPs is that it is hard to provide absolute position and orientation of the WMP, which is known as localization. Surveys of sensors and techniques for localization are in Everett 1995, Borenstein et al. 1997, Siegwart and Nourbakhsh 2004. Sensors can be categorized into two groups: relative and absolute, internal and external, or

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proprioceptive and exteroceptive. Since any single sensor or technique can not solve the problem, the most common method is optimally combining data from each group by using an extended Kalman filter.

The Kalman filter processes all measurements to estimate the system state optimally using (1) the knowledge of the system and the measurement device dynamics, (2) a statistical description of the system noise, measurement errors, and uncertainty in the dynamics models, and (3) any available information about initial conditions of the system state Maybeck 1979. The system noise and measurement errors are assumed white, zero mean, additive and Gaussian. If these assumption are not fulfilled, the Kalman filter runs in a suboptimal, and possibly unstable, manner Larsen et al. 1998.

Odometry, also referred to as dead reckoning, is the most widely used method of relative position measurements, due to it being simple, inexpensive, and easy to accomplish in real time. The drawback of odometry is its unbounded accumulation of error. Odometry error may be categorized into two groups; systematic errors, which come from inaccurate WMPs physical parameters (wheel radii, wheel base) and sensor limitations, and nonsystematic errors which come from irregular surfaces and wheel slippage Borenstein and Feng 1996.

Systematic errors are time dependent, and they are not zero mean nor are they Gaussian. Fortunately, since they originate from physical parameters, they do not usually change unless the load distribution of the WMP changes or the wheels are excessively worn. Several methods are presented to calibrate physical parameters of differential-drive WMPs. Borenstein and Feng Borenstein and Feng 1996 present an off-line systematic calibration procedure, UMBmark. Bak, et al Bak et al. 1999 propose an on-line calibration procedure using an augmented extended Kalman filter. This procedure estimates not only the position and orientation of the WMP, but also the radius of wheels and the wheel base by using encoders and an external vision system. Roy and Thrun Roy and Thrun 1999 present an on-line calibration procedure using a maximum likelihood estimation. After calibration, dead-reckoning error caused by systematic errors can be reduced by an order of magnitude. Adaptive controllers are presented for compensating systematic uncertainties Fukao et al. 2000, Do et al. 2004. However, these methods do not consider unequal wheel diameters, and they require an absolute position and orientation, which are not practical to determine. As a different approach, additional unloaded disk wheels with

encoders have been used to reduce systematic uncertainties Chong and Kleeman 1997, Louchene and Bouguechal 2003.

6.3 Controller Objective

The objective of this thesis is to design a motion controller for an Omnidirectional WMP with two ball wheels (OWMP). The proposed controller estimates not only uncertain dynamic parameters, but also uncertain kinematic parameters, and uses the estimated parameters in the control input computation and the Jacobian matrix. Therefore, traction position errors are significantly reduced. The previous work on adaptive controllers, which estimate both parameters, do not consider unequal wheel diameters, and they require an accurate absolute position and orientation. However, kinematic parameters estimation method on the proposed controller does not depend on absolute position and orientation feedback, and it estimates each wheel diameter separately. Therefore, the proposed controller is more practically applicable.

Its kinematic and dynamic models are derived, and a robust adaptive motion controller with kinematic parameters compensation is presented. A knowledge based kinematic parameters compensation method is proposed. The proposed controller was simulated with different trajectories to show feasibility and efficacy.

A localization method for the OWMP will be studied. This method will be used to compensate nonsystematic errors cooperating with the presented controller. It is anticipated that this work will result in a new kinematic parameters compensation method based on localization, which does not depend on the desired trajectory.

6.4 Ball wheel platform

In this section, a theoretical study about a new omnidirectional wheeled mobile platform based on two new ball wheel drive mechanism is introduced. Its kinematic models is derived. The Lagrange formulation is used to derived its dynamic model. The dynamic model is transformed into a more appropriate representation for controls purposes using the kinematic constraints. An inner robust adaptive velocity tracking controller is presented and its stability is proved by Lyapunov's direct method. For a position control in task space, an outer Proportional (P) controller is added to it. A kinematic parameters calibration method is introduced. The basic assumptions for typical kinematic and dynamic models are that the wheeled mobile platforms (WMPs) are rigid carts with non-deformable wheels, they are moving on a flat plane, and the wheels are always vertical to the plane. The wheels are assumed to have a pure rolling constraint.



Figure 6.3.1 Ball Wheel Concept

Our new ball wheel design concept is shown in Figure 6.3.1. The spherical wheel has good properties for an omnidirectional wheel: three d.o.f. on the floor, rotational symmetry in all directions, and fixed contact points with respect to the platform. According to Sordalen et al. 1994, the axis of rotation of the ball lies in a constraint plane, which is a plane involving the drive wheel axis and the center of the ball. Two different constraint planes can uniquely determine the rotation axis of the ball. If the rotating axes of the drive wheels are on the same constraint plane, the drive wheels do not add further constraints to the ball. The two drive wheels are in contact with the ball wheel on its equator, and the ground is in contact with the ball wheel at the south pole. The two drive wheels are separated by 90 degrees in the equatorial plane. With both point contact and no slip assumed, the two drive wheels constrain the rotation axis of the ball wheel on the equator plane, but the rotation axis can change orientation on that plane. The orientation of the rotation axis is determined by the ratio of the velocities of the two drive wheels. Changing the angular velocities of the two drive wheels can change the magnitude of the velocity and the direction of the velocity at the south pole, which is the contact point with the ground. Therefore, the ball wheel can move in any direction without changing configuration, which is instantaneous steer ability.



Figure 6.3.2 Ball Wheel Kinematic Diagram

Consider the ball wheel as shown in Fig. 6.3.2. A reference frame is instantaneously fixed on the ground and the origin A of the frame is located at the contact point of the ball wheel and the ground. With the rolling without slip condition, the angular velocity of the ball wheel and that of the drive wheel i are related as follows:

$$\omega_{b} = \frac{r_{d}}{r_{i}} \cdot \dot{\varphi}_{i}$$

$$r_{i} = r_{b} \cdot \cos(\sigma_{i} - \gamma)$$
(6.4.1)

where ω_b denotes the magnitude of the angular velocity of the ball wheel, r_d denotes the radius of the drive wheel, r_i denotes the distance from the ball rotation axis to the contact point between the ball wheel and the drive wheel, $\dot{\phi}_i$ denotes the magnitude of the angular velocity of the drive wheel *i*, r_d denotes the radius of the ball wheel, σ_i denotes the angle between the reference axis

X and the wheel plane, and γ denotes the angle between the reference axis X and the heading direction of the ball wheel. The velocities V_x and V_y of the center of the ball wheel are

$$\begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} r_b \cdot \cos \gamma \cdot \omega_b \\ r_b \cdot \sin \gamma \cdot \omega_b \end{bmatrix}.$$
 (6.4.2)

In the ideal case, which means that the contact between the ball wheel and the drive wheels are assumed as point contacts, two drive wheels are used on one ball wheel with 90 degrees separation in the equatorial plane, which are $\sigma 1 = 0^{\circ}$ and $\sigma 2 = 90^{\circ}$, and the angular velocities of the drive wheels can be derived from combining (1) and (2), which are written as

$$\begin{bmatrix} \dot{\varphi}_1 \\ \dot{\varphi}_2 \end{bmatrix} = \frac{1}{r_d} \cdot \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix},$$
(6.4.3)

or in a compact form

$$\dot{\phi} = J_b \cdot V \,. \tag{6.4.4}$$

In general, the drive wheels and the ball wheels are deformed, thus finite size contact patches are produced at the contact points. This contact involves rolling with longitudinal traction and spin. The spin motion produces lateral traction and microslip by twisting the contact patches Johnson 1985. Gillespie, et al Gillespie et al. 2002 studied rolling contact with spin on a continuously variable transmission (CVT), which is similar to the ball wheel. In their study, a line contact model with uniform pressure was used to describe the limitation of the nonideal CVT, which shows that a very high transmission ratio, which is the case when the rotational axis is close to the drive wheel's contact patch, is unattainable and a very low transmission ratio, which is the case when the rotational axis should not be close to the drive wheel's contact patch.

To overcome this aspect, a third drive wheel is added to the ball wheel, and, when the rotational axis is close to one of the drive wheel's contact patch, that contact is released, and as a result, the rotational axis is always located some distance from the drive wheel's contact patch. In the three drive wheels on one ball wheel case, the drive wheels are separated on the equatorial plane equally so that $\sigma 1 = 0^{\circ}$, $\sigma 2 = 120^{\circ}$, and $\sigma 3 = 240^{\circ}$, and the angular velocities of the drive wheels are written as

$$\begin{bmatrix} \dot{\varphi}_{1} \\ \dot{\varphi}_{2} \\ \dot{\varphi}_{3} \end{bmatrix} = \frac{1}{r_{d}} \cdot \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \cdot \begin{bmatrix} V_{x} \\ V_{y} \end{bmatrix}.$$
 (6.4.5)

6.5 Dynamics

A dynamic model is derived using the Lagrange formulation for control design. If the WMP moves on the horizontal plane, the Lagrangian is given by

$$L = \frac{1}{2} \dot{q}^{T} \cdot M(q) \cdot \dot{q}$$
(6.5.1)

where M(q) denotes the n × n symmetric positive definite WMP inertia matrix, and q is the n × 1 vector of state variables.

The dynamical equations of the WMP can be expressed as

$$M(q) \cdot \ddot{q} + V_m(q, \dot{q}) \cdot \dot{q} + \tau_d = A^T(q) \cdot \lambda + B \cdot \tau_a$$
(6.5.2)

where $V_m(q,\dot{q})\cdot\dot{q}$ is the n × 1 vector of centripetal and Coriolis torques, A is the n-r × n matrix associated with the constraints, r denotes the dimension of degrees of freedom, λ is the n-r × 1 vector of constraint forces, B is the n × m input transformation matrix, τ_a is the m × 1 input torque vector, and τ_d is the n × 1 bounded unknown disturbances vector including unstructured, unmodeled dynamics.

If the no slip condition is applied, the kinematic constraints can be expressed as

$$A(q) \cdot \dot{q} = 0, \qquad (6.5.3)$$

and the configuration kinematic model is

$$\dot{q} = S(q) \cdot v(t), \tag{6.5.4}$$

where S(q) is a $n \times r$ full rank matrix formed by a set of vectors spanning the null space of A(q), so that

$$S^{T}(q) \cdot A^{T}(q) = 0,$$
 (6.5.5)

and v(t) is the r × 1 new state variable vector. By multiplying by S^T and substituting for \dot{q} from equation (6.5.4), equation (6.5.2) becomes

$$S^{T} \cdot M \cdot S \cdot \dot{v} + S^{T} \cdot \left(M \cdot \dot{S} + V_{m} \cdot S\right) \cdot v + S^{T} \cdot \tau_{d} = S^{T} \cdot A^{T} \cdot \lambda + S^{T} \cdot B \cdot \tau_{a}.$$
(6.5.6)

By appropriate definitions, equation (6.5.6) can be rewritten as

$$M \cdot \dot{v} + V \cdot v + \bar{\tau}_d = \tau , \qquad (6.5.7)$$

where \overline{M} is a r × r symmetric, positive definite matrix, \overline{V} is a r × r skew-symmetric matrix, $\overline{\tau}_d$ is a r × 1 bounded disturbance torques vector, and τ is a r × 1 applied torques vector.

6.6 Control

In this section, a robust adaptive controller is designed for asymptotically tracking a smooth desired trajectory, which can be at least twice continuously differentiable. The joint space adaptive tracking controller for a manipulator is presented by Slotine and Li Slotine and Weiping 1988, and Wilson and Robinett Wilson and Robinett 2001 apply such a controller to a differential drive WMP. A filtered error signal is defined as

$$s = e + \Lambda \cdot \int e \cdot dt \tag{6.6.1}$$

where $e = v_d - v$, vd is a vector of desired velocities, and Λ is a positive definite matrix. Equation (6.5.7) can be written as

$$\overline{M} \cdot \dot{s} + \overline{V} \cdot s = Y \cdot p - \tau + \overline{\tau}_d \tag{6.6.2}$$

Where

$$Y \cdot p = \overline{M} \cdot (\dot{v}_d + \Lambda \cdot e) + \overline{V} \cdot (v_d + \Lambda \int e \cdot dt)$$
(6.6.3)

p is a $k \times 1$ vector of unknown parameters, which can be linearly separated from the right side of equation (6.6.3) and Y is a n × k matrix independent of these parameters. The control and parameter estimation update laws are chosen as follows

$$\tau = \hat{Y} \cdot \hat{p} + K_v \cdot s + C \cdot \operatorname{sgn}(s), \qquad (6.6.4)$$

$$\dot{\hat{p}} = \Gamma \cdot \hat{Y}^T \cdot s \tag{6.6.5}$$

where K_{ν} , C, and Γ are positive definite matrices, and \hat{Y} and \hat{p} are an estimated matrix and an estimated vector of Y and p, respectively. The regression matrix Y may include uncertain kinematic parameters, although any uncertain parameters can be linearly separated with a combined form. If the regression matrix Y includes uncertain kinematic parameters, these parameters will be updated by a parameter calibration method.

To prove the global convergence of the velocity tracking errors, a Lyapunov function candidate is considered as follows

$$V = \frac{1}{2} \cdot s^{T} \cdot \overline{M} \cdot s + \frac{1}{2} \cdot \widetilde{p}^{T} \cdot \Gamma^{-1} \cdot \widetilde{p} , \qquad (6.6.6)$$

where $\widetilde{p} = p - \hat{p}$. Differentiation of V leads to

$$\dot{V} = s^T \cdot \overline{M} \cdot \dot{s} + \tilde{p}^T \cdot \Gamma^{-1} \cdot \dot{\tilde{p}} .$$
(6.6.7)

By substituting for $\overline{M} \cdot \dot{s}$ from equation (6.6.2), equation (6.6.6) becomes

$$\dot{V} = s^{T} \left(Y \cdot p - \tau \right) - s^{T} \cdot \overline{V} \cdot s + s^{T} \cdot \tau_{d} + \widetilde{p}^{T} \cdot \Gamma^{-1} \cdot \dot{\widetilde{p}} .$$
(6.6.8)

The matrix \overline{V} is skew symmetric, so that the second term on the right side of equation (6.6.8) is eliminated, and by substituting the control law (6.6.4), equation (6.6.8) becomes

$$\dot{V} = -s^T \cdot K_v \cdot s + s^T \left(Y \cdot p - \hat{Y} \cdot \hat{p} \right) - s^T \left(C \cdot \operatorname{sgn}(s) - \overline{\tau}_d \right) + \widetilde{p}^T \cdot \Gamma^{-1} \cdot \dot{\widetilde{p}} .$$
(6.6.9)

The matrix \widetilde{Y} is defined as

$$\widetilde{Y} = Y - \widehat{Y} \,. \tag{6.6.10}$$

Substituting for Y from equation (6.6.10), equation (6.6.9) can be written as

$$\dot{V} = -s^T \cdot K_v \cdot s + \widetilde{p}^T \left(\Gamma^{-1} \cdot \dot{\widetilde{p}} + \hat{Y}^T \cdot s \right) - s^T \left(C \cdot \operatorname{sgn}(s) - \tau_d - \widetilde{Y} \cdot p \right).$$
(6.6.11)

The parameter estimation update law (6.6.5) removes the second term from the right side of equation (6.6.11), and a positive definite matrix C is chosen as $C > \max\{\overline{\tau}_d | + \|\widetilde{Y}\| \cdot |p|\}$. Then,

$$\dot{V} = -s^T \cdot K_v \cdot s - s^T \cdot \left(C \cdot \operatorname{sgn}(s) - \tau_d - \widetilde{Y} \cdot p\right) < 0.$$
(6.6.12)

Using Lyapunov's direct method, the stability of the proposed controller is established.

A Proportional (P) controller is added to the robust adaptive controller. The angular position errors of the ball wheels converge to zero by the robust adaptive controller, but the position error of the mobile robot in inertia space does not converge for several reasons, including wheel slippage, uncertain kinematic parameters, and non-zero velocity error in joint space. The P controller may use absolute position feedback from localization. The tracking error is expressed as

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_r - x \\ y_r - y \\ \theta_r - \theta \end{bmatrix}.$$
 (6.6.13)

Then the vector of desired velocities vd is given by

$$\boldsymbol{v}_{d} = \boldsymbol{J}_{d} \cdot \begin{bmatrix} \boldsymbol{u}_{d} + \boldsymbol{k}_{1} \cdot \boldsymbol{e}_{1} \\ \boldsymbol{v}_{d} + \boldsymbol{k}_{2} \cdot \boldsymbol{e}_{2} \\ \boldsymbol{\omega}_{d} + \boldsymbol{k}_{3} \cdot \boldsymbol{e}_{3} \end{bmatrix}$$
(6.6.14)

where ud, vd, and ω_d denote desired velocities in the body fixed frame, and J_d is a transformation describing the relation between the actuator space and the body fixed space. A general structure for the robust adaptive control system is presented in Figure 6.6.1.



Figure 6.6.1 Tracking Control Scheme

6.7 Kinematic parameters calibration



Figure 6.7.1 Geometric Relations of Platform

In this section, a knowledge based kinematic parameters compensation method is presented. There are three systematic error sources: misaligned wheel coordinate, unequal wheel diameters, and uncertainty about the wheelbase. First, the ball wheels' coordinate should be aligned with the OWMP's coordinates. In order to calibrate this angle, only one of the two ball wheels drives to the Xm direction, and the other ball wheel is passively driven. If the actively driving ball wheel is not aligned, the contact point of the passively driven ball wheel and the floor runs in a circle as shown in Figure 6.7.1. The misaligned angle α is calculated from the following equations.

$$\alpha = \tan^{-1} \left(\frac{2d}{R} \right), \tag{6.7.1}$$

where $R = \frac{\sqrt{x^2 + y^2}}{2\sin\beta}$, and $\beta = \tan^{-1}\left(\frac{y}{x}\right)$. After calibrating the misalignment angle α , the OWMP can move in a straight line, and the actual radius of the ball wheels r can be calculated

from the following equation:

$$r = \frac{x}{2 \cdot \pi \cdot n} \tag{6.7.2}$$

where n is the number of rotations of the actively driven ball wheel.

The wheelbase is defined as the distance between the contact points of the two ball wheels of the OWMP and the floor. There is uncertainty in the effective wheelbase because the ball wheels contact the floor in finite size contact patches. According to Borenstein and Feng Borenstein and Feng 1996, the uncertainty in the effective wheelbase of some commercially available robots is on the order of 1 %. The UMBmark test proposed by Borenstein and Feng Borenstein and Feng 1996 is used to calibrate the wheelbase, since the motion of the OWMP is identical with that of the differential-drive WMP, if it does not move to the Xm direction in Figure 9. In the UMBmark test, the OWMP travels along a square path five times in both clockwise and counterclockwise directions. Initial and final positions are measured, and then the actual values of the wheelbase are determined.



Figure 6.7.2 Mobile Platform with Two Ball Wheels

Since actual kinematic parameters: wheel diameters and the wheelbase, change with the different load distributions of the OWMP, calibration should be done with different loading conditions from no loading to maximum loading. By interpolation with calibrated data, all actual

values of kinematic parameters Kp could be estimated, and these values are function of mass and inertia of a mobile robot, which can be expressed as

$$K_p = f(m, I), \tag{6.7.3}$$

Its dynamic parameters are updated by parameter estimation update laws of the robust adaptive controller as in equation (6.6.5). Then, the kinematic parameters are updated according to the function (6.7.3).

6.8 Simulation

In this section, the proposed controller was simulated with linear, circular, and persistently exciting trajectories in order to show feasibility and efficacy. A simulation is implemented in Simulink. The performance of the adaptive controller with radius compensation is compared to those of the Proportional and Derivative (PD) controller and the adaptive controller without radius compensation. These controllers are implemented on the OWMP, as shown in Figure 6.7.2, and its equations of motion are derived in Appendix I. The moment of inertia of the drive wheel is small compared to other parameters, so that it is not considered in this simulation. Only angular velocities and angular positions of the ball wheels are used for the feedback signals. Real absolute position of the mobile robot is calculated by using the true Jacobian matrix and angular velocities of the radii of the ball wheels. The dynamic parameters and the kinematic parameters are shown in Table 6.8.1.

	m [kg]	I [kg·m2]	Iw [kg·m2]	r1 [m]	r2 [m]	d [m]
platform only	150	53.79	0.009	0.15	0.15	0.6
after loading	200	172.53	0.009	0.147	0.149	0.6

Table 6.8.1 Mobile Robot Physical Parameters

Control gains are tuned to their best values, so that the best performance of the three controllers can be compared, and the same values are used for all simulations. Slippage and other disturbance forces are not considered in this simulation. A PD controller is considered as

$$\tau = K_a \cdot \dot{v}_d + K_d \cdot (v_d - v) + K_p \cdot \int (v_d - v) dt .$$
(6.8.1)

6.9 Linear trajectory

In the first simulation, a mobile robot moves in the Ym direction without changing orientation on Figure 6.7.2. The desired velocity changes as a sine wave; the maximum speed is 0.5 m/sec and the frequency is 0.01 Hz. When values of kinematic parameters used in the Jacobian matrix are equal to their actual values, no significant position error occurs. After 50 seconds, additional load is applied on the mobile robot, and its physical parameters are thus changed. Since absolute position data by external sensors is not used in this simulation, and position and orientation data of a mobile robot in the inertial coordinates are calculated by dead reckoning, the difference between desired position and real position er is growing, although the difference between desired position calculated by dead reckoning ei converges to zero. The results of the three controllers are plotted in Figure 6.9.1.



Figure 6.9.1 Trajectories after Loading (Simulation 1)

After the mobile robot travels 16 meters during 50 seconds, position error er for the PD controller become 1.4 meters, position error for the adaptive controller become 1.4 meters, and position error for the adaptive controller with radius compensation become 0.8 meters. With low

acceleration and low velocity motion, there is no recognizable difference between the result for the PD controller and that for the adaptive controller in position error, but the result for the adaptive controller shows better velocity tracking. Since the desired trajectory is simple, the regression matrix Y does not satisfy the persistency of excitation conditions, dynamic parameters do not converge to actual values for the adaptive controller, and as a result, kinematic parameters do not converge either. However, even though the values of the parameters do not reach the actual values, they are updated to values close to actual values. Consequently, position errors are reduced when the adaptive controller with kinematic parameter compensation is used compared to the other two cases.

6.10 Circular trajectory

In this simulation, a mobile robot moves in the Ym direction with changing orientation; as a result, it runs in a circle. The desired velocities vd and ω d, with respect to the body fixed frame and the desired trajectory with respect to the inertial frame are shown in Figure 6.10.1.



Figure 6.10.1 Desired Velocity and Desired Trajectory (Simulation 2)

The mobile robot completes four loops of about a 5 meter diameter circular path in 200 seconds. The loading condition is changed at 100 seconds, when the desired velocities vd and ωd are zero. Table 6.10.1 shows the maximum position and orientation errors for the three controllers, Figure 6.10.2 shows the position and orientation errors, Figure 6.10.3 shows the first loop trajectories after loading, and Figure 6.10.4 shows the second loop trajectories after loading.

	Position error [m]		Orientation error [°]		
	actual	Dead reckoning	actual	dead reckoning	
PD	1.34	0.028	29.88	0.024	
Adaptive	1.34	0.010	29.87	0.016	
Adaptive plus	0.51	0.010	10.00	0.016	



Table 6.10.1 Maximum Position and Orientation Errors (Simulation 2)

Figure 6.10.2 Position and Orientation Error (Simulation 2)







Figure 6.10.4 Second Loop Trajectory (Simulation 2) 54

The result for the PD controller shows that there are velocity tracking errors and a position tracking error before 100 seconds, even though they are small, where the maximum position error is 0.02 meters. After 100 seconds, the position and orientation tracking errors increase, although those by the dead reckoning are almost zero. The result for the adaptive controller shows better velocity tracking and position tracking compared to that for the PD controller before 100 seconds, even though the position and orientation tracking errors for the adaptive controller are similar to those of the PD controller after 100 seconds. The dynamic parameters do not converge to their actual values. The dynamic parameters converge to their actual values in 70 seconds after the loading condition is changed for the adaptive controller with kinematic parameter compensation. Consequently, the position and orientation tracking errors stop growing after that.

6.11 Persistently exciting trajectory

	Position error	Position error [m]		Orientation error [°]		
	actual	dead reckoning	actual	dead reckoning		
PD	0.60	0.58	4.40	0.20		
Adaptive	0.15	0.05	4.08	0.12		
Adaptive plus	0.05	0.05	0.49	0.12		

Table 6.11.1 Maximum Position and Orientation Errors (Simulation 3)

In this simulation, a mobile robot moves in Xm and Ym directions simultaneously with changing orientation, so that parameter error convergence can be established for the adaptive controller. The desired velocities with respect to the body fixed frame and the desired trajectory with respect to the inertial frame are shown in Figure 6.11.1. The mobile robot travels 36 meters in 100 seconds, and the loading condition changes at 50 seconds, when the desired velocity is zero. Table 3 shows the maximum position and orientation errors for the three controllers, Figure 6.11.2 shows the position and orientation errors, Figure 6.11.3 shows trajectories before loading, and Figure 6.11.4 shows trajectories after loading.



Figure 6.11.1 Desired Velocity and Desired Trajectory (Simulation 3)



Figure 6.11.2 Position and Orientation errors (Simulation 3)



Figure 6.11.3 Trajectories before loading (Simulation 3)



Figure 6.11.4 Trajectories after loading (simulation 3)

Due to the high acceleration, the result for the PD controller shows large position and orientation errors both before loading and after loading. The result for the adaptive controller shows similar performance before loading compare to that for the adaptive controller with kinematic parameter compensation. But, the position and orientation errors for the adaptive controller grow faster than those for the adaptive controller with kinematic parameters converge, but not to their actual values for the adaptive controller. However, the dynamic parameters converge to their actual values for the adaptive controller with kinematic parameter compensation.

6.12 Conclusion and Future work

The primary contribution of this thesis is the development of the robust adaptive controller for the Omnidirectional Wheeled Mobile Platform with the ball wheels (OWMP). The OWMP involves the loading and unloading of an unknown object, which changes not only dynamic parameters, including the mass and inertia, but also kinematic parameters, including radii of the ball wheels. The proposed controller estimates both parameters, and uses them in the controller. Thus, as shown in the simulation, the position errors for the proposed controller are significantly reduced compared to those for the PD controller and the adaptive controller.

Several issues remain as future work. First, the stability of the controllers should be proved theoretically and experimentally. Stability of the inner loop velocity tracking controller is proved in this thesis, but stability of the controller, which includes proportional controller and changing Jacobian matrix is not yet proven.

Second, localization using the absolute position method will be studied. During the period when the estimated kinematic parameters are different from the actual values, error for the dead reckoning position measurement increases, and it stops increasing when the estimated kinematic parameters converge to the actual values. However, accumulated error remains, and it does not converge to zero. Therefore, localization using an absolute position method is required, and then the actual position data should be feedback to the motion controller, in order to converge position errors to zero. Also, the nonsystematic errors caused by wheel slippage and irregular surfaces can be compensated.

According to the simulation results, the performance of the kinematic parameters compensation method highly depends on the desired trajectory. Thus, a new method based on

localization will be studied. While the worked is aimed at the OWMP, the work is applicable to any wheeled platform and is thus a much broader contribution.

7 Grasp and Lift Manipulator

The robots to assist humans in their routine activities must perform many different complex tasks. However the status of robotics research is far from building robots that can independently decide how to grip an object to accomplish every day tasks. At this point, a robot gripping system with enough intelligence to grasp an object with correct force and velocity, as humans do, is considered.

Analytical studies of the grasping and finger by robot hand have been done by many researches Bicchi 2000, Henrich and Worn 2000, Hirai and Wada 2000, Xydas et al. 2000. Yoshikawa and Nagai have divided the finger forces into two different forces, manipulation force and internal force, defined the manipulation force, which generates the required external object force. Shimoga and Goldenberg 1992 have studied modeling and controlling the impedance of a soft finger and showed experimentally how the presence of passive damping helps reduce the peak impact forces that occur as a rigid object is grasped by fingers of a robotic hand from soft materials. Another approach to control robot hands is several force and position control schemes devised for robotic interaction tasks. Chiavervini and Sciavicoo (1993) proposed a parallel approach to force and position control, where position trajectories are sacrificed due to force demands. For physiotherapy, specifying specific position demands would be difficult, as they would be masked by the dominance of the force loop. Force is controlled in constrained directions, while position is controlled in unconstrained directions McClamroch 1986, McClamroch and Wang 1987, Yun 1988, Wen and Murphy 1991. Based on the force control current researchers have studied the grasping robot, gripper and finger of the manipulator. However the requirement of the dexterous manipulation of an object with robotic mechanism in sophisticated tasks and the difficulties in realizing such dexterity are stimulating many researchers to tackle the problem regarding the development.

Additionally, the technology has enabled the automation of many process, however, these are mainly focused on grasping without slip. In the grasp of rigid objects, additional considerations have to be made with respect to manipulation, gripping, and sensor required. Such objects may slip during operation of robot for example by increasing mass of object or obtaining external force which may result in drop of the object grasped by the gripper of robot.

7.1 Manipulator Description

The gripper is a critical component of an industrial robot since it interacts with the environments and object, which is grasped and manipulated. Among many problems such as rigidity, lightness, multi-task capability and lack of maintenance, basic requirements for an industrial robot gripper can be recognized in a low-cost and reliable design. Recent developments in pneumatic actuators and valve allow them to be considered for application which previously only electric motors were suitable. Pneumatic system's inherent low stiffness and direct drive capabilities enable smooth compliant geared electric motor systems. Moreover, pneumatic actuators can cost up to 10 times less than electric motors, while offering a higher power to weight ratio.

Each joint of the HANDL arms is revolute and actuated by a pneumatic actuators consisting of a low friction pneumatic cylinder and a regulator valve with a position sensor. Each valve supplies regulated pressure to a single chamber of pneumatic cylinder. The pneumatic cylinder extends gradually with the applied force-causing side arm to grasp. As stated earlier, the grasping motion of HANDL is produced by four pneumatic cylinders as shown in Fig. 7.1.1.



Figure 7.1.1 Grasping direction of manipulator
As a result of the HANDL physical configuration, the force exerted on the arms depends on the position of stroke of the right and left arms. In HANDL, grasping motion is initiated by the pneumatic actuators with two touch sensors for ensured grasping of the object. Lifting motion is engaged after grasping motion. Figs. 7.1.1 and 7.2.2 illustrate the grasping and lifting motion of the HANDL gripper system.



Figure 7.1.2 Lifting motion of manipulator

7.2 Controls Design

The primary objective of the HANDL gripper is to lift an object to a position without losing contact or slip as fast as possible. Hence, it is necessary to control both the position and velocity of the end effector and the constraint force between the gripper and the environment. First, grasping motion is initiated by applying a force to the object based on its weight for secure grip. Then, lifting motion is engaged to move up the object to a desired position. In case slip of the object occurs, the grasping force is controlled to maintain stable grasp while the reference trajectory for lifting is modified on line to improve stability of the object. Therefore, the control system to be developed has two active controllers – one for grasping and the other lifting. The developed control method will have a closed-loop structure similar to hybrid control methods.

The HANDL system can be modeled using a Lagrangian formulation expressed by a set of differential-algebraic equation. Let $q \in R^n$ be a generalized coordinated vector and $\dot{q} \in R^n$ be a generalized velocity vector. Suppose the holonomic constraints of the system are described by

$$\phi(q) = 0 \tag{7.2.1}$$

where $\phi^T = [\phi_1, \dots, \phi_m]$ is at least twice differentiable. The potential and kinetic energy functions are denoted by p(q) and $k(q, \dot{q}) = \frac{1}{2} \dot{q}^T M(q) \dot{q}$, respectively, where $M : \mathbb{R}^n \to \mathbb{R}^{n \times n}$ is a positive definite inertia matrix, and the potential energy function $P : \mathbb{R}^n \to \mathbb{R}^{n \times n}$ is at least twice differentiable. A Lagrangian function is defined as

$$L(q, \dot{q}) = K(q, \dot{q}) - P(q).$$
(7.2.2)

Using the definition of L, the equation of constrained motion can be expressed as

$$M(q)\ddot{q} + F(q,\dot{q}) = J^{T}(q)\lambda + u.$$
 (7.2.3)

The constrained dynamics are described by *n* second order differential equations as shown in Eq. (7.2.3) and *m* algebraic equations as shown in Eq. (7.2.1) in terms of n + m variables *q* and λ . The vector of the variable λ determines the constraint forces.

Regulation vectors are specified by a desired constant position vector $\phi(q_d) = 0$ and $f_d = J^T(q_d)\lambda_d$ for some constant vector $\lambda_d \in R^m$. To achieve regulation of position and force to the specified position and force vector (q_d, f_d) , it is necessary to guarantee the desired values are an equilibrium of the closed loop equations. This can be achieved by the following controller:

$$u = \frac{\partial P(q)}{\partial q} - \frac{\partial P_d(q)}{\partial q} - C\dot{q}$$
(7.2.4)

where $P_d(q)$ is a desired potential energy function that is chosen to satisfy the following equation:

$$\frac{\partial P_d(q_d)}{\partial q} = f_d. \tag{7.2.5}$$

Thus, (q_d, λ_d) is an equilibrium of the closed loop system Eq. (7.2.6), which requires that the gradient of the desired potential energy function $P_d(q)$ at q_d be parallel to the constant force vector f_d . The $n \times n$ matrix C is assumed to be symmetric and to satisfy $\dot{q}^T C \dot{q} > 0$ for all $\dot{q} \neq 0$ satisfying $J(q_d)\dot{q} = 0$.

A Lyapunov function for the constrained system can be used to guarantee the local stability of the equilibrium (q_d, λ_d) . In particular, the modified potential energy is represented as

$$P_{md} = P_d(q) - P_d(q_d) - \phi^T(q)\lambda_d.$$
(7.2.6)

The modified potential energy function can be used to form a Lyapunov function for the constrained system as

$$V(q, \dot{q}) = \frac{1}{2} \dot{q}^{T} M(q) \dot{q} + P_{md} .$$
 (7.2.7)

Therefore, (q_d, λ_d) is locally asymptotically stable based on the invariance principle. However in case of HANDL, the force feedback is necessary due to applying in the direction normal to the constraint surface at the contact point during the gripping motion. Therefore, this is done by using the Jacobian matrix $J^T(q)$ as a projection. The reason is that $\dot{q}^T J^T(q) = 0$ or the range of $J^T(q)$ is normal to the velocity \dot{q} which is on the tangent plane at the contact point. Therefore, the control with force feedback is

$$u = \frac{\partial P(q)}{\partial q} - \frac{\partial P_d(q)}{\partial q} - C\dot{q} + J^T(q)G_f(\lambda - \lambda_d), \qquad (7.2.8)$$

where G_f is an $m \times m$ force feedback matrix. This control can be used for position/force control. It is straight forward to show that the closed loop system is asymptotically stable by using Eq. (7.2.7).

The controller, Eq. (7.2.4) is in general a nonlinear feedback controller. In the following, we choose a particular function $P_d(q)$ which results in a simple affine linear feedback control law. The desired potential energy function is chosen as

$$P_d(q) = P(q) - P(q_d) - \left[\frac{\partial P(q_d)}{\partial q} - J^T(q_d)\lambda_d\right]^T e + \frac{1}{2}e^T We.$$
(7.2.9)

Where $e = q - q_d$ and W is a diagonal matrix. By checking Eq. (7.2.5) the modified energy function is

$$P_{cd}(q) = P_d(q) - \lambda_d^T \phi(q).$$
 (7.2.10)

It is easy to verify that $P_{cd} = 0$ and $\frac{\partial P_{cd}}{\partial q} = 0$. Thus $P_{cd}(q)$ has a local minimum at P_d .

With this choice, the controller, Eq. (8) takes the following specific form:

$$u = \frac{\partial P(q_d)}{\partial q} - C\dot{q} - J^T(q_d)\lambda_d - W(q - q_d).$$
(7.2.11)

Eq. (7.2.15) represents an affine feedback control law. The first two terms form a constant bias term, and the third and fourth terms represent the feedback of position and velocity errors. C is a diagonal matrix. In addition to Eq. (7.2.11), feedback of the constraint force error can be introduced to tune the constraint force error response. Such a feedback control, including feedback of the constraint force error, is

$$u = \frac{\partial P(q_d)}{\partial q} - C\dot{q} - J^T(q_d)\lambda_d - W(q - q_d) + J^T(q_d)G_f(\lambda - \lambda_d).$$
(7.2.12)

Here, Eq. (7.2.12) is the control with force feedback. However, when the HANDL slips the object, the desired force and position should be changed to prevent the object from falling down. During the slipping motion, the energy E_p of the object is dissipated. Therefore, the energy to grasp the object should be added to the dissipated energy to prevent the object from falling down while the slip occurs. Also, the lifting velocity should be reduced to facilitate regrasp of the object subject to slip. Therefore, the new desired velocity is changed during slip as

$$\dot{q}_{nd} = \dot{q}_d - \dot{q}_s,$$
 (7.2.13)

where \dot{q}_s is the reduction of the velocity due to slip. It is obtained from the slip sensor mounted on the HANDL. In addition, the original grasping force is modified to a new one as

$$f_{nd} = \frac{E + E_d + f_d}{S},$$
 (7.2.14)

where E is the energy of the HANDL to grasp the object without slip, E_d is the dissipated energy during slip, and S is the position to increase the force of the gripper. Therefore during slip of the object, the lifting velocity of lift and the grasping force are modified on line.

7.3 Simulation

Simulation study of the HANDL was performed to investigate efficacy of the developed control method. Fig.7.3.1 illustrates slip motion of the object employed for simulation study. The object slips to 0.05m between 3 to 4 second during a lifting motion. Simulation parameters were chosen as $M_{11}=15 \ kg$, $M_{22}=5 \ kg$, $M_o=1.5 \ kg$, $W_{11}=55$, $W_{22}=24$, $C_{11}=4.3$, $C_{11}=5.3$, and $G_f=5$ where M_{11} is the mass of the first link for lifting motion of HANDL, M_{22} is the mass of the second link for grasping motion of HANDL, and M_0 is the object mass.



Figure 7.3.1 Slip motion of object

Figure 4 (a) shows a desired trajectory modified according to Eq. (7.2.13). The trajectory for lifting motion is modified based on the amount of slip. This means that when the object slips,

the lifting velocity is reduced by the slipping velocity of the object. Fig. 7.3.2 (b) shows the actual position of the lift, which is consistent with Fig. 7.3.2 (a). Fig. 7.3.3 (a) shows the desired grasping force by Eq. (7.2.14), which prevents further slip of the object. Fig. 7.3.3 (b) shows the actual grasping force.



Figure 7.3.2 (a) New desired trajectory and (b) output position



Figure 7.3.3 (a) New desired force and (b) actual gripper force

7.4 Conclusion

A control method for the HANDL system was developed based on the Lyapunov's direct method to control the lifting position and the grasping force of an object. The developed control system consists of a position and force controllers. The controllers work independently until slip of the object occurs. Once slip is detected, the controllers are coordinated to ensure the lifting motion of the object without further slip. In case slip of the object occurs, the grasping force is controlled to maintain stable grasp while the reference trajectory for lifting is modified on line to improve stability of the object.

APPENDIX I: Equations of motion for simulation

In this section, the equations of motion for an Omnidirectional Wheeled Mobile Platform with two ball wheels (OWMP) are derived. These equations are used in the simulation discussed in Chapter 3. The dynamic model of the OWMP is described in equation (12)

$$\overline{M} \cdot \dot{v} + \overline{V} \cdot v + \overline{\tau}_d = \tau \tag{A1}$$

Where

$$\overline{M} = \begin{bmatrix} \frac{mr_1^2r_2^2 + I_wr_1^2 + I_wr_2^2}{r_2^2} & 0 & 0\\ 0 & \frac{mr_1^2d^2 + Ir_1^2 + 4I_wd^2}{4d^2} & \frac{r_1^2r_2^2(md^2 + I)}{4d^2}\\ 0 & \frac{r_1^2r_2^2(md^2 + I)}{4d^2} & \frac{mr_2^2d^2 + Ir_2^2 + 4I_wd^2}{4d^2} \end{bmatrix}$$
(A2)

$$\overline{V} = \begin{bmatrix} 0 & -\frac{mr_1^2\dot{\theta}}{2} & -\frac{mr_1r_2\dot{\theta}}{2} \\ \frac{mr_1^2\dot{\theta}}{2} & 0 & 0 \\ \frac{mr_1r_2\dot{\theta}}{2} & 0 & 0 \end{bmatrix}$$

$$V = \begin{bmatrix} \omega^x & \omega_1^y & \omega_2^y \end{bmatrix}^T$$
(A4)

The disturbance torques τ_d are set to zeros. The regressor matrix Y and the unknown parameter vector p in equation (15) are given by

$$Y = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix}$$

$$= r_1^2 (\dot{\omega}_d^x + \Lambda e_4) - \frac{1}{2} r_1 \dot{\theta} \Big[r_1 (\omega_{1d}^y + \Lambda \int e_5 dt) + r_2 (\omega_{2d}^y + \Lambda \int e_6 dt) \Big]$$

$$= 0$$
(A5)

 Y_{11}

 Y_{12}

$$\begin{split} Y_{13} &= \left(\frac{r_{1}^{2}}{r_{2}^{2}} + 1\right) (\dot{\omega}_{d}^{x} + \Lambda e_{4}) \\ Y_{21} &= \frac{r_{1}}{4} \Big[r_{1} (\dot{\omega}_{1d}^{y} + \Lambda e_{5}) + r_{2} (\dot{\omega}_{2d}^{y} + \Lambda e_{6}) \Big] + \frac{1}{2} r_{1}^{2} \dot{\theta} (\omega_{d}^{x} + \Lambda \int e_{4} dt) \\ Y_{22} &= \frac{r_{1}}{4d^{2}} \Big[r_{1} (\dot{\omega}_{1d}^{y} + \Lambda e_{5}) + r_{2} (\dot{\omega}_{2d}^{y} + \Lambda e_{6}) \Big] \\ Y_{23} &= \dot{\omega}_{1d}^{y} + \Lambda e_{5} \\ Y_{31} &= \frac{r_{2}}{4} \Big[r_{1} (\dot{\omega}_{1d}^{y} + \Lambda e_{5}) + r_{2} (\dot{\omega}_{2d}^{y} + \Lambda e_{6}) \Big] + \frac{1}{2} r_{1} r_{2} \dot{\theta} (\omega_{d}^{x} + \Lambda \int e_{4} dt) \\ Y_{32} &= \frac{r_{2}}{4d^{2}} \Big[r_{1} (\dot{\omega}_{1d}^{y} + \Lambda e_{5}) + r_{2} (\dot{\omega}_{2d}^{y} + \Lambda e_{6}) \Big] \\ Y_{33} &= \dot{\omega}_{2d}^{y} + \Lambda e_{6} \\ p &= \Big[m \quad I \quad I_{w} \Big]^{T} \end{split}$$
(A6)

The transformation matrix Jb in equation (26) is given by

$$J_{b} = \begin{bmatrix} \frac{1}{r_{1}} & 0 & 0\\ 0 & \frac{1}{r_{1}} & \frac{d}{r_{1}}\\ 0 & \frac{1}{r_{2}} & -\frac{d}{r_{2}} \end{bmatrix}$$
(A7)

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