Chapter 1

Introduction

1.1. Background and Motivation

In a parallel manipulator, as opposed to a serial manipulator, the end effector is connected to the base by a number of separate and independent linkages working in parallel. The word ‘Parallel' is used to describe the topology of the system, *i.e.*, the linkages of the manipulator act together. A parallel manipulator can be used to perform various tasks like path tracking, force control *etc*.

Gough and Whitehall first developed a parallel manipulator system for the purpose of testing tyres [Gough & Whitehall, 1962] because this system offered high load capacity, good rigidity and high precision. Stewart [Stewart, 1965–1966] formally introduced a closed-loop six degrees-of-freedom (DOF) parallel manipulator (Stewart platform) in 1965 as a flight simulator. Therefore, the parallel robot manipulator is also referred to as the Stewart-Gough platform. The Stewart platform is a 6-DOF mechanism with an upper movable end effectors-platform and a fixed base-platform connected together by six prismatic-legs. These hydraulically or

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electrically actuated legs are connected to the platforms through passive spherical and/or universal joints.

Robotic systems have to be precisely controlled to perform the desired task. The control objective is usually to follow a specific path at some specified speed. The motion is specified within the workspace of the manipulator which is obtained from kinematic analysis. In addition, there can be constraints on forces resulting from interaction of the manipulator with its work environment. Such control actions need computation of the forces to be applied by the linkages of the parallel manipulator. When a robotic system is acted upon by a set of forces, computation of the resultant motions is performed by using a forward dynamics model, *i.e.*, the dynamic model of the system itself. On the other hand, computation of the forces for specified motions is obtained from an inverse dynamics model of the system. The inverse dynamics model is fundamentally different from inverse kinematics model because it takes into account the effect of the dynamical forces on the system.

Overwhelming control, which is robust with respect to parameter and measurement uncertainties, is a type of implicit system inversion scheme used in robot control. Overwhelming control strategy has been previously applied to serial manipulators. However, it is difficult to apply it directly to parallel manipulators due to the closed loop kinematic chain formed by the members of the manipulator. This thesis concerns adaptation of overwhelming control strategy for control of parallel manipulators. To the knowledge of this author, no such work has been reported in the literature.

The performance of the parallel manipulator controller designed in this thesis is studied through two examples. The first concerns the use of the Stewart platform as a driving simulator and is extended to a full virtual reality application. In the second application dealing with machining operation through a tool mounted on the Stewart platform, compensations are designed so that the controller allows impedance control, *i.e.*, both position and force control depending upon the environment interaction.

The reason for selecting the vehicle simulator application as a test case arises from the lack of proper driver training facilities in India. Road safety is a major concern for

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any government as the number of motor vehicles ownership among the young people is increasing rapidly. So, the vehicle simulator has great importance in education and research area. It has capability of producing virtual environments so that the driving skill of the novice drivers can be enhanced before facing the real world. The other important application areas are road safety research, vehicle system development and traffic control device development.

There are three types of driving simulators: high level, medium level and low level. The first driving simulator based on human-in-the-loop simulation was developed in 1970s. Such simulators provide safe and easily controlled road conditions for roadway design compared to real road or field tests. The Federal Highway Administration driving simulator and VTI driving simulator were developed in mid 90s [Shiong, 2009a]. A lot of simulation on the computer is required for the new design of a car. This was the main reason for Daimler Benz AG to build their first driving simulator in 1985. They have improved that simulator over the years with regard to sound system, visual system and motion system.

A driving simulator needs a realistic model of the vehicle which has to be simulated with online inputs from the operator. The online inputs are the driver controlled parameters, *i.e.*, the accelerator or gas pedal position, brake pedal position, clutch position, gear change, steering wheel position *etc*. These control parameters may change if the vehicle has an automatic transmission. Other parameters which affect psychometric factors like heating or air-conditioning, mirror position, seating potion and inclination, behaviour of co-passengers, … are usually considered in very advanced simulators. The driving simulator developed in this thesis does not include the psychometric factors. Rather, importance is placed on the vehicle dynamics.

Modern vehicles come with a variety of control systems. The developed vehicle simulator emphasizes on the brake control system. It may be note here that a driving simulator is helpful in controller prototyping through software-in-the-loop and hardware-in-the-loop simulations. This way, driver or operator feedback can be obtained before actual field trials. This improves the product quality, reliability and reduces the product development time. Three brake systems are considered in the

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vehicle model developed in this thesis: standard mechanical/hydraulic brake, anti-lock brake and regenerative brake. A common behaviour model is developed and the operator can select the vehicle parameters (type of vehicle, engine power, transmission system, brake system, tyre pressure, *etc*.) at the start and then drive the virtual vehicle while being seated on a Stewart platform. Thus the same simulator can be used for various types of vehicles, road conditions, *etc*. The visual feedback to the operator is given through dedicated a graphics simulator which receives data (vehicle position, orientation, roll, pitch and yaw angles, *etc*.) from the vehicle simulator.

The motivating factor behind consideration of several brake systems in the vehicle simulator system is the conditions that prevail in Indian roads, especially in sub-urban, semi-urban and rural areas, where road infrastructure is poor and traffic is chaotic. The vehicle performance is severely challenged in these conditions and optimizing the performance of the mechatronic systems require controllers to be tuned by trial and error through exhaustive simulations and field testing. Thus, the brake system has to be designed for extreme driving conditions, especially where frequent braking and acceleration is required. Increasing the life of the braking system in these conditions becomes important.

The antilock braking system (ABS) uses a control strategy to maintain the wheel slip with in a predefined range. A sliding mode controller (SMC) for ABS is required to be developed to maintain the optimal slip value. Combined regenerative and antilock braking in electric/hybrid-electric vehicles provides higher safety in addition to energy storing capability. Development of control law for this type of braking system is a challenging task. The braking of the vehicle, performed by using both regenerative and antilock braking, is based on an algorithm which decides on how to distribute the braking force between the regenerative braking and the antilock braking in emergency/panic braking situations as well as in normal city driving conditions. A driving simulator application serves as a platform for prototyping these controllers.

Overwhelming controller used in the system inversion scheme of Stewart platform as a motion platform for vehicle driving simulator is used only for trajectory tracking. While real-time simulation is important in the vehicle simulator application, other

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operational constraints are more important in some other applications. The parallel manipulator is also used to perform other tasks like machining, docking of space vehicles and medical operations where control of the interaction force is as important as the positioning accuracy. The control of both position and the interaction force, called impedance control, is a challenging task.

The overwhelming controller can be used for force/impedance control with appropriate modifications. The interaction forces can be accommodated during the interaction period by modulating the impedance at the interface of manipulator and environment. This impedance modulation is done in the controller side. The second test case considered in this thesis considers a machining operation performed in three-dimensional space with limits placed on the interaction forces. This test case is representative of other applications of the parallel manipulator involving impedance control.

A common tool enabling a unified approach to the physical system modelling in various disciplines is bond graph modelling. Bond graph technique is well suited for modular modelling of large physical systems, especially complex multibody systems. Moreover, efficient control algorithms can be derived from analysis of the bond graph structure and subsequent modifications to the model can be easily incorporated. Thus, bond graph is a convenient tool for integrated system modelling. The causal structure of the bond graph shows how element constitutive relations should be combined to produce computer simulation of the system. The bond graph model can be causalled differently to yield the inverse dynamics model. That is why bond graph models have been extensively used for design of mechatronic systems.

The parallel manipulator system is a multibody system and it involves various energy domains: mechanical, hydraulics in the leg actuation and electrical/electronics in solenoid control. Moreover, the vehicle system model considered in the vehicle simulator test case application involves multibody dynamics, thermodynamics (engines), hydraulics (brakes, transmission system, …), mechatronics, *etc*. Therefore, bond graph has been used as the common model and controller development tool throughout this thesis.

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1.2. Contributions of the Thesis

The main contributions of this work are summarised as follows:

- A detailed bond graph model of a hydraulic actuator with constraints and frictional forces has been developed. For this purpose, bond graph sub-models of Newton-Euler equations, co-ordinate transformations, calculation of Euler angles *etc.* are developed. The slider component model and other multi-body component models are validated through available benchmark models.
- Six degrees-of-freedom model of parallel manipulator including dynamics of electro-hydraulic actuator and servo-valve have been developed.
- An accurate and computationally efficient inverse model of parallel manipulator to be used in a real-time application is developed. It is shown that a controller based on an approximate inverse model which correctly represents the kinematic constraints, but neglects some dynamical components, is sufficiently accurate because of the high feedback gains used in the overwhelming control strategy.
- Various control strategies of parallel manipulator such as overwhelming control and force/impedance control are investigated. An alternative scheme for impedance control with amnesia removal technique is proposed and evaluated through simulation studies.
- A detailed bond graph model of a four wheel vehicle its sub-systems is developed and integrated with vehicle control systems for antilock braking system, sliding mode brake control and regenerative braking. This model is used for designing a driving simulator system using a Stewart platform. A simple graphics display interface for the driving simulator showing the terrain and the skyline is developed.
- The impedance control strategy has been verified by considering a machining operation where there are constraints placed on the tool–job interaction force. When the interaction force is controlled in the parallel manipulator, there is a loss of positioning accuracy. This position error, called amnesia, is removed during the non-interaction period through an amnesia removal controller.

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1.3. Organisation of the Thesis

This thesis is organised into six chapters other than this chapter. Overviews of the contributions made in those chapters are given in the following:

A comprehensive survey of the literature pertaining to modelling of the multibody systems and the bond graph modelling of Stewart platform and vehicle system are presented in Chapter 2. Literature on the simulation and control aspects of the Stewart platform are also discussed in the same chapter.

Chapter 3 details the modelling of multibody systems in non-inertial frame. Bond graph representations of Newton-Euler equations, coordinate transformations, Euler angle calculations are developed. Finally, the developed models are validated by considering two applications: a Rapson slide and a spinning top.

The bond graph model of a planar Stewart platform and hydraulic servo system are developed in Chapter 4. The basic concepts of overwhelming control and its properties are derived. Bond graph implementation of an overwhelming controller for the planar Stewart platform system with a simplified inverse dynamics model is also presented therein and the importance of using a proper forward dynamic model with respect to right leg force computation is demonstrated. It is further shown that an approximate inverse dynamics model, which is computationally efficient, gives reasonably accurate trajectory tracking performance. Thereafter, bond graph model of 3-D hydraulic actuator is developed which is used to construct the forward and inverse bond graph models of six degrees-of-freedom Stewart platform.

Chapter 5 concerns the first test case for validation of the developed overwhelming control strategy on a vehicle simulator system. The simulation studies based on the single-wheel, bicycle and full vehicle models along with the switching and sliding mode ABS control algorithms, and regenerative braking are presented. A Human-in-the-loop simulator for six degrees-of-freedom vehicle is described along with some results.

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In Chapter 6, the concept of interaction force or impedance control with a virtual foundation in the controller domain is discussed. Then, a revised concept of impedance control adopted by the author along with amnesia removal technique is presented. Finally, the second test case application relating to machining operation through a parallel manipulator with constraints placed on the interaction force is discussed with some simulation results.

The conclusions drawn from this thesis and the scope for future research work are given in Chapter 7.

Thereafter, a list of relevant references is presented. All these references are cited in the main chapters and appendices of this thesis.

Finally, the thesis ends with two appendices which give the basic bond graph theory and the list of files given in the companion compact disc.

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