UNIVERSITI PUTRA MALAYSIA

SIMULATION BASED ANALYSIS OF KINEMATICS, DYNAMICS AND CONTROL OF SPACE ROBOTS

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SIMULATION BASED ANALYSIS OF KINEMATICS, DYNAMICS AND CONTROL OF SPACE ROBOTS

By

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Dedicated
to
my Parents

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LIST OF ABBREVIATIONS

Ω : the angular velocity of the platform

w_i : angular velocity of body *i*

$\sum i$: frame fixed on body *i*

$\sum I$: inertial reference frame

I_i : inertial tensor of body *i* about its center of mass

m_i : mass of body *i*

$Z_i q_i$: unit vector of the rotational axis of joint 1 and its joint angle

$\hat{S}_i$: vector from joint 1 to the center of mass of body *i*

S_G : vector from joint 1 to the system center of mass

$r_i G$: vector from the system center of mass to the center of mass of body *i*

G_i : center of mass of body *i*

$M(q)(\ddot{q})$: the inertia matrix

${}^0D$: the 3 by 3 inertia matrix with respect to the CM

BDJP : Bounded Deviation Joint Path

CM : Center of Mass

$h(q, \dot{q})$: the Centrifugal and Coriolis term

J^* : System's Jacobian matrix

R_i : the orientation of the body *i*

VB : Virtual Base

VG : Virtual Ground

VM : Virtual Manipulator

q_i : Joint angles of the joint *I*.

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SIMULATION BASED ANALYSIS OF KINEMATICS, DYNAMICS AND CONTROL OF SPACE ROBOTS

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Faculty: Engineering

The space robotics kinematics, dynamics and control were studied by simulation. An emerging concept in space robotics is the Virtual Manipulator (VM) concept. In this study, the VM concept was enhanced and verified through simulation. The mathematical software package MATHEMATICA was used to compute the formulations. In the kinematics simulation of free-floating space robotics systems the concept of VM was enhanced which relates to the homogeneous matrix formulation. This was established by simulation results, there are no external forces condition, the inverse kinematics solution can be solved. In the area of space robot dynamic identification, the method based on conservation

law of linear and angular momentum of a space robot from the VM approach was introduced. It was shown that the acceleration of the Virtual Base (VB) was proportionally equal to the change of its position in inertial space from the applied forces or torques. The forces or torques rotates about the system center of mass. A PD control law was used with the simulation test to identify the dynamic parameters. In the problem of trajectory planning, the VM concept was utilized that allow the space robot translation and rotation with respect to an inertial reference frame. A method was developed that can compute the satellite platform moments from the manipulator's motion. The resolved motion rate control algorithm was used for time periodic feedback control. In the simulation results, a satellite-based three degrees of freedom robot was simulated using schematic illustrations. The telerobotic control system was used in the space robotics control. In the master-slave control environment study, several considerations were taken into account, like the master and slave arm configuration, telemonitoring force feedback algorithm, and dynamic characteristics of master and slave arm. In this study a complete and enhanced master-slave space robotics system was established by simulation.

Abstrak disertasi yang dikemukakan kepada Senat Universiti Pertanian Malaysia sebagai memenuhi keperluan memperoleh ijazah Master Sains.

ANALISIS BERASAS SIMULASI KINETIK, DINAMIK DAN KAWALAN ROBOT RUANG

Oleh:

Shafina Sultana

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Pengerusi: Dr. Iskandar B. Baharin

Fakulti: Kejuruteraan

Kinetik, dinamik dan kawalan robotick ruang telah dikaji melalui simulasi. Konsep yang muncul dalam robotik ruang ialah konsep pengolah maya (Virtual Manipulator VM). Dalam kajian ini, konsep VM tersebut telah diperluas dan disahkan melalui simulasi pakej perisian matematik (MATHEMATICA). Pakej tersebut telah digunakan untuk mengira perumusan. Dalam simulasi kinematik sistem robotik yang apung bebas konsep VM telah dibaiki yang berkait dengan perumusan matriks yang homogen. Ini telah dikukuhkan dengan keputusan simulasi yang bukan satu keadaan daya luaran, di mana penyelesaian kinematik songsang dapat diselesaikan. Dalam aspek pengenal pastian dinamik robot ruang telah

diselesaikan. Dalam aspek pengenal pastian dinamik robot ruang, kajian ini telah memperkenalkan kaedah berdasarkan hukum pengabdian momentum linear dan sudut sesebuah robot ruang daripada pendekatan VM. Telah ditunjukkan bahawa pecutan Virtual Base (VB) adalah sama secara berkadaran dengan perubahan kedudukannya dalam ruang inertia daripada daya kenaan atau kilasan. Daya atau kilasan berputar mengelilingi sistem pusat jisim. Hukum (PD) digunakan dengan ujian simulasi untuk mengenal pasti parameter dinamik. Tentang masalah perancangan trajektori, konsep VM digunakan untuk membolehkan robot membuat peralihan dan pemutaran bersandarkan rangka rujukan inersia. Satu kaedah telah dibina yang dapat mengira momen pelantar satelit tersebut daripada gerakan pengolahnya. Kadar gerakan algoritma kawalan yang terhasil digunakan untuk kawalan suap-balik berkala masa. Dalam keputusan simulasi, robot tiga darjah kebebasan yang berasas satelit disimulasikan dan ditunjukkan dengan menggunakan ilustrasi skema. Sistem kawalan telerobotik dilaksanakan dalam kawalan robotick ruang. Dalam kajian persekitaran kawalan tuan-hamba beberapa pertimbangan telah diambil kira, seperti tatarajah lengan tuan dan hamba, pengawasan algoritma suapa balik daya, dan ciri-ciri dinamik lengan tuan-hanba. Dalam kajian ini sistem yang lengkap dan luas robotick ruang tuan-hamba telah ditetapkan melalui simulasi.

CHAPTER I

INTRODUCTION

In general, robotic systems are designed, developed and operated to assist or replace humans in accomplishing tasks that are either tedious and boring, or too dangerous, costly or simply impossible for humans. Many space tasks fall in the latter categories, such as retrieving, repairing and servicing satellites in earth orbit. The study of space robotic is dedicated to the application of robotic technologies for exploration and servicing in space. The application of robotic technologies in space deserves special attention because the nature and operation of space systems, as well as their working environment, represent important modifiers for the design and use of robots in space.

Any robotic activity in earth orbit is strongly influenced by the zero gravity (Bejczy et. al., 1993). Furthermore, robots on a planetary surface, function on a more or less unknown and rugged terrain. In fact, all robotic activities in space are always performed in harsh thermodynamic and/or atmospheric environment. Also space robots have to be extremely economical in mass, volume and power consumption, and tolerate severe bandwidth limitations and considerable time delays in communicating with a ground control station. These, combined with the stringent and unique environment, system and operation constraints, have motivated considerable research and development (R&D) in space telerobotics over the past two decades. The space robotic systems provide a logical way of exploring the space for mankind. There are reluctance by the human race to delegate the task of exploration in near space, in earth orbit, on the moon, and even on near planets. It is likely that this will be overcome in the near future, by the advancement of space robotic system.

To accurately produce an earth-based zero gravity conditions testbed is difficult if not impossible through experimentation. The use of software simulation is possible, but it requires accurate models of manipulator dynamics with extensive simulation programming for the environment.

This thesis deals with the topics of space robotic system's kinematics, dynamics, control and master-slave systems of space robotic systems for space application. The fixed based robot kinematics formulation is not suitable because of free-floating and free-flying nature of the satellites. The dynamic of space robotics system deal with the base and joint reactive forces (Vafa and Dubowsky, 1990[1,2]). In the space robotics control system, the resolved motion acceleration control method has been proposed due to its concurrent joint control strategy for the problem domain. As the task is uncertain, it was essential that a supervisory controlled master-slave paradigm be considered for the overall control strategy. An extensive simulation study of space robot maneuverbility in space was observed and estimated.

Space robotic manipulator systems will be required to perform complex tasks in space such as satellite repair. These robotic manipulators will encounter a number of kinematics, dynamic, and control problems caused by the dynamic coupling between the manipulators and its spacecraft.

Many mechanical tasks on space vehicles and space stations can be efficiently carried out by robotic manipulators. These tasks include delicate experiments as well as production and maintenance operations in space. The base reactions of a space manipulator are directly transmitted to the supporting structure, which is generally a part of the space vehicle or space station. This thesis explores kinematics and dynamic formulation and control strategy for a master-slave control system.

Space Robot Kinematics Control

Manipulation is one of the important fields in robotics because it deals with direct interactions of the robot with the physical world. Robot manipulators are spatial multi-link mechanisms. This nature of the mechanism had caused several problems for controlling robot manipulators. For example kinematics is important in trajectory control because the tasks are usually given as the motion of the end-effector in Cartesian space, whereas the manipulator motion depends on the motion of each joint.

Structural flexibility in robotic systems is becoming an issue of increasingly greater concern. The demand for faster lightweight manipulators has brought into focus the importance of elasticity in links and joints. The space manipulators' systems will likely have one or more mechanical arms carried by a spacecraft. The mechanical arms will generally have at least six degrees of freedom. The manipulators will most likely be driven by photovoltic powered electric actuators, which is a renewable source of power (Vafa and Dubowsky, 1990[2]). The spacecraft will generally be equipped with both reaction jets and reaction wheels for control. Reaction jets, which can control both position and orientation of a spacecraft, operate on the principle of conservation of linear momentum. Reaction wheels operate on the principle of conservation of angular momentum and can only control orientation of a spacecraft.

Any manipulator payloads are assumed to be rigid and fixed to the manipulator’s end effector. Therefore these payloads and the end effectors form rigid bodies. When the manipulator grabs a payload, the system model will change. The spacecraft is also assumed to be rigid and is represented by a single rigid body. The mass of this body is not necessarily large compared with the masses of the manipulators. All joints of the manipulators are assumed to be either prismatic or revolute joints (Yoshida et al., 1991).

In this study, the manipulators are assumed to move sufficiently slow that the flexibility in their drive shafts, links, and gear transmissions can be neglected. Therefore the manipulators are assumed to be composed of rigid bodies. The masses of these rigid bodies are time invariant and the position of the center of mass within each body is fixed. Bodies whose centers of mass do not move relative to each other such as a link, its actuators and its gear train can be combined into one rigid body. The formulation of kinematics function utilizing the concept of Virtual Base (VB) and Virtual Ground (VG) to identify the relative kinematics position of the space robot in the virtually undimensional space is proposed.

Space Robot Dynamic Control

Dvnamics are important in analysis, simulation and highly accurate motion control of robot manipulators. Robot manipulators are spatial linkage mechanisms that have very complicated dynamics where nonlinear terms and dynamic coupling exist at each joint. The dynamics of space robotic systems can be quite complex and hence their control can be difficult.

A space mission will require the construction, repair, and maintenance of satellites and space structures on orbits by means of space robots. Space robot consists of a satellite base and manipulators, which can fly freely on an orbit. This type of space robots are called as a free-flying space robot. Since a robot manipulator is mounted on a satellite, there is an interaction between the manipulator dynamics and the dynamics of the satellite with zero gravity effect (Murotsu et al., 1991). This raises lots of new complicated dynamic problems which are difficult to be treated by conventional technology on the ground. Such technically ambitious systems have yet to be realized, in part, because new technology is needed to achieve the robotic system's capabilities as required. Some critical technical problems must be solved in a number of areas, including dynamics and control. A number of dynamics and control problems faced by the designers of space robotic systems are unique to this area, because of the distinctive and complex dynamics found in many potentially important space robotic applications. This research considers some representative types of space robotic and telerobotic systems, identifying some of their unique planning and control problems, with a particular focus on the very challenging problems posed by free-flying and free- floating space robots.

Space Robot Control

The control of space robotic systems is made difficult by the number of factors. For example, the need for space systems to be light weight means that space robots will be flexible and have relatively small actuators. Hence, their control systems must be able to handle the difficult problems of accommodating and compensating for low frequency resonances and nonlinear actuator saturation. Also, planetary exploration systems will be faced with the problems of controlling a system with long time-delays, while operating with a mobile compliant base in a highly unstructured environment with relatively limited sensing information for control. Clearly, the controls of future robotic systems present difficult challenges to the research community.

Coordinated motion control of robot arms is sometimes required for advanced applications. Coordinated motion control has been studied by several authors (Vafa, 1987), (Papadopoula and Dubowsky, 1991) and (Yokokohji et al., 1993). The issue of how to coordinate the motion of arms in a nonconflicting way and how to control the internal forces applied to object are major problems in coordinated motion control. In most of the control algorithms published so far, robot arms have been assumed to have a non geometric error. Stability has been considered when the breakage of the object occurs. However, a robot arm has geometric errors caused by uncertainties due to its geometric parameters. Also errors some times lead to excessive internal force applied to an object.

The control schemes for space robots, for example, the resolved acceleration control based on generalized Jacobian which contains kinematics and dynamics parameters (Yokokohji et al., 1993) of a robot has been proposed. In the study, the identification of dynamic parameters of a space robot was looked into. Two identification methods for space robots have been proposed. The first method considers space robot manipulators on an inertially fixed base. The dynamic parameters of these space robots can be determined from the relations between motions of a manipulator and applied joint forces and/or torques. The second method is a novel identification method for space robots which can freely move in both transitional and rotational directions. The method was based upon the conservation laws of linear and angular momentum of a space robot. An efficient computational algorithms has been proposed for the generalized Jacobian and resolved acceleration control to overcome the associated problems such as measurements utilized, amount of algorithm computation, and so on.

Space Robot Master-Slave Control

Autonomous telerobotic systems have been suggested for a number of important missions in space. For example, free-flying robotic and telerobotic systems have been considered for retrieving, repairing and servicing satellites in earth orbit. A free-floating space robotic system is one in which the spacecraft's position and attitude are not actively controlled for driving manipulator actively to conserve attitude control (Sheridan, 1992). Such a system is clearly highly redundant giving it versatility, and a nearly unlimited workspace. In a free-flying space manipulator system, position and attitude of the system's spacecraft is controlled actively by the operator. Hence the space robotic system will usually need a master-slave control strategy.

A robotic teleoperator system installed with space manipulators will play an important role in future space projects, such as constructing space structures or servicing satellites. However, in space environment, the lack of a fixed base raises several serious problems in controlling such space manipulators (Yokokohji, 1991). For example any motion of the manipulator arm will induce reaction forces and moments, which will disturb the position and attitude of the satellite which represents the footing base of the arm. In this respect, the research treats the space robotics control problem as a two-folded approach. Firstly, the Generalized Jacobian Matrix (GJM) which guarantees proper motion control of free-floating manipulators, was formulated for the system. Secondly, the concept of telemonitoring was proposed as a means of coordinating the resolved acceleration rate control. A human hand kinematics and dynamics model of teleoperation system were proposed. The master and slave arm dynamics was actively modified based on some local criteria. A comparative study was also carried out based on results of an extensive simulations work.

Aim and Objectives

The research study was carried out in four stages:

1) The space robotic's kinematics formulation.
2) The space robotic's dynamics formulation.
3) The space robotic's control.
4) The master-slave control system for space robots.

A detailed simulation study was carried out to validate the proposed space robotic's kinematics, dynamics and control algorithms.

It is very important to verify the feasibility of modeling, identification and control methods of space robots by means of simulation study. In this simulation, the system of space robot satellite base and a manipulator was considered. The objective was to develop free-floating robots, which can in the future, work in space with a safety factor and at low cost. In developing the free-floating robots,