FEEDFORWARD MODEL WITH CASCADING PROPORTIONAL DERIVATIVE ACTIVE FORCE CONTROL FOR AN ARTICULATED ARM MOBILE MANIPULATOR

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

DECEMBER 2016

DEDICATION

All praises are due to Allah, All praises are due to Allah, All praises are due to Allah,

To my beloved mother Hj. Maznah bte Alias, this thesis is dedicated to her for without her never ending sacrifices, support and unconditional love, I would still be standing looking at an imaginary wall instead of looking beyond. May Allah bless her with the greatest blessing of all.

To my beloved father Alm. H Abdullah bin Awang, thank you for teaching the true meaning of education – never-ending pursue of knowledge for the sake of the greatest blessing from Allah.

To my beloved sibling, years of joys and respect, may Allah bring us all closer.

To my beloved wife Alice Sabrina Ismail, Thank you for loving me for who I am. I owe you a vacation.

To my beloved children's, it is my hope that I could be as good as a parent to you as your grandparent was with me. May Allah guides us all.

ACKNOWLEDGEMENTS

The author would like to express the highest gratitude and sincerest admirations to Professor Dr. Musa Mailah for his firm guidance, relentless support, enduring patient, invaluable idea and professional supervision throughout the progress of the research. Despite several delays, postponement of datelines, myriad of experimental setback and the challenges of thesis writing, his continuous motivation shine a bright optimistic light onto a road that could have otherwise be a very scary pessimistic path. For without his contribution this research and thesis would not have come to light. It is the genuine hope of the author that someday he could become as good as a postgraduate supervisor as Profesor Dr. Musa Mailah.

The author would also like to express the deepest appreciation and heartfelt respect to Dr. Collin Tang Howe Hing for his invaluable comment, contributing ideas, constant assistance and professional co-supervision throughout the progress of the research. For without his contribution also this research would not have been concluded.

The upmost salutations also is due to Mr. Akmal Baharain for his priceless involvement toward the procurement of equipment for the MMer and indispensable design ideas for without his contribution the research would have taken a much longer time to complete. The inmost acknowledgement toward Mr. Rahim for setting up the Robotic Lab at P23 to performed the research and to all of the IAFC lab member past, present and future including Dr. Suhail Kazi, Mollah, Mohammad Ali, Rosmazi, Yasser, Nazmin and many others thank you all.The sincerest gratefulness also is due to my UTeM colleagues Effendi, Azrul, Arfauz, Amri, Dr. Rizal, Hisham, Lokman, Asaari, Mahasan, and Dr. Zamberi for their continuous support and encouragement. Finally to the author sponsor UTeM and FKP for believing in the future generation with the current stakeholder investment, I am forever grateful. May Allah blesses us all.

ABSTRACT

This thesis presents an approach for controlling a mobile manipulator (MM) using a two degree of freedom (DOF) controller which essentially comprises a cascading proportional-derivative (CPD) control and feedforward active force control (FAFC). MM possesses both features of mobile platform and industrial arm manipulator. This has greatly improved the performance of MM with increased workspace capacity and better operation dexterity. The added mobility advantage to a MM, however, has increased the complexity of the MM dynamic system. A robust controller that can deal with the added complexity of the MM dynamic system was therefore needed. The AFC which can be considered as one of the novelties in the research creates a torque feedback within the dynamic system to allow for the compensation of sudden disturbances in the dynamic system. AFC also allows faster computational performance by using a fixed value of the estimated inertia matrix (**IN**) of the system. A feedforward of the dynamic system was also implemented to complement the **IN** for a better trajectory tracking performance. A localisation technique using *Kalman* filter (KF) was also incorporated into the CPD-FAFC scheme to solve some MM navigation problems. A simulation and experimental studies were performed to validate the effectiveness of the MM controller. Simulation was performed using a co-simulation technique which combined the simultaneous execution of the MSC Adams and MATLAB/Simulink software. The experimental study was carried out using a custom built MM experimental rig (MMer) which was developed based on the mechatronic approach. A comparative studies between the proposed CPD-FAFC with other type of controllers was also performed to further strengthen the outcome of the system. The experimental results affirmed the effectiveness of the proposed AFC-based controller and were in good agreement with the simulation counterpart, thereby verifying and validating the proposed research concepts and models.

ABSTRAK

Tesis ini membentangkan satu pendekatan untuk mengawal pengolah robot mudah alih (MM) menggunakan pengawal dua darjah kebebasan (DOF) yang terdiri daripada kawalan berkadaran-terbitan melata (CPD) dan kawalan daya aktif suap depan (FAFC). MM mempunyai kedua-dua ciri pelantar robot mudah alih dan pengolah robot industri. Ini dapat memperbaiki prestasi MM dengan peningkatan kapasiti ruang kerja dan ketangkasan operasi sistem. Kelebihan mobiliti kepada MM, walau bagaimanapun telah menambah kerumitan dinamik sistem tersebut. Oleh itu, sebuah sistem kawalan teguh yang boleh memampas kerumitan tambahan seperti dinyatakan adalah diperlukan. AFC merupakan salah satu novelti kajian dengan mewujudkan satu daya kilas suap balik ke dalam sistem dinamik untuk pemampasan terhadap sebarang gangguan mendadak. AFC juga mempercepatkan lagi prestasi kiraan komputer dengan menggunakan nilai pemalar tetap anggaran matriks inersia (**IN**) di dalam sistem. Satu model sistem dinamik suap depan juga telah dilaksanakan untuk mengimbangi **IN** demi menghasilkan prestasi pengesan trajektori yang lebih baik. Kawalan CPD-FAFC juga digabung dengan satu teknik penyetempatan menggunakan penapis *Kalman* (KF) yang akan membantu MM untuk mengatasi masalah berkaitan dengan pemanduan berarah. Kajian simulasi dan eksperimen telah dilakukan terhadap MM untuk mengesahkan keberkesanan sistem kawalan yang digunapakai. Simulasi dilaksanakan berdasarkan teknik simulasi bersama yang menggabungkan pelaksanaan dua perisian MSC Adams dan MATLAB/Simulink di dalam kerangka masa yang sama. Kajian eksperimen juga telah dilakukan menggunakan sebuah pelantar ujikaji MM (MMer) yang dibangunkan berdasarkan pendekatan mekatronik. Satu kajian perbandingan di antara sistem kawalan CPD-FAFC dengan beberapa sistem kawalan lain juga telah dilakukan untuk mengukuhkan lagi dapatan sistem. Hasil keputusan mengesahkan keberkesanan pengawal berasaskan AFC yang dicadangkan dan juga sejajar dengan keputusan simulasi, dengan demikian memperakukan konsep dan model penyelidikan yang dicadangkan.

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LIST OF ABBREVIATIONS

ADC	-	Analog to Digital Converter
AFC	-	Active Force Control
AN	-	Analog Signal
CAD	-	Computed Aided Design
CDac-MMer	-	Command and Data Acquisition Centre-Mobile Manipulator Experimental Rig
CPD	-	Cascading Proportional Derivative
CPD-FAFC	-	Cascading Proportional Derivative - Feedforward Active Force Control
CTC	-	Computer Torque Control
D	-	Derivative
DAC	-	Digital to Analog Converter
DC	-	Direct Current
DOM	-	Degree of Matching
EKF	-	Extended Kalman Filter
GPS	-	Global Positioning System
GUI	-	Graphical User Interface
IR	-	InfraRed
MDS	-	Multibody Dynamic Software
MIMO	-	Multi Input Multi Output
MM	-	Mobile Manipulator
MMer	-	Mobile Manipulator Experimental Rig
NN	-	Neural Network
DOF	-	Degree of Freedom
KF	-	Kalman Filter
LiPo	-	Lithium Polymer
P	-	Proportional

PC	-	Personal Computer
PCB	-	Printed Circuit Board
PD	-	Proportional Derivative
PI	-	Proportional Integral
PIC	-	Programmable Interface Controller
PID	-	Proportional Integral Derivative
PWM	-	Pulse Width Modulation
RF	-	Radio Frequency
ROS	-	Robot Operating System
SISO	-	Single Input Single Output
SLAM	-	Simultaneous Localization and Mapping
UKF	-	Unscented Kalman Filter
UART	-	Universal Asynchronous Receiver Transmitter

LIST OF SYMBOLS

A^T	-	Mobile manipulator constrain matrix
C_{r1}	-	Centripetal and Coriolis matrix of arm manipulator
C_{r2}	-	Centripetal and Coriolis matrix cause by the angular motion of the mobile platform onto the manipulator
C_{p1}	-	the centripetal and Coriolis matrix of the mobile platform
C_{p2}	-	Centripetal and Coriolis effect due to the present of the manipulator reflected onto the mobile platform
$C(q)$	-	general representation of Coriolis and Centrifugal force
E_p	-	a constant matrix
$G(q)$	-	general representation of gravity force
I'	-	estimated inertia matrix
I_1	-	Moment of inertia of link 1 about joint 2 axis
I_2	-	Moment of inertia of link 2 about joint 3 axis
IN	**-**	Inertia matrix parameters for AFC
K_{tnr}	-	Motor constant of right wheels
K_{tnl}	-	Motor constant of left wheels
K_{tn1}	-	Motor constant of joint 1 of the arm manipulator
K_{tn2}	-	Motor constant of joint 2 of the arm manipulator
K_{tn3}	-	Motor constant of joint 3 of the arm manipulator
k_{p1}	-	Proportional gain parameter for position CPD control
k_{p2}	-	Proportional gain parameter for velocity CPD control
k_{d1}	-	Derivative gain parameters for position CPD control
k_{d2}	-	Derivative gain parameters for velocity CPD control
l_1	-	Length of link 1 for the arm manipulator

l_2 - Length of link 2 for the arm manipulator

$L1$ - Length from joint 2 to link 1 center of gravity for the arm manipulator

$L2$ - Length from joint 3 to link 2 center of gravity for the arm manipulator

λ - Lagrange multipliers vector subject to the kinematic constrains of the mobile platform

M_r - Inertia matrix of the arm manipulator

M_{p1} - the mass inertia matrix of the mobile platform acting towards the arm manipulator

M_{p2} - Inertial term due to the presence of the manipulator reflected onto the mobile platform

$M(q)$ - General representation of mass inertia

m_p - Mass of platform

m_w - Mass of wheel

m_1 - Mass of link 1

m_2 - Mass of link 2

$\hat{p}(k+1|k)$ - Predicted MM position based on measured optical sensors using EKF

$\sum_p(k+1|k)$ - Updated covariance matrix for the predicted robot position

$\hat{p}(k+1|k+1)$ - Final predicted MM position based on map and measured optical sensors using EKF

$K(k+1)$ - Covariance matrix based on the final predicted position

Q - Disturbance torque

Q' - Estimated disturbance torque

q - Generalize coordinate for MM

q_r - Generalized coordinate for the arm manipulator

q_p - Generalized coordinate for mobile platform wheel

R_r - Inertia matrix of the mobile platform dynamic effect toward the manipulator

R_p - The inertia matrix which reflect the manipulator motion effect on the mobile platform

τ - Input torque to the MM

τ_p - Input torque to the mobile platform wheels

τ_r - Input torque to the arm manipulator

θ - Angular position

$\dot{\theta}$ - Angular velocity

$\ddot{\theta}$ - Angular acceleration

θ_1 - Joint angle of each of the arm joint 1

θ_2 - Joint angle of each of the arm joint 2

θ_3 - Joint angle of each of the arm joint 3

θ_R - Joint angle for right wheel

θ_L - Joint angle for left wheel

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CHAPTER 1

INTRODUCTION

1.1. Research Background

Recent developments in mobile robot and robot arm manipulator have attracted abundant research efforts to combine these two robotic features into one to create a new type of robot, i.e., mobile manipulator. Precision and reliability of a typical industrial robot arm is well proven to be an essential part in modern manufacturing processes. These industrial robot arms have a wide application range: expanding from a simple process like point-to-point material transfer to a more complicated operation, like continuous trajectory tracking, spray painting, and welding. The fixed base of the industrial robot arm limits the working range and flexibility of the system. By adding mobility to the robot arm, it can significantly increase the working range and flexibility of the robot, but at the same time, this will increase the control system complexity. Most of the recent industrial manipulators are still using PID position controller by neglecting the dynamic model of manipulator. This approach is sufficient, since most of the parameters surrounding the manipulator is controllable. Adding mobility to the manipulator, however, will change the system dynamics and may expose the system to an unexpectable external disturbance and the dynamic system of mobile manipulator is coupled which means any movement from the mobile platform will affect the arm manipulator and vice versa. The dynamic model is also highly nonlinear and difficult to control using conventional control method. To further complicate the system most of mobile robot is consider as a nonholonomic system with constrains which require some consideration when dealing with the system kinematics, and hence, a robust control system is required.

A typical mobile manipulator (MM) is comprised of a mobile platform and an industrial arm or manipulator placed on top of it. Over the years, the performance of the MM has greatly improved with increased workspace capacity and better operation dexterity. The added mobility advantage to a MM, however, has increased the complexity of robotic control system management. In this research, a new and enhanced method for controlling a MM with a three degree-of-freedom (DOF) articulated arm or manipulator mounted on top of the mobile platform is studied and presented. A robust controller using an active force control (AFC) based strategy was introduced to eliminate the effect of any disturbances present in the system. AFC creates a force or torque feedback within the dynamic system to allow the compensation of sudden disturbance spike in the dynamic system, before passing the loop to the position and velocity controller. AFC also allows for a faster computational performance by using a fixed estimated inertia matrix, **IN** of the system dynamics instead of the entire system dynamic model. A feedfoward of a simplified model of the dynamic system was implemented to complement the IN for a better trajectory tracking performance of the system. Another control method called the computed torque control (CTC) was also considered to benchmark the robustness and performance of the proposed AFC. The dynamic model of the system is developed using Lagrangian approach. A 3D simulation of the 3 DOF manipulator attached to a skid-steering non-holonomic four wheeled drive mobile platform was carried out to show the effectiveness of the proposed system. The simulation of the system is to be performed using MATLAB software together with the MSC Adams software, hence the term - co-simulation. An experimental rig was also designed and developed, taking into account the control algorithms to validate the effectiveness of the proposed system in the wake of the prescribed disturbances.

1.2. Research Objectives

The main objectives of the proposed research are:

1. To introduce and implement a new method of refining the positioning and tracking accuracy of a MM using a simplified feedfoward model based AFC and *Kalman* filter (KF) localisation by taking into consideration the effect of dynamic interactions between the mobile platform and manipulator in the presence of disturbances.

2. To evaluate and validate the robustness of the system experimentally on the MM prototype executing the proposed controller while performing specific tasks.

1.3. Research Scope

The scope of the research includes the theoretical and the experimental aspects of the proposed MM control system and is defined as follows:

1. The configuration of the mobile platform is constrained to skid steering with four wheel drive setup. Although skid steering drive setup was used in this research, the kinematic of the skid steering setup is assumed to be similar to the differential drive setup. The difference between the differential drive and skid steering setup is in the computation for the centre of rotation of the mobile platform. In skid steering drive system, the centre of rotation can be varied compared to a differential drive system where the centre of rotation is always fixed. This condition usually affects the automated trajectory generation of the MM and has minimal effect on the dynamic model of the MM.

2. The manipulator is limited to 3 DOF with articulated arm configuration. In the dynamic model of the MM, the centre of gravity of each link is considered at

the half length of the link. The inertia of each link is assumed to be equal to a thin cylinder rod to simplify the dynamic model.

3. The theoretical framework involves the study of various underlying principles related to AFC, cascading proportional-derivative (CPD) control, feedforward control and MM localisation. Computed torque control (CTC) was used as the basis for a comparative study against the proposed controller. Simulation of the above framework model was executed considering a co-simulation environment involving MSC Adams and MATLAB computing platforms, noting that MSC Adams is a multibody dynamic software used for studying the complex interaction of the MM dynamics while MATLAB is dedicated for the controller computation. A multibody dynamic software was used to provide better physical dynamic assimilation to a real world application. However, it should be noted that the dynamic model in the MSC Adams software did not consider the friction effect of each joint in the MM. This limitation was necessary to provide reasonable computation time in MATLAB.

4. The experimental MM prototype was designed and developed using the mechatronic approach comprising a PC-based system, embedded microcontroller, brushless DC motor equipped with encoder and various sensors. The proposed controller was programmed into an embedded microcontroller system based on *Microchip dsPIC* 16 bit chip. A PC based system was used to provide graphical user interface (GUI) where data logging and command for the MM was sent. Data obtained from the experimental setup was analysed using MATLAB.

5. The research concentrates on the capability of the MM controller to follow a prescribed trajectory as accurately as possible. There are some limitations that are related to specific research area, i.e., mobile robot navigation and localisation problem. Due to the vastness of the mobile robot navigation area, some forms of localisation methods need to be introduced to demonstrate the navigation capability of the MM for performing a specific task. A localisation method used is based on *Kalman* filter (KF) technique. It requires a map of the MM operating environment to be made known. The map is assumed to be static

with no moving object taken into consideration. The map should also be in 2D configuration. The initial starting point of the mobile platform is provided and the “robot kidnap” problem is not considered in this research.

1.4. Research Methodology

The research methodology used to guide the direction of the research can be described as follows:

1. Literature review on various works performed by other researchers in areas related to MM control, design, dynamics and localisation technique.
2. Derive the mathematical models of the MM, proposed CPD-FAFC controller and CTC.
3. Implement full mechatronic system design approach involving the followings:
    a. Design the mechanical concept of the MM to include the number of joints and DOF, torque capacity requirement, type of actuators to be used, structure supports and mounting, parts drawing and fabrication and manufacturing processes.
    b. Design the electrical/electronic and programming aspects of the MM including the motor driver connection, various sensors connection and mounting, power system management, embedded microcontroller design, system communication requirements and GUI for the PC system.
    c. Design the proposed CPD-FAFC controller together with the CTC controller for benchmarking, concurrently identifying and solving the dynamic model of the MM.

4. Simulate the above controllers based on the co-simulation technique using MSC Adams and MATLAB through various testing, loading and operating conditions. Thereafter, perform a comparative study between the two controllers to derive a meaningful conclusion. Various models are converted into suitable embedded system coding for simulation.

5. Develop the MM test rig through complete system integration including the fabrication and assembly processes.

6. Perform experiments on the MM test rig which is already loaded with the proposed CPD-FAFC embedded controller under various testing conditions. A study on the MM test rig localisation capability using the KF localisation method is also experimented.

7. Evaluate and analyse both results obtained through simulation and experimental works of the MM system.

The flow chart of the research methodology is shown in Figure 1.1, noting that some of the research activities do not necessarily and strictly follow the above description sequentially.

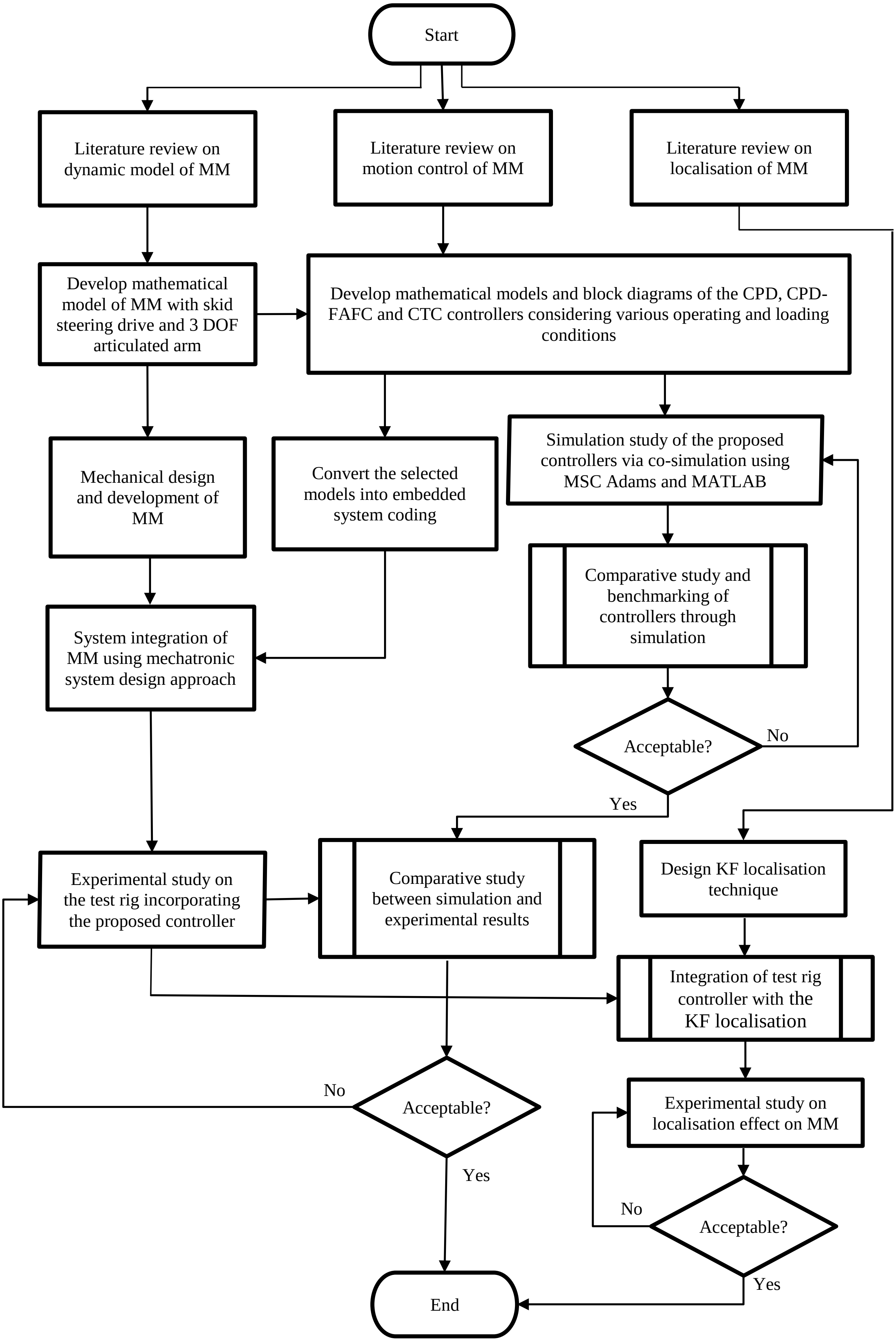

Figure 1.1: Flowchart of the proposed research methodology

1.5. Problem Statement

In describing the control of a MM, the added mobility also increases the complexity of the MM dynamic system caused by the interaction between mobile platform and manipulator. This problem greatly limits the application of the MM in the real world. A robust control method is needed to control the complex dynamic of the MM. In (Mailah *et al.*, 2005) a MM equipped with a two-link planar manipulator was tested using the AFC-based method with various **IN** (estimated inertia matrix) tuning algorithms applied. The tuning methods which include iterative learning and knowledge based fuzzy techniques were performed on-line in an experimental setup. The results show encouraging performance when tracking a prescribed trajectory. The capability of the MM was however limited in terms of its manipulability because of the planar configuration. An articulated 3 DOF MM was thus proposed in this research to enhance the capability of the MM. In the two-link planar MM, the dynamic model is relatively simple and the on-line computation readily implementable. However, with an articulated 3 DOF manipulator MM, the mathematical model of its dynamic has become too intensive for **IN** on-line computation of the AFC-based controller. Thus, a new control algorithm dealing with this problem is needed to counter the given condition.

In this research, the advantages of AFC was enhanced using a feedfoward model control where a simplified inertia of the MM derived from its dynamic equation was injected into the AFC scheme. The feedfoward model was made available from the outside of the AFC control loop, thus enabling for a lesser computation time in the AFC loop. The feedfoward model control helps to estimate some of the dynamic interactions within the system and produces better tracking error performance. AFC also requires adding a position and velocity control scheme to operate effectively. Instead of conventional type of pure PD control, this research introduces the use of a cascading PD control into the position and velocity control loop. The cascading PD control should improve the steady state error and helps the AFC capability to reject disturbances by monitoring the velocity loop. By presenting a viable and physically executable solution to this problem, it will hopefully escalate the application of a MM in the real world environment.

1.6. Research Contributions

The research contributions are described as follows:

1. The work on the MM is actually an extension to the previous works done by Pitowarno (2006) who only considered a two-link planar manipulator as the mounted device on the mobile platform. The proposed research uses an articulate 3 DOF manipulator which is more complex and highly non-linear. Besides the present work employs a skid steering drive system compared to differentially driven wheels for the physical navigation of MM. The controller utilises an improved version of AFC, i.e., cascaded PD with feedforward AFC (CPD-FAFC) scheme unlike the previous works that employed AFC-Resolve Accelerated Control (RAC) and knowledge-based fuzzy (KBF) AFC MM schemes.

2. The research employs a co-simulation technique based on MSC Adams and MATLAB/Simulink computing platform which provide a new method of evaluating and testing the proposed controller through simulation. Compared to a more common simulation method which usually employs a single MATLAB/Simulink computing tools the co-simulation method provide the advantages of not having to fully rely on manually computing the complicated dynamic system model of the MM by incorporating the multibody dynamic software solution such as the MSC Adams. The co-simulation technique also present a new approach to solving the MM problem through virtual rapid prototyping concept which in turn could be extended into a rapid embedded system prototyping.

3. As a continuation from the co-simulation technique a method of rapid embedded system prototyping concept was introduce to construct a seamless transfer of program from the co-simulation MATLAB/Simulink software into an embedded system for the MM. The automated transferring of the controller algorithm from the MATLAB/Simulink to the MM embedded system would significantly reduce the development time and eliminate the possibility of human error to occur if the transfer were to be performed manually.

4. The AFC method can be considered to be robust, accurate and simple to implement; thus it is deliberately chosen as the main controller in the research. However, the AFC relies heavily on effective use of the system sensors. In the proposed research, using the MM sensors effectively in AFC will be one of the main contributions of this research. Acceleration measurement technique using the indirect method as mentioned in the above literature hopefully will provide better implementation of AFC in an embedded system of MM compared to previous solution.

5. Another factor that need attention with AFC application in a control system is tuning of the **IN**. Tuning the **IN** parameter within the AFC feedback loop can be the limiting factor of a successful implementation of the AFC system in a practical solution. The calculation of the tuning process is performed simultaneously with the measurement from the sensors, thereby increasing the system bandwidth. In the proposed research, a feedfoward model based control is utilised to help estimate the inertial effect of the system outside the feedback control loop and hopefully reduce the system tracking error.

6. The control system of the MM alone cannot provide an accurate enough localisation in its environment. The non-deterministic parameters affecting the wheel of the MM will cause it to deviate from the goal and cause error even if the control system is perfect. Localisation is a big research topic in mobile robotic but application of localisation in MM is not common. This is probably caused by the assumption that if the localisation is applied to conventional control system (PID control) is suitable for control of a mobile platform than the system is assumed also suitable for a mobile platform attached with a manipulator. In the purposed research, combining a localisation technique using the KFs together with the AFC control to achieve better tracking performance of a MM is another contribution of the research.

7. As previously mentioned, the reported research works on mobile manipulator (MM) are relatively scarce due to its higher level of complexity and sophistication. The undertaken research serves to enrich the subject matter academically as it

focuses on the robust motion control and localisation of MM based on enhanced AFC-based strategy.

1.7. Organization of the thesis

This thesis is organized into eight chapters. Chapter 2 discusses about the literature review that is relevant to the proposed research. This chapter provides some insights about past and current research trend which in turn yields some general guidelines towards developing a suitable methodology for the research. A research gap is also explicitly identified to ensure that the proposed research is indeed relevant, up-to-date and aligned with the latest development in the research area.

Chapter 3 relates the main theoretical ideas and concept which was further conceptualised through a detailed extraction of the mathematical models of various essential components in the proposed system. These include the MM dynamics, various selected controllers to be implemented in the research, i.e., the proposed CPD-FAFC and CTC controllers and KF localisation method. All the derivations of the dynamic equations were done based on the *Euler-Lagrange* method.

Chapter 4 presents a simulation study on the proposed MM design. The simulation was performed based on the co-simulation technique where two simulation programming software were executed simultaneously by swapping and exchanging data in-between the two computing platforms. The two are MSC Adams and MATLAB/Simulink software packages; the former is a multibody dynamic software which simulates the dynamic aspect of the MM while the latter simulates the controller aspect in the simulation. The CPD, CPD-FAFC and the CTC were simulated considering three sets of different scenario settings. The relevant results related to the position time response, position tracking error and joint driving torque were rigorously analysed and discussed.

Chapter 5 provides a detailed explanation on the development and construction of the MM experimental rig (MMer) using full mechatronic system design approach. The development of MMer includes several aspects of the design mainly related to mechanical, electrical/electronics and computing elements, i.e., pertaining to the software and hardware of the MMer core system. The use of a rapid prototyping software to hardware application which enables a fast development on the proposed controller hardware was also highlighted and discussed.

Chapter 6 discusses the MMer actual experimental test procedure, data and results obtained from the experiments based on the CPD-FAFC control scheme. In the experimentation, the proposed CPD-FAFC controller was tested through similar test environments, taking into account three scenarios as previously described in Chapter 4. Chapter 6 also describes the implementation of a localisation technique based on the adaptive *Kalman* filter (KF) algorithm. It also explains the procedure for performing the localisation test on the developed MMer system. The experiment was performed by integrating a well-known robot operating software (ROS) into the MMer system. Data gathered from a laser range finder sensor was combined with the position data obtained from the CPD-FAFC controller into the ROS vector of simultaneous localisation and mapping (SLAM) node which estimates the position of the MMer based on the KF algorithm.

Chapter 7 presents a comparative study between the simulation and the experimental results. The results obtained from both simulation and experimental works are compared, side by side to verify the effectiveness of the proposed CPD-FAFC controller in performing specific trajectory tracking and pick-and-place tasks considering various loading and operating conditions.

Finally, Chapter 8 presents an overall conclusion of the research. A brief discussion on some recommendations for future research works and possible extension that can be performed were explained and elaborated. Some of the relevant specifications and datasheet related to the research are also included in the appendices for further clarification and references.

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