

DUAL LOOP FEEDBACK ERROR LEARNING  
CONTROLLER WITH NARX FOR MECANUM  
WHEELS MOBILE ROBOT

BY

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degree of Master of Science (Mechatronics Engineering)

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## ABSTRACT

A Motorized Adjustable Vertical Platform (MAVeP) is needed by National Space Agency of Malaysia (also known as ANGKASA) at their Satellite Assembly, Integration and Test Centre (AITC), Banting, Selangor. AITC is a clean room used for satellite assessment before it is qualified to be launched into the orbit. Designed as the facility that will provide the similar testing condition as the spacecraft and its payload, AITC is a controlled environment area which having a clean room of class ISO 8. Since it is a confined space for testing, a satellite is carefully transported within the test area as it is very sensitive. Therefore, mecanum wheels are the most suitable wheel for MAVEP mobility mechanism. However, the mecanum wheels come with their common issue like slippage that leads to low accuracy and repeatability of the movement. Each mecanum wheel motor which act as an actuator needs to be properly controlled to avoid overshoot that cause jerk and oscillation that leads to vibration. MAVEP mobility need to transport the satellite with minimum vibration and jerk also achieve positional accuracy and repeatability. This research focuses on the development of dual loop feedback error learning controller with nonlinear autoregressive exogenous neural network (NARX-NN) for MAVEP mobility mechanism. A MAVEP mobility mechanism prototype has been developed and the kinematic model has been derived. Simulations and experiments have been conducted in the linear and diagonal axis. The vibration and jerk issues have been overcome by dual closed loop positioning control system while the slippage problem have been eliminated and improved by using feedback error learning (FEL) control technique which is a dynamic inverse control method that combines simultaneous action of proportional (P) as a feedback controller and NARX as the feedforward controller. NARX learns the inverse dynamic of the MAVEP mobility mechanism in the feedforward controller to improve the response of non-adaptive feedback controller performed by P controller. The experimental result shows that the steady state tracking error is 5%, the maximum overshoot is 0%, the settling time are between 2.9 second to 3.0 second, the RMSE are between 1.83 cm to 2.01 cm and the repeatability are between 98.3% to 100% for all linear movement. Both simulation and experimental results have proven that the proposed controller is successful in controlling the MAVEP mobility mechanism to achieve the desired position accurately and eliminate slippage and jerking.

## خلاصة البحث

هناك حاجة إلى منصة عمودية بمحركات قابلة للتعديل (MAVeP) من قبل وكالة الفضاء الوطنية الماليزية (المعروفة أيضاً باسم ANGKASA) في مركز تجميع ودمج واختبار الأقمار الصناعية (AITC), بانتانج, سلانجور. (AITC) هي غرفة خالية تستخدم لتقييم القمر الصناعي قبل أن تكون مؤهلة للانطلاق في المدار. تم تصميمه كوسيلة لتوفير ظروف اختبار مماثلة للمركبة الفضائية وحمولتها، AITC هي منطقة بيئية خاضعة للرقابة بما غرفة خالية من فئة 8 ISO. نظراً لأنها منطقة محدودة للاختبار، يتم نقل القمر الصناعي بعناية داخل منطقة الاختبار لأنه حساس للغاية. لذلك، فإن عجلات الميكانيوم وهي العجلات التي تعمل على مبدأ تعدد الاتجاهات هي العجلة الأكثر ملاءمة لآلية الحركة في MAVeP. ومع ذلك، فإن عجلات الميكانيوم يرافقها مشاكل شائعة مثل الانزلاق الذي يؤدي إلى انخفاض في الدقة وتكرار في الحركة. يحتاج كل محرك عجلة في الميكانيوم والذي يعمل كمشغل إلى التحكم فيه بشكل صحيح لتجنب التجاوز الذي يسبب الارتجاج والتذبذب الذي يؤدي إلى الاهتزاز. يحتاج القمر الصناعي للنقل عن طريق MAVeP بأقل اهتزاز وارتجاج لتحقيق الدقة الموضوعية والتكرار. يركز هذا البحث على تطوير التحكم بمعرفه الخطأ في العقيب ذات الحلقة المزدوجة مع الشبكة العصبية الخارجية غير الخطية ذاتية الانحدار (NARX-NN) لآلية النقل MAVeP. تم تطوير نموذج أولي لآلية النقل MAVeP وتم اشتقاق النموذج الحركي. تم إجراء المحاكاة والتجارب في المحور الخطي والقطري. تم التغلب على مشكلات الاهتزاز والارتعاش من خلال نظام التحكم في تحديد المواقع ذو الحلقة المغلقة المزدوجة بينما تم التخلص من مشكلة الانزلاق وتحسينها باستخدام تقنية التحكم في تعلم الخطأ (FEL) وهي طريقة تحكم ديناميكية عكسية تجمع بين الإجراء المتزامن المناسب (P) كوحدة تحكم في التغذية الراجعة وNARX كوحدة تحكم في التغذية. تفهم NARX الديناميكية العكسية لآلية النقل MAVeP في وحدة التحكم في التغذية لتحسين استجابة وحدة التحكم في التغذية الراجعة غير التكرارية التي تقوم بها وحدة التحكم P. تظهر النتيجة التجريبية أن خطأ تتبع الحالة المستقرة هو 5٪، والحد الأقصى للتجاوز هو 0٪، ووقت الاستقرار بين 2.9 ثانية إلى 3.0 ثانية، و RMSE بين 1.83 سم إلى 2.01 سم والتكرار بين 98.3٪ إلى 100٪ لجميع الحركات الخطية. أثبتت كل من المحاكاة والنتائج التجريبية أن جهاز التحكم المقترح ناجح في التحكم في آلية النقل MAVeP لتحقيق الوضع المطلوب بدقة والقضاء على الانزلاق الاهتزاز.

## APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science (Mechatronics Engineering).

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## DECLARATION

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# TABLE OF CONTENTS

Abstract .....	ii
Abstract in Arabic .....	iii
Approval Page.....	iv
Declaration .....	v
Copyright .....	vi
Acknowledgement .....	vii
Table of Contents .....	viii
List Of Table .....	x
List Of Figure.....	xi
List Of Abbreviations .....	xiv
List of Symbols .....	xvi
<b>CHAPTER ONE : INTRODUCTION .....</b>	<b>1</b>
1.1 Background .....	1
1.2 Problem statement and its significance.....	4
1.3 Research objective .....	5
1.4 Research methodology.....	5
1.5 Scope of research .....	7
1.6 Contribution of the research.....	7
1.7 Organization of the thesis .....	8
<b>CHAPTER TWO : LITERATURE REVIEW .....</b>	<b>9</b>
2.1 Introduction.....	9
2.2 Mecanum wheel mobile robot (MWMR) .....	9
2.3 Control law.....	15
2.3.1 Vibration and jerk issues.....	21
2.3.2 Slippage issue on mobile robot.....	23
2.3.3 Feedback error learning (FEL) controller .....	25
2.4 Chapter summary .....	28
<b>CHAPTER THREE : RESEARCH METHODOLOGY .....</b>	<b>29</b>
3.1 Introduction.....	29
3.2 MAVeP mobility kinematics analysis .....	29
3.3 Mathematical model of DC motor .....	32
3.4 Control system design.....	33
3.5 Inner loop controller design.....	35
3.5.1 PID controller design .....	37
3.5.2 Ziegler-Nichols PID tuning .....	38
3.6 Outer loop controller design .....	39
3.6.1 NARX-NN controller dynamic modelling .....	41
3.6.2 FEL Controller .....	45
3.7 MAVeP mobility prototype development.....	46
3.8 Chapter summary .....	51



<b>CHAPTER FOUR : RESULTS AND DISCUSSIONS.....</b>	<b>52</b>
4.1    Introduction.....	52
4.2    Simulation setup.....	52
4.2.1  MAVeP mobility prototype kinematic block.....	52
4.2.2  DC motor simulation block.....	53
4.2.3  MAVeP mobility prototype simulation block .....	54
4.3    Simulation result .....	56
4.3.1  Inner loop feedback controller tuning.....	56
4.3.2  Outer loop feedback controller tuning.....	60
4.3.3  NARX batch dynamic modelling .....	63
4.3.4  NARX sequential dynamic modelling.....	72
4.4    Experimental setup.....	77
4.4.1  Calibration for DC motor synchronization .....	79
4.5    Experimental results.....	83
4.5.1  Inner loop feedback controller tuning.....	83
4.5.2  Outer loop feedback controller tuning.....	84
4.5.3  NARX batch dynamic modelling .....	88
4.5.4  NARX sequential dynamic modelling.....	90
4.6    Discussions .....	92
4.7    Chapter summary .....	96
<b>CHAPTER FIVE : CONCLUSIONS AND RECOMMENDATIONS .....</b>	<b>97</b>
5.1    Conclusions.....	97
5.2    Recommendations.....	98
<b>REFERENCES.....</b>	<b>99</b>
<b>PUBLICATION .....</b>	<b>104</b>
<b>APPENDIX I .....</b>	<b>105</b>
<b>APPENDIX II.....</b>	<b>106</b>
<b>APPENDIX III .....</b>	<b>107</b>
<b>APPENDIX IV .....</b>	<b>108</b>
<b>APPENDIX V .....</b>	<b>109</b>
<b>APPENDIX VI .....</b>	<b>110</b>
<b>APPENDIX VII.....</b>	<b>111</b>

## LIST OF TABLES

Table 2.1 Comparison of omnidirectional driving implementations.	12
Table 2.2 Combination of wheels rotation in producing MWMR directions.	14
Table 2.3 Several researches conducted in improving MWMR.	17
Table 2.4 Previous study on controlling DC motor with PID controller	22
Table 2.5 Previous study conducted to eliminate slippage issue.	25
Table 2.6 Previous research on FEL.	27
Table 3.1 Ziegler-Nichols method one tuning formula.	39
Table 3.2 MAVeP mobility prototype components.	48
Table 4.1 MAVeP mobility prototype parameter.	53
Table 4.2 DC motor parameters.	54
Table 4.3 Transient response data analyse.	57
Table 4.4 Ziegler-Nichols tuning.	57
Table 4.5 Training performance of four networks movement.	64
Table 4.6 Maximum overshoot (%)	92
Table 4.7 Settling time (second)	93
Table 4.8 Trajectory accuracy (%)	94
Table 4.9 Root mean square error (cm)	94
Table 4.10 Repeatability (%)	95

## LIST OF FIGURES

Figure 1.1 MGSE trolley with satellite loaded.	2
Figure 1.2 MAVeP design concept (Woo et al., 2015).	3
Figure 1.3 MAVeP CAD drawing (Mutalib et al, 2019).	4
Figure 1.4 Flowchart of research methodology.	6
Figure 2.1 Implementation of omnidirectional drives (Park et al, 2010).	10
Figure 2.2 Different types of omni wheels (Team, 2018).	11
Figure 2.3 Mecanum wheel (Group, 2006).	12
Figure 2.4 DOF in a mecanum wheel (Lieping et al, 2017).	13
Figure 2.5 Illustrated of wheels rotation combination in producing MWMR directions (Zhang et al, 2019)	14
Figure 2.6 Illustration of S curve response (Instrument, 2012).	21
Figure 3.1 Schematic of MAVeP mobility prototype model.	29
Figure 3.2 Electric circuit of armature and rotor free-body diagram	32
Figure 3.3 Overview of MAVeP mobility prototype control system.	34
Figure 3.4 Linear movement direction of MAVeP mobility prototype.	35
Figure 3.5 Inner loop 1	36
Figure 3.6 Various DC motor tuning response.	37
Figure 3.7 Ziegler-Nichols 1 <sup>st</sup> method transient response manipulated (Jenkins, 2005)	38
Figure 3.8 Dual loop control system.	40
Figure 3.9 Location of input and output data set collected.	42
Figure 3.10 NARX batch training and sequential training.	43
Figure 3.11 Standard parallel architecture model	44
Figure 3.12 Details of NARX-NN model.	45
Figure 3.13 MAVeP mobility prototype control block diagram.	46

Figure 3.14 MAVeP mobility prototype control system architecture.	47
Figure 3.15 Drawing of MAVeP mobility prototype base structure.	49
Figure 3.16 Development of MAVeP mobility prototype.	50
Figure 3.17 Complete assembly of MAVeP mobility prototype.	51
Figure 4.1 MAVeP mobility prototype forward kinematic block diagram.	53
Figure 4.2 DC motor simulation block diagram.	53
Figure 4.3 DC motor position control.	54
Figure 4.4 Four DC motors to be connected to MAVeP prototype kinematic block.	55
Figure 4.5 MAVeP mobility prototype simulation model.	55
Figure 4.6 DC motor close loop transient response.	56
Figure 4.7 DC motor Ziegler-Nichols tuning response.	58
Figure 4.8 DC motor close loop system with P controller.	59
Figure 4.9 DC motor P parameter after MATLAB fine tuning.	60
Figure 4.10 Motor position response under P controller with Ziegler-Nichols and MATLAB automatic tuning.	60
Figure 4.11 P controller parameter of X axis movement after fine tuning.	61
Figure 4.12 Simulation results of MAVeP mobility prototype under P controller.	62
Figure 4.13 X axis data collection.	63
Figure 4.14 Validation performance of NARX model for X axis movement.	65
Figure 4.15 Regression value of NARX model for X axis movement.	65
Figure 4.16 Error autocorrelation function of NARX model for X axis movement.	66
Figure 4.17 Input-error cross-correlation function of NARX model for X axis movement.	67
Figure 4.18 Time series response of NARX model for X axis movement.	67
Figure 4.19 Block diagram for comparing the output signal of P controller to NARX model.	68

Figure 4.20 Comparison of NARX batch training output and P controller output.	69
Figure 4.21 Execution of NARX model to MAVeP mobility prototype system.	70
Figure 4.22 Simulation results of MAVeP mobility system under P controller and P controller with NARX batch training.	71
Figure 4.23 MAVeP mobility prototype system for sequential training.	72
Figure 4.24 SIMULINK listener setup	73
Figure 4.25 Comparison of NARX sequential training output and P controller output.	75
Figure 4.26 Simulation results of MAVeP mobility system under P controller, P controller with NARX batch training, P controller with NARX sequential training.	77
Figure 4.27 Experiment conducted in a controlled environment.	79
Figure 4.28 Four DC motors' responses before calibration.	79
Figure 4.29 Calibration of DC motors block diagram	81
Figure 4.30 Response of DC motor after calibration	82
Figure 4.31 MAVeP mobility prototype experiment model.	83
Figure 4.32 DC motor after tuning response.	84
Figure 4.33 DC motor P parameter after MATLAB fine tuning.	84
Figure 4.34 P controller parameter for X and Y movements.	85
Figure 4.35 P controller parameter for diagonal <b>a</b> and <b>b</b> movements.	85
Figure 4.36 Experimental results of MAVeP mobility prototype under P controller.	87
Figure 4.37 Experimental results of MAVeP mobility prototype under P controller and P with NARX batch training controller.	89
Figure 4.38 Experimental results of MAVeP mobility prototype under P controller, P with NARX batch training controller and P with NARX sequential training controller.	91

## LIST OF ABBREVIATIONS

AGV	Autonomous Guide Vehicle
AITC	Satellite Assembly, Integration and Test Centre
ANGKASA	National Space Agency of Malaysia
CAD	Computer-Added Design
CMM	Coordinate Measuring Machine
DC	Direct Current
DOF	Degree of Freedom
FEL	Feedback Error Learning
FF	Feed Forward
FLC	Fuzzy Logic Controller
IMU	Inertia Measurement Unit
ISO	International Standard Organisation
JOA	Jaya Optimization Algorithm
LADRC	Linear Active Disturbance Rejection Control
LM	Levenberg Marquardt
LQR	Linear Quadratic Regulator
MAVeP	Motorized Adjustable Vertical Platform
MGSE	Mechanical Ground Support Equipment
MPC	Model Predictive Control
MSE	Mean Squared Error
MWMMR	Mecanum Wheel Mobile Robot
NARX	Nonlinear Autoregressive Exogenous

NDT	Non-Destructive Test
NN	Neural Network
P	Proportional
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PSO	Particle Swarm Optimization
PWM	Pulse Width Modulator
R	Regression
RMSE	Root Mean Square
SMC	Sliding Mode Control
TSK	Takagi-Sugeno Kang
TVC	Thermal Vacuum Chamber

## LIST OF SYMBOLS

$V_{iw}$ ( $i = 1,2,3,4$ )	Velocity vector corresponding to wheels revolutions
$R_w$	Radius of wheel
$\omega_{iw}$ ( $i = 1,2,3,4$ )	Angular velocity of the wheel
$V_{ir}$ ( $i = 1,2,3,4$ )	Tangential velocity vector of the free roller
$L$	Half-length of the platform
$W$	Half width of the platform
$V_{ix}$ ( $i = 1,2,3,4$ )	Linear movement of the MAVeP mobility prototype respect to X axis
$V_{iy}$ ( $i = 1,2,3,4$ )	Linear movement of the MAVeP mobility prototype respect to Y axis
$U_{NN}$	FF controller output
$U_p$	Feedback controller output signal
$U$	FEL controller output
$w$	Wheel
$\theta_1, \theta_2, \theta_3$ and $\theta_4$	Angle of wheel 1, wheel 2, wheel 3, wheel 4
<b>a</b>	Diagonal axis <b>a</b>
<b>b</b>	Diagonal axis <b>b</b>
$X_d$	Robot desire trajectory
$X_e$	Error between robot desire trajectory
$X_p$	Distance produce by mobile robot
$K_p$	Proportional gain tuning parameter
$K_i$	Integral gain parameter and



$K_d$	Derivative gain tuning parameter.
$e(t)$	Signal error between system trajectory and system output
$t$	Time or instantaneous time (the present)
$e^\tau$	Variable of integration.
$f$	Approximation function of NARX-NN
$p$	Input to the network
$W$	Weight of the network.
$b$	Bias of the network
$S$	Number of neurons in network
$1W, 2W, 3W, 4W$	Wheel 1, wheel 2, wheel 3 and wheel 4
$J$	Rotor moment of inertia
$b$	Damping coefficient
$K_e$	Electromotive force constant
$K_t$	Motor torque constant

# CHAPTER ONE

## INTRODUCTION

### 1.1 BACKGROUND

The development and launched of the first Malaysian communication satellites namely, MEASAT-1 and MEASAT-2 in year 1996 have made the nation proud. The communication development does not only stop there. Malaysia had launched their first remote sensing satellite called TiungSAT-1 in year 2000, about four years after the first satellite was launched. The growth of space technology continues with the development of the second national remote sensing satellite named RazakSAT in the beginning of 2001. Since there is rapid development of space technology in both broadcasting and telecommunication industries, National Space Agency of Malaysia (ANGKASA) has taken an additional step by setting up the Satellite Assembly, Integration and Test Centre (AITC), which is required for assembly and integration works, as well as the launching and environmental testing of a medium-sized satellite (Leng et al., 2009).

As soon as a satellite is launched, it faces huge environmental influence both while on earth and in space. The vibro-acoustic and electromagnetic effect during launch and thermal effect in space may harm the satellite before it even begins its lifetime (Perl E. et al., 2005). Therefore, a satellite must be thoroughly tested before it can be launched into the orbit. There are several tests that need to be performed such as vibration, acoustic, electromagnetic and thermal vacuum tests. These tests are important to ensure that a satellite achieves design, performance and quality requirements before the satellite faces the worst conditions in the orbit (Lee et al., 2002).

During the test procedure, a satellite needs to be transported to several test areas. A mobile trolley is required to ensure the satellite mobility is handled in a proper manner. It is equipped with a platform that serves as a workstation for assimilation work in setting up the satellite for the required tests. Figure 1.1 shows a standard mechanical ground support equipment (MGSE) trolley or called multi-purpose satellite trolleys offered at most of the test centers that is not suitable to AITC in terms of mobility and height. These mobile platforms come with manual mobility system only. Operator is required to move the 1000 kg satellite plus another 1000 kg of the platform itself. The trolley can only rotate the satellite from horizontal to vertical position instead of lifting it. Usually, an adjustable high mechanism with no mobility feature is embedded on the floor to lift the satellite up or down. The existing condition in the test facility requires a special platform equipped with mobility system and adjustable height. This platform also ensures a safe satellite handling (Woo et al., 2015).

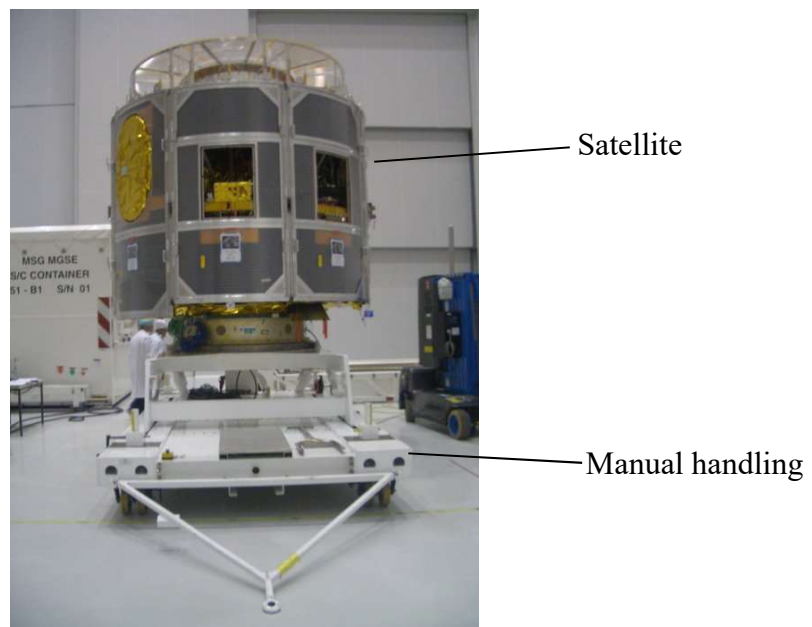


Figure 1.1 MGSE trolley with satellite loaded.

To cater the requirement, a Motorized Adjustable Vertical Platform (MAVeP) is designed and developed to ensure an easier and smooth operation, as well reduce the handling risks that may jeopardize the satellite. This platform is equipped with an automatic mobility control and adjustable height mechanism to elevate the satellite according to ANGKASA requirement.

MAVeP design concept is shown in Figure 1.2 while Figure 1.3 shows the computer-added design (CAD) drawing of MAVEP model. MAVEP consists of five main mechanism; mobility, lifting, extended beam, locking and base plate loading. The mobility is dealing with four mecanum wheels while lifting is performed by a scissor lifter concept with ball screw mechanism to meet the clean room requirement based on the International Standard Organisation (ISO) 14644-1 and ISO Class 100000. The cleanroom cleanliness condition level shall be at least 3,520,000 particles/m<sup>3</sup> and greater than or equal to 0.5  $\mu\text{m}$  size of particles (Zwiener, 1986). The extended beam is manually moved and locked with a motorized locking system. Finally, the base plate mover is motorized to transfer the satellite into the thermal vacuum chamber (TVC).

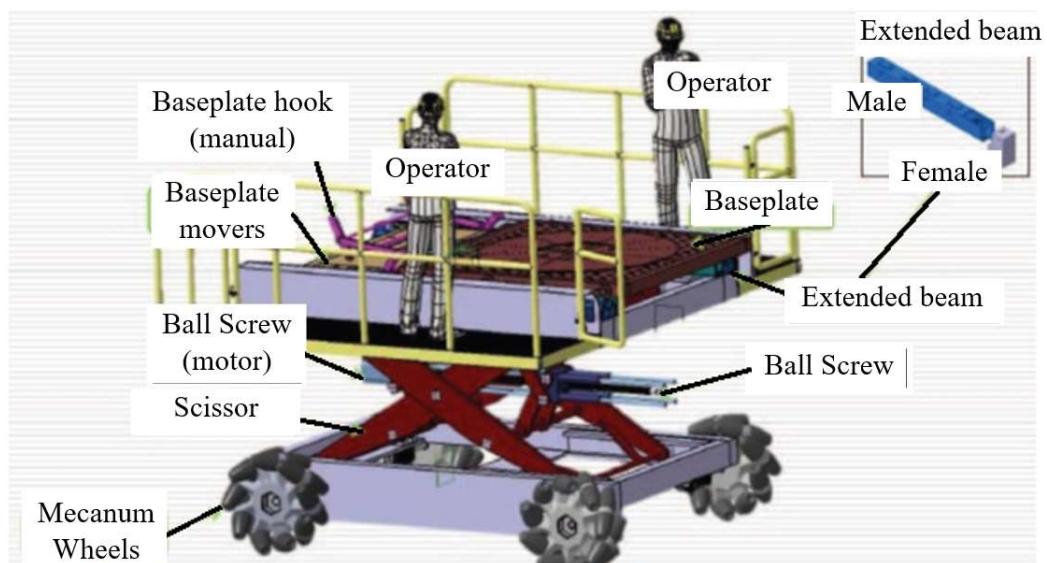


Figure 1.2 MAVEP design concept (Woo et al., 2015).

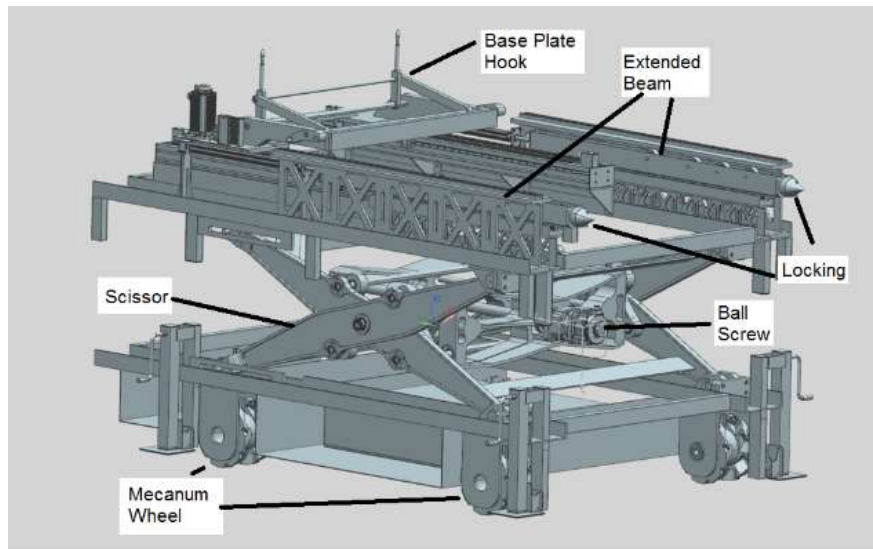


Figure 1.3 MAVeP CAD drawing (Mutalib et al., 2019).

## 1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

MAVeP is designed to be used in clean room area. It is a huge and heavy mobile trolley, equipped with mecanum wheels to allow mobility in confined areas at AITC to transport a satellite. Therefore, the motor which act as the mobility actuator must be large to deliver a high torque value, but a motor that has high torque produces overshoots and oscillation during its rotation without a proper control. This phenomenon leads to jerk and vibration issues that could damage the satellite's parts or influence the satellite test result. Since the main function of MAVeP is to transport and lift a satellite into the TVC, MAVeP must be parked very close, in front of the TVC before the lifting process. The fact is that MAVeP is very difficult to be parked accurately with a tolerance below 2 cm (Woo et al., 2015) due to mecanum wheel slippage issue. The slippage comes from the mecanum wheel design that uses free rollers or passive rollers. The rollers are able to rotate in accordance to the wheel rotation and leads to low accuracy and repeatability of MAVeP movement. An accurate position control that enable the parking process needs to be done quickly and precisely without affecting the highly sensitive satellite.

### 1.3 RESEARCH OBJECTIVES

The objectives of this research are:

- 1- To develop a kinematic model of MAVeP mobility mechanism for controller design and simulation.
- 2- To design dual loop feedback error learning controller with NARX sequential training to overcome jerk, vibration and slippage issues for MAVeP mobility prototype.
- 3- To validate the performance of proposed controller by simulations and hardware experimental tests.

### 1.4 RESEARCH METHODOLOGY

The summary of the research methodology is summarized in Figure 1.4. The methodology consists of:

- i. **Literature Review.** Literature reviews is focuses on the technical and specific papers related to the research study.
- ii. **MAVeP prototype kinematic equation development.** The kinematic model of the MAVeP mobility is developed for controller design and simulation purposes.
- iii. **Dual loop FEL with NARX controller design.** The design for the controller is iterated and analysed through simulations that are run in computer simulation applications.
- iv. **MAVeP prototype development.** Experiments are conducted to a developed prototype that is similar to MAVeP mobility.
- v. **Simulation and Experimental Tests.** Complete controller with optimized parameters is applied to the real system and tested.

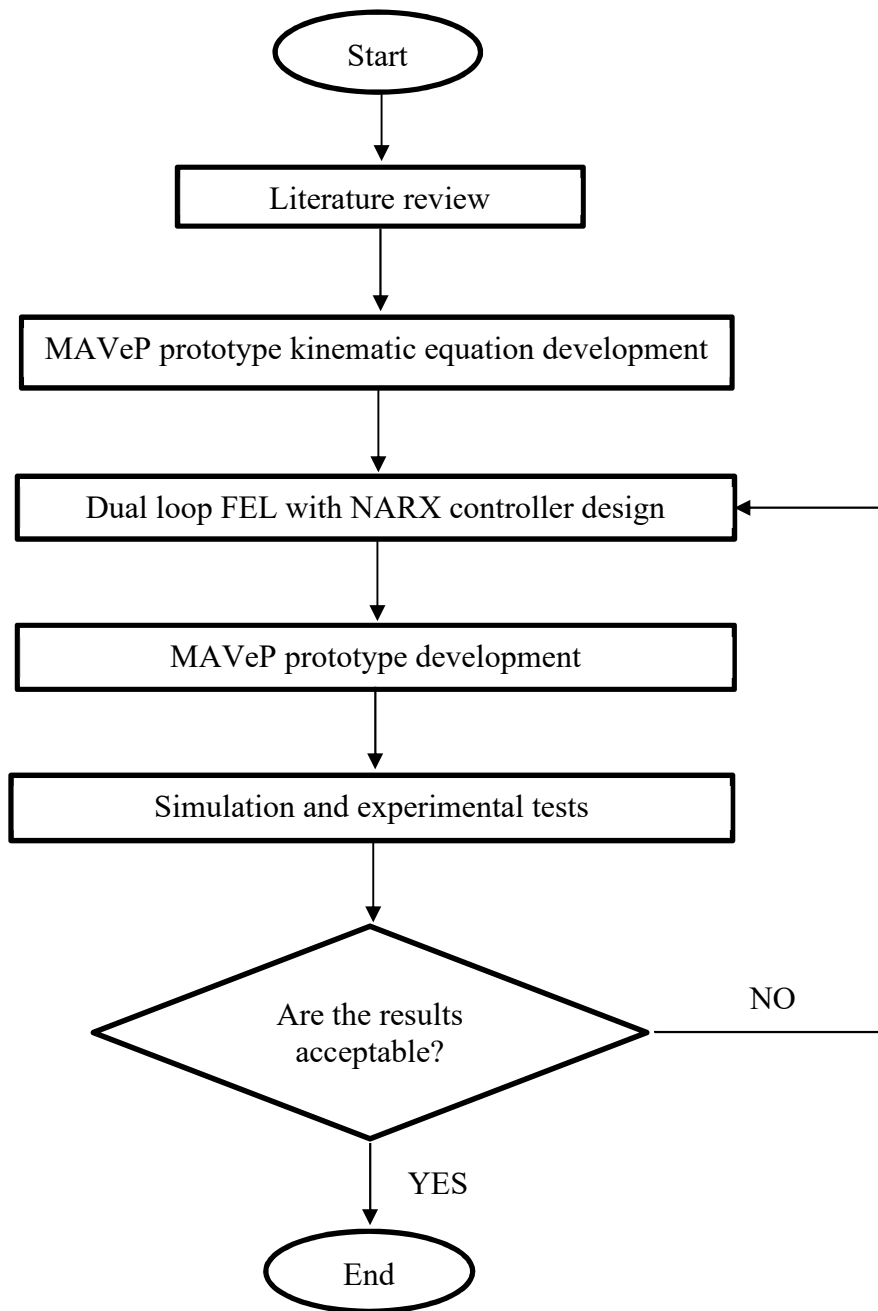


Figure 1.4 Flowchart of research methodology.

## **1.5 SCOPE OF RESEARCH**

The following is the scope of the research:

1. Only four mecanum wheels are considered in the prototype development as to represent the actual MAVeP mobility.
2. Experimental tests are performed on the developed prototype. Experimental on real MAVeP is outside this research scope.
3. Experimental test is running on flat surface to ensure all four wheels are contacted to the surface. Other type of surfaces is beyond the scope of this study.
4. No weight change during movement of the prototype. Variation of MAVeP's weight is beyond the scope of this study.
5. Experiment conducted on linear movement; X, Y and diagonal direction. Nonlinear movements are outside the scope of this study.

## **1.6 CONTRIBUTION OF THE RESEARCH**

The contributions or originalities of the research is a new controller method based on dual loop feedback error learning controller with NARX for MAVeP mobility mechanism to compensate jerk, vibration and eliminate the slippage issues. The controller has been tested in the simulation and experimental tests on the prototype of MAVeP mobility.