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

BY

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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 overcame 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 أيضًا 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 كوسيله لتوفير ظروف اختبار مماثلة للمركبة الفضائية وحمولتها، AITC هي منطقة بيئية خاضعة للرقابة بها غرفة خالية من فئة ISO 8. نظرًا لأنها منطقه 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 شائعه 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 الموضعية 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 التنقل MAVeP. تم تطوير نموذج أولي لآلية التنقل 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 المتناسب (P) كوحدة تحكم في التغذية الراجعة وNARX كوحدة تحكم في التغذية. تفهم NARX الديناميكية العكسية لآلية التنقل MAVeP في وحدة التحكم في التغذية لتحسين استجابة وحدة التحكم في التغذية الراجعة غير التكيفية 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 التنقل MAVeP لتحقيق الموضع 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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Sany Izan Ihsan
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DECLARATION

I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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‘’In the name of Allah, the most Gracious, the most Compassionate’’

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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
MWMR	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
θ_1, θ_2, θ_3 and θ_4	Angle of wheel 1, wheel 2, wheel 3, wheel 4
a	Diagonal axis **a**
b	Diagonal axis **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^{τ}	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
Ke	Electromotive force constant
Kt	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).

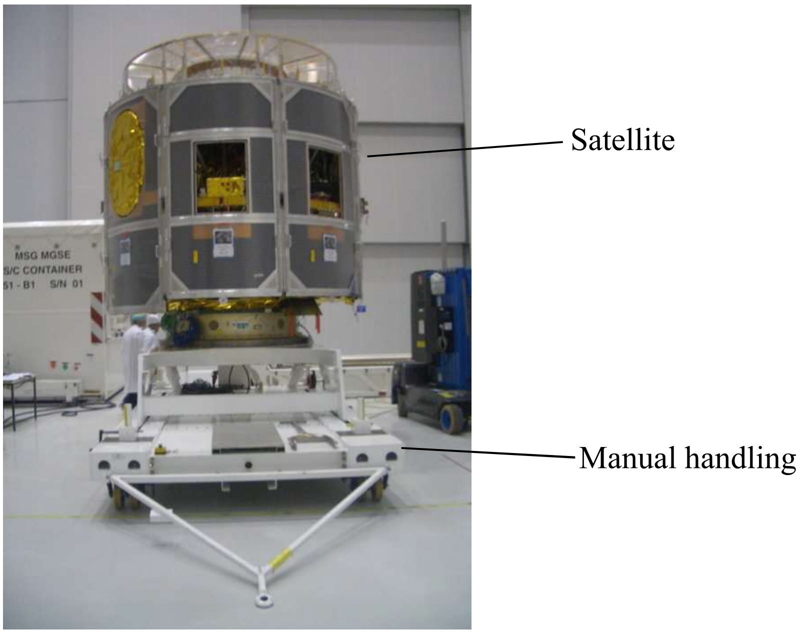

Figure 1.1 MGSE trolley with satellite loaded.

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/m3 and greater than or equal to 0.5 µm 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).

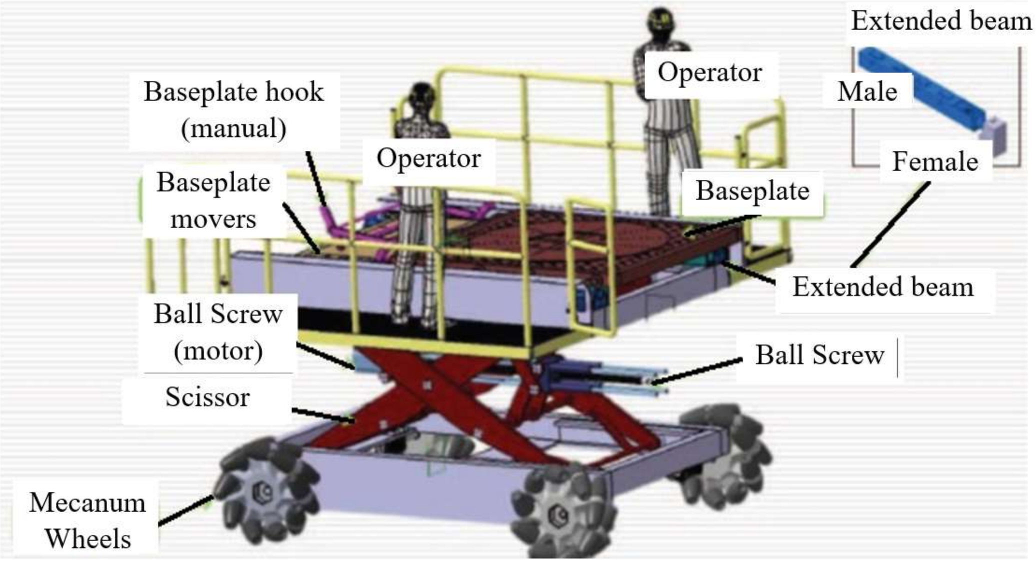

Figure 1.2 MAVeP design concept (Woo et al., 2015).

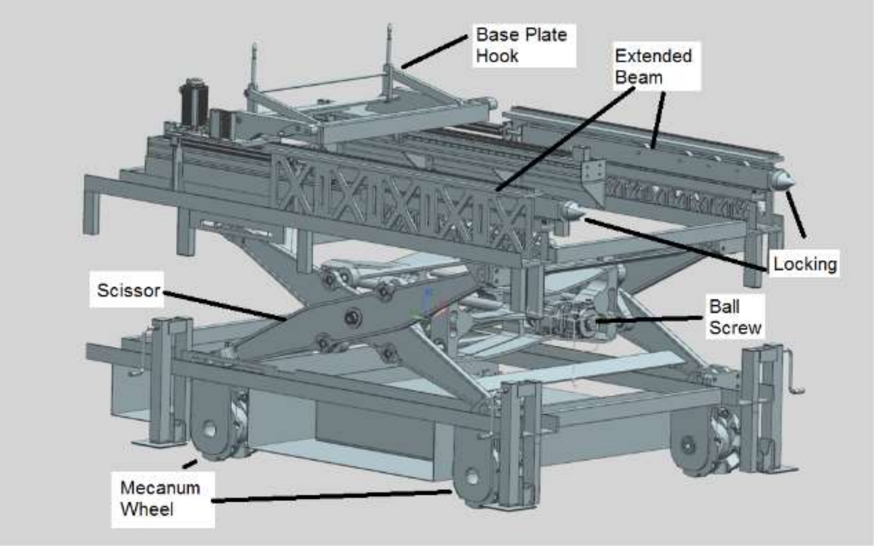

Figure 1.3 MAVeP CAD drawing (Mutalib et al., 2019).

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.

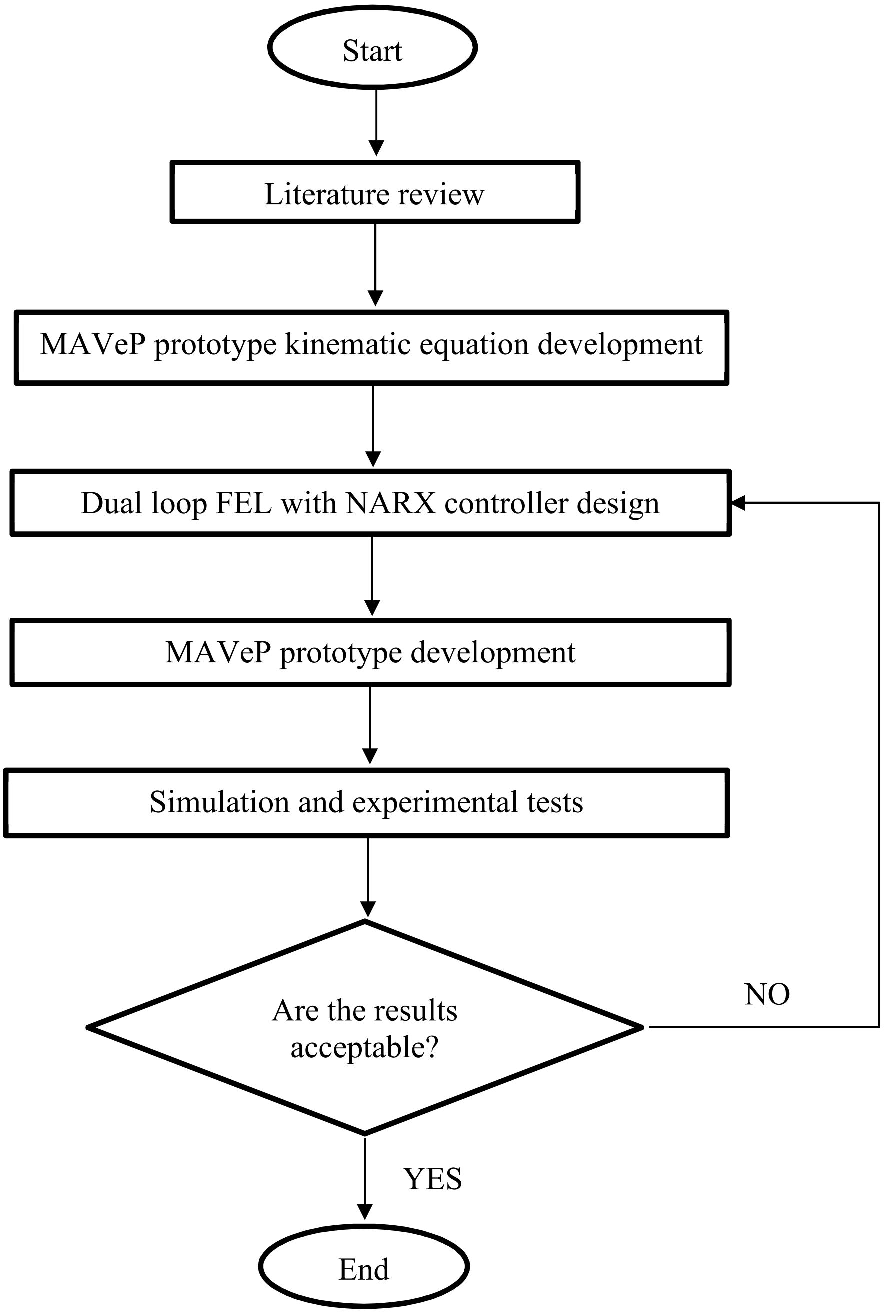

Figure 1.4 Flowchart of research methodology.

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.