International Journal of Engineering & Technology, 7 (4.25) (2018) 43-52

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Development of Motion Manipulator System for a Generic Aircraft Flight Dynamic Simulator

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Abstract

The purpose of this development program is to apply some prior studies about hexapod manipulator for designing aircraft simulator motion platform in terms of acceleration cue. Acceleration would represent human perception to describe a motion. By giving acceleration cues in a simulator, the operator would obtain similar sensation corresponding to real phenomenon/condition. Iteration process is used to collect relations between hexapod manipulator parameters, platform size and actuator position, and manipulator performances describing as manipulator displacement and acceleration range. Its kinematics and dynamics are modelled by using Newton-Euler approach and validated by using SimScape feature provided in MATLAB/Simulink. Hereafter, actuation control scheme would be implemented in order to convey manipulator from a conceptual world into real world based on its dynamics. As part of this development, constructing hexapod manipulator numerical model becomes the main objective of this current research.

Keywords: *Acceleration Cue; Aircraft Simulator; Inverse Dynamic; Hexapod Manipulator; Newton-Euler Approach; SimScape Feature.*

1. Introduction

In this era, aircraft simulator system could be built using some computers work in parallel. Development of aircraft simulator system becomes faster since microelectronics revolution was begun. Aircraft simulator system consists of many components that has one main goal: replicating how an aircraft flies based on its characteristics, database, and environment condition without flying the aircraft. The organization of aircraft simulator based on Baarspul (1990) could be presented on Fig.1.

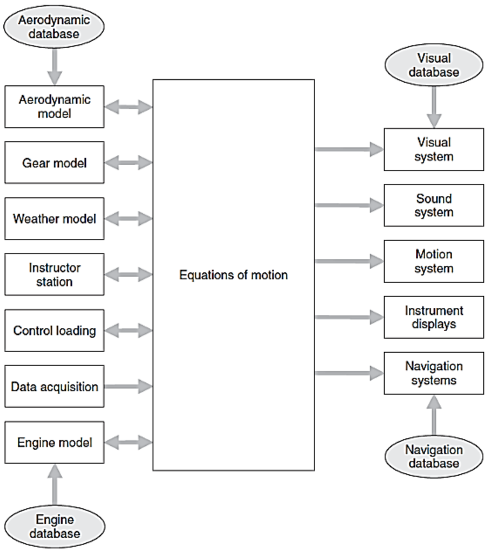

Fig. 1: Organization of aircraft simulator [1].

Aerodynamic, gear, and engine model are intended to describe aircraft characteristics in simulator. Weather model is used to represent where and when the aircraft flies based on meteorological aspect. So that condition would affect how aircraft would fly. Load which is acted on control surfaces would be denoted as feedback for aircraft control scheme in order to give operator true feeling of controlling the aircraft. Beside operator, there is someone that could give input to the simulator, instructor. Instructor could manipulate aircraft and environmental condition as training purpose for the operator or to learn the effect of one condition to flight characteristics. Flight characteristics could be analyzed if there is, one main part, equations of motion which describe influences of any conditions to aircraft motion.

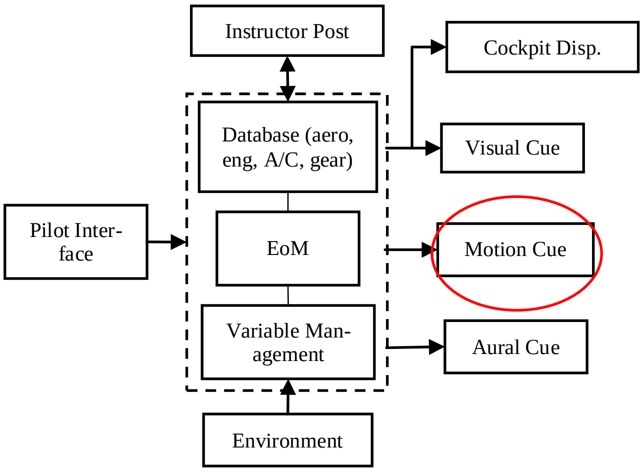

Fig. 2: ITB Flight Physics Research Group development plan of generic flight simulator (red circle means paper research scope).

In order to give flight sensation to operator, several cue systems are developed. Motion cue could be obtained from many sources, visual, aural, and motion itself. Instrument display and navigation system would create cockpit environment for the operator. So, simulator role for making operator familiar with cockpit could be achieved.

Development of aircraft simulator system in ITB Flight Physics Research Group has reached several parts of flight simulator complete scheme as shown in Fig.1 and 2. Aerodynamic model, instructor station, engine model, and equations of motion have been built and could be applied to provide generic aircraft simulator needs. X-Plane still supports other part in aircraft simulator scheme, such as environment model, cockpit display, and visual and aural cue. As final objective, ITB Flight Physics Research Group would build integrated generic aircraft simulator. To continue that development, hexapod manipulator as simulator motion platform would be discussed in this paper. It would provide acceleration to simulator system as motion cue for the operator. Human perception about motion becomes foundation to control platform acceleration every time.

Fig. 3: Current condition of one of ITB Flight Physics Research Group flight simulator.

As a part of aircraft simulator system, hexapod manipulator is widely applied to provide motion cue of many types of aircraft. Hexapod manipulator is chosen as simulator motion platform due to its high stiffness, less required installation space, and performances (accuracy, kinematic, and dynamic characteristics). However, this type of manipulator also has drawbacks in terms of complexity, both in dynamic modelling and control scheme, if comparing with serial structure/open kinematics chain manipulator.

Hexapod manipulator, which could move in six degrees of freedom, consists of a fix plate (base), a moving plate (platform), and six linear actuators or combination of rotary actuators and linkages in every actuator. Lower part of actuator and base are connected by using universal joint (two rotational degrees of freedom) while the upper part and platform are connected by spherical joint (three rotational degrees of freedom). In concept, hexapod manipulator could be formed by attaching three pairs of actuator in three points of base and platform. Hence, manipulator kinematic could be obtained.

Newton-Euler approach is used to model manipulator dynamic characteristics. Newton-Euler approach considers every forces and moments acting in system to determine its dynamic response. There are several assumptions applied in this approach: links are rigid (no deflection nor distortion), Coulomb friction is negligible, all forces could be well-estimated, and inertia of universal and spherical joint could be neglected. These assumptions are made to simplify manipulator dynamic model complexity.

Afterwards, manipulator kinematics and dynamics model are implemented to earn the design and find the relation between every design parameter. In this study, plate dimension, attachment position, manipulator payload, and platform kinematic and dynamic performance are chosen as the design parameters. Optimum manipulator model could be developed by analyzing the relation between design parameters. Moreover, after manipulator model is developed, control scheme could be developed. PID method, currently, is used as control scheme to obtain desired trajectory.

Development of hexapod manipulator system for generic aircraft simulator is aimed to anticipate possibility of modification or other development of hexapod manipulator with different structure or configuration. Before doing research of human-sized manipulator, miniature manipulator model is developed to validate the objective of this study. This model is conducted by using numerical model of hexapod manipulator. This study is intended to comprehend hexapod manipulator kinematic and dynamic characteristics in terms of equation of motion.

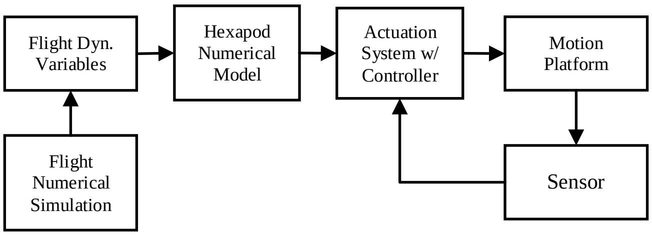

Fig. 4: Hexapod manipulator system scheme.

The next section discusses manipulator kinematic and dynamic model by using Newton-Euler approach. Section 3 describes manipulator design iteration process. Section 4 represents current hexapod manipulator development process. The last section describes further development of hexapod manipulator.

2. Hexapod Manipulator Kinematic and Dynamic Model

For modelling hexapod manipulator, its configuration, i.e. actuator attachment position, plate size, actuator configuration, and joint characteristics, has to be known. Hence, its equation of motion could be developed properly.

2.1. Actuator Attachment Position

As mentioned earlier, as a concept [2], hexapod manipulator just consists of two plates and six actuator systems with three points of attachment on each plate. Therefore, its attachment position could be illustrated as shown in Fig.5 and 6. So, actuator lower and upper part attachment position on base and platform, respectively, could be formulated as:

$$\text{angle\_b}_i = \begin{cases} -120^\circ + (i-1)60^\circ + \dfrac{\mu_b}{2}, & i = 1, 3, 5 \\ (i-2)60^\circ - \dfrac{\mu_b}{2}, & i = 2, 4, 6 \end{cases} \tag{1}$$

$$\overrightarrow{b_i} = \begin{bmatrix} r_b \cos(\text{angle\_b}_i)\ \hat{i} \\ r_b \sin(\text{angle\_b}_i)\ \hat{j} \\ 0\ \hat{k} \end{bmatrix} \tag{2}$$

$$\text{angle\_p}_i = \begin{cases} -60^\circ + (i-1)60^\circ - \dfrac{\mu_p}{2}, & i = 1, 3, 5 \\ -60^\circ + (i-2)60^\circ + \dfrac{\mu_p}{2}, & i = 2, 4, 6 \end{cases} \tag{3}$$

$$\vec{p}_i=\begin{bmatrix} r_p\cos(\text{angle\_p}_i)\ \hat{i} \\ r_p\sin(\text{angle\_p}_i)\ \hat{j} \\ 0\ \hat{k} \end{bmatrix} \tag{4}$$

Definition 2.1:

$[\text{angle\_b}_i, \text{angle\_p}_i]$	Angular position of actuator attachment on base and platform, respectively.
$[\mu_b, \mu_p]$	Pair of actuator attachment spacing on base and platform, respectively.
$[r_b, r_p]$	Base and platform radius, respectively, correspond to actuator attachment position.
$[\vec{b}_i, \vec{p}_i]$	Actuator lower and upper part attachment position on base and platform framework, respectively.

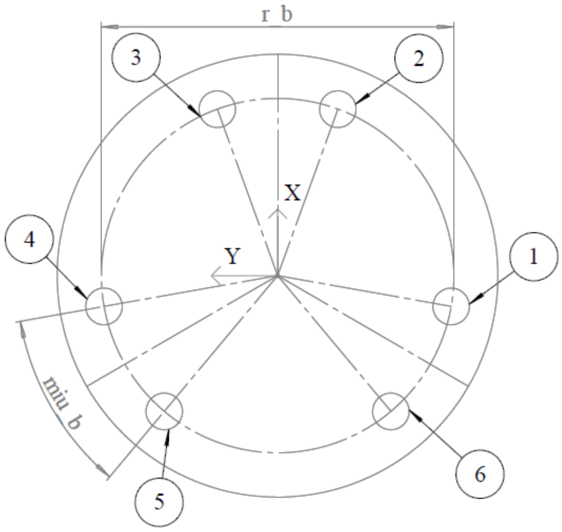

Fig. 5: Illustration of actuator lower part attachment position on base with r_b = base radius and miu_b = pair of actuator lower part attachment spacing.

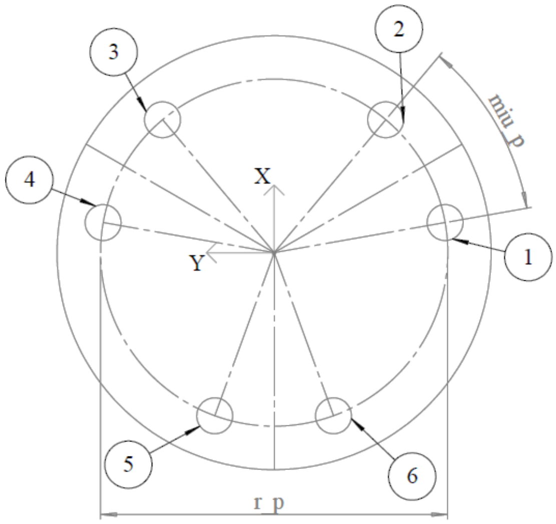

Fig. 6: Illustration of actuator upper part attachment position on platform with r_p = platform radius and miu_p = pair of actuator upper part attachment spacing.

2.2. Hexapod Manipulator Kinematic and Dynamic Model

Equation of motion is mathematic model representing how dynamic of system behave in terms of motion or its derivatives as a function of time. By using inverse dynamic process, calculation of platform kinematic should be provided as data before subsequent calculation of actuator kinematic and dynamic could be done. Equation of motion of hexapod manipulator, which is used in this study, is provided by Dasgupta [3].

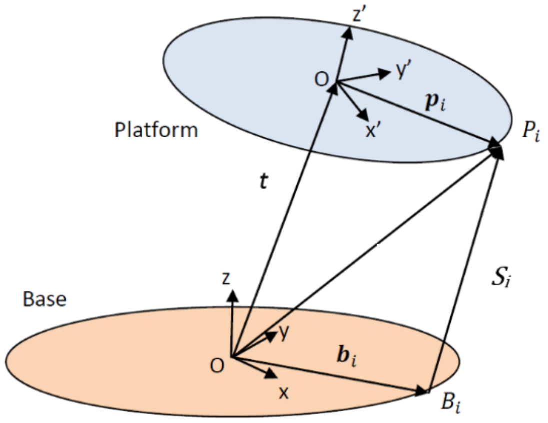

Fig. 7: Hexapod manipulator vector analysis [10].

This following equation describes relation of variables in Fig.7.

$$\vec{S}_i = R_p^b\vec{p}_i+\vec{t}-\vec{b}_i \tag{5}$$

By finding the norm of $\vec{S}_i$, actuator length could be obtained. To analyze actuator driving force of every motion, derivatives of actuator length should be calculated, both in rotational and translational terms.

$$\vec{a}_{d_i}=\overrightarrow{A_i}\times\vec{r}_{d_i}+\overrightarrow{W_i}\times\left(\overrightarrow{W_i}\times\vec{r}_{d_i}\right) \tag{6}$$

$$\vec{a}_{u_i}=\ddot{L}_i\hat{s}_i+\overrightarrow{A_i}\times\vec{r}_{u_i}+\overrightarrow{W_i}\times\left(\overrightarrow{W_i}\times\vec{r}_{u_i}\right)+2\dot{L}_i\overrightarrow{W_i}\times\hat{s}_i \tag{7}$$

By identifying the whole parts of actuator, 12 equations (three equations of force and moment for each part of actuator, lower and upper) could be developed for solving 13 unknowns (three unknown forces and three unknown moments of prismatic joint, three unknown forces and one unknown moment of universal joint, and three unknown forces of ball/spherical joint). As a consequence, one additional equation should be conducted. All the unknowns should be expressed in terms of one unknown, actuator driving force for each actuator.

To obtain actuator driving force, platform dynamic should be analyzed since it connects to the actuator by joints. This following equation would describe relation of actuator driving force, platform motion, external forces, and its configuration.

$$\overrightarrow{H}x=\vec{c} \tag{8}$$

$$\overrightarrow{H}=\begin{bmatrix} \vec{s}_1 & \vec{s}_2 & \vec{s}_3 & \vec{s}_4 & \vec{s}_5 & \vec{s}_6 \\ \vec{q}_1\times\vec{s}_1 & \vec{q}_2\times\vec{s}_2 & \vec{q}_3\times\vec{s}_3 & \vec{q}_4\times\vec{s}_4 & \vec{q}_5\times\vec{s}_5 & \vec{q}_6\times\vec{s}_6 \end{bmatrix} \tag{9}$$

$$x=[x_1\quad x_2\quad x_3\quad x_4\quad x_5\quad x_6]^T \tag{10}$$

$$\vec{c}=\begin{bmatrix} R_p^b\vec{F}_{ext}+M(\vec{g}-\vec{a})-\sum_{i=1}^{6}\overrightarrow{K_i} \\ M\overrightarrow{R}\times(\vec{g}-\vec{a})-I\vec{\alpha}-\vec{\omega}\times I\vec{\omega}+R_p^b\overrightarrow{M}_{ext}-\sum_{i=1}^{6}\left(\vec{q}_i\times\overrightarrow{K_i}-\vec{f}_i\right) \end{bmatrix} \tag{11}$$

$$\overrightarrow{K_i}=\frac{\overrightarrow{C_i}\times\hat{s}_i}{L_i} \tag{12}$$

Definition 2.2:

$\vec{S}_i$	Actuator length vector.
$[\dot{L}_i, \ddot{L}_i]$	Actuator linear velocity and acceleration.
$\hat{s}$	Actuator length unit vector.
R_p^b	Transformation matrix from platform framework to base framework.
$\vec{q}_i$	Attachment position of actuator upper part on base framework.
$\vec{b}_i$	Attachment position of actuator lower part on base framework.
$\vec{t}$	Translation vector from base center into platform center.
$[\vec{a}_{d_i}, \vec{a}_{u_i}]$	Actuator lower part and upper part, respectively, acceleration.
$[\vec{r}_{d_i}, \vec{r}_{u_i}]$	Actuator lower part and upper part, respectively, C.G. position in base framework.
$[\overrightarrow{W}_i, \overrightarrow{A}_i]$	Actuator angular velocity and acceleration in base framework, respectively.
x_i	Spherical joint constraint force vector in actuator framework.
$[\overrightarrow{F}_{ext}, \overrightarrow{M}_{ext}]$	External force and moment act on platform.
M	Platform mass.
[R,I]	Platform radius and moment of inertia.
$\vec{g}$	Gravity constant.
$\vec{a}$	Platform linear acceleration.
$[\vec{\omega}, \vec{\alpha}]$	Platform angular velocity and acceleration.
$\vec{C}_i$	Moment that act on actuator.
$\vec{f}_i$	Moment of viscous friction at spherical joint

Hereafter, this following block diagram is given to describe the entire equations in simplified way as shown in Fig.8.

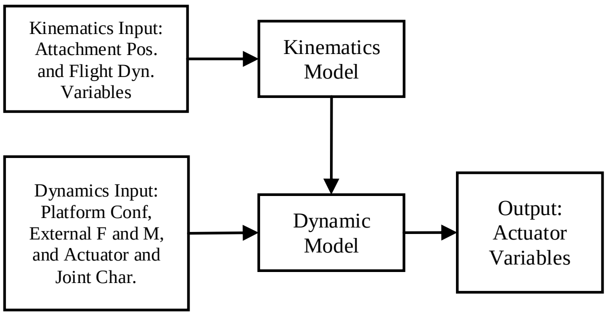

Fig. 8: Hexapod manipulator modelling algorithm.

3. Hexapod Manipulator Design Process

Commonly, design consideration should be determined at the beginning of design process due to its relations with manipulator function. For aircraft simulator, manipulator function should mimic aircraft motion in order to give true perception for the operator. Design consideration parameter could be concluded as displacement motion range and acceleration performance. As motion perception, acceleration becomes the main consideration instead of motion range. However, motion range also supports the manipulator for a long-term acceleration application.

3.1. Design Process Flowchart

From following flowchart, DR&O and design limitations are formed by comparing reference designs which have enter the market and actuator specification. Design iteration could be begun by doing sensitivity analysis towards design parameters. Base and platform radius and attachment spacing are chosen as design parameters. By varying the configuration, optimum design that has acceptable motion range and acceleration performance could be determined. So, CAD process could be done to visualize manipulator model. During doing CAD process, consultation and discussion are needed to enter manufacture session. If DR&O has been fulfilled, thus the final design that has optimum performance is obtained.

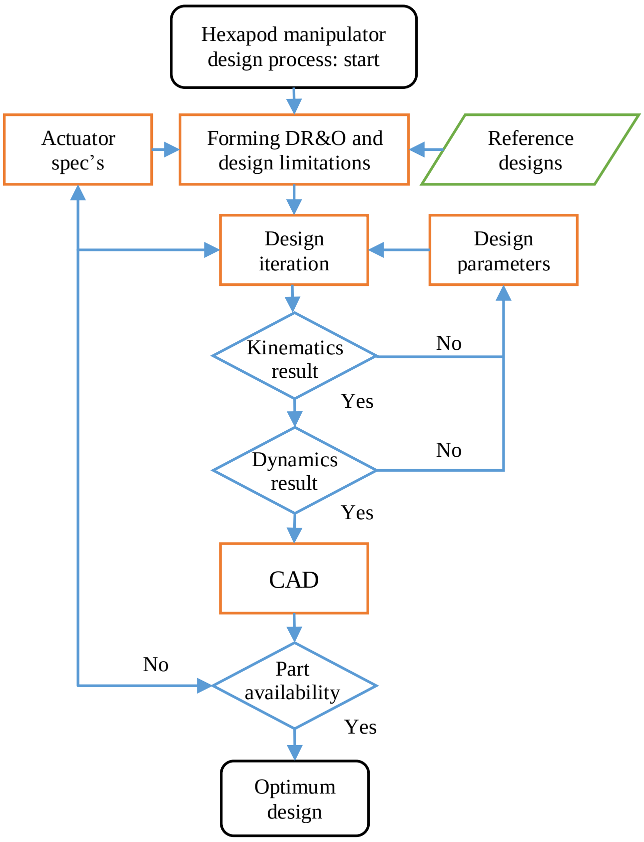

Fig. 9: Hexapod manipulator design process flowchart.

3.2. Design Requirements and Objectives

According to Ref. [12], there are three classes of hexapod manipulator, i.e. miniature, high dynamics, and high load. Based on high load and high dynamics manipulator platform, actuator must have high load resistance and high maximum velocity, respectively, which are higher-cost instead of miniature one. For recent study scope, miniature class is the best option to learn manipulator characteristics in terms of kinematic and dynamic characteristic relation due to manufacture complexity, required space, and cost. So, one day, modification of human scale hexapod manipulator could be undergone optimally based on configuration and performance relations. Thus, manipulator reference design would be shown as follows.

Table 1: Miniature Manipulator Reference Designs

Parameter/ Name	H840 Hexapod	HXP50 MECA	HXP100P MECA
Max payload (kg)	10	5	6
Init. height (mm)	292	151	209
Platform radius (mm)	125	62.5	100
Base radius (mm)	174	100	150
X translation (mm)	50/-50	17/-17	27.5/-27.5
Y translation (mm)	50/-50	15/-15	25/-25
Z translation (mm)	25/-25	7/-7	14/-14
X rotation (deg)	15/-15	9/-9	11.5/-11.5
Y rotation (deg)	15/-15	8.5/-8.5	10.5/-10.5
Z rotation (deg)	30/-30	18/-18	19/-19
Stroke length (mm)	50	-	-

Hereafter finding reference design of hexapod manipulator, main component of manipulator, actuator, should be determined. For this study, linear actuator is utilized as driving force which adjusted to developed equations in Section 2.2 to physical manipulator model. This following figure and table would describe actuator specification.

Fig. 10: Actuonix Miniature Linear Actuator L16-50-35-6-R [11].

Table 2: Actuator Specification [11]

Specification	Value
Peak power point	50N @16mm/s
Peak efficiency point	24N @24mm/s
Maximum speed (no load)	32mm/s
Maximum force (lifted)	50N
Stroke length	50mm
Mass	56g
Input voltage	6VDC
Controller type	RC linear servo

By comparing reference designs and actuator specification, DR&O could be defined as follows.

Table 3: Hexapod Manipulator Design Requirements and Objectives

Parameter	Value
Hexapod manipulator class	Miniature class
Degree of freedom	6
Manipulator motion range	Near with reference designs
Manipulator acceleration	0.25g

3.3. Manipulator Parameter Sensitivity Analysis

By varying the value of design parameters, relations between design parameters and manipulator performance could be concluded. Plate dimension and attachment position, also load in platform would become independent variables while platform kinematic range and actuator driving force become observed variables. For this study, every independent variable is varied in three different values. Hence, finally, the relations of its variables could be described as follows.

Table 4: Hexapod Manipulator Parameter Sensitivity Analysis

Parameter	Relation	Has maximum value?
Increasing μ_b	Decreasing motion range, exclude negative translation in Z axis.	Yes
Increasing μ_P	Decreasing motion range, exclude negative translation in Z axis.	Yes
Increasing r_P	Decreasing rotational motion range. Increasing translational motion range, exclude in Z axis.	Yes
Increasing load in platform	Decreasing manipulator acceleration range	No

This process uses hexapod manipulator mathematical model as shown in Fig.8. By knowing the relations, optimization could be done towards existing design.

4. Development process

4.1. Numerical Model Development

By using equation from section 2.2, hexapod manipulator modelling algorithm could be implemented in MATLAB/Simulink. This simulation goal is to obtain actuator driving force for planned trajectory. Therefore, the inputs are platform and base configuration, actuator and joints characteristics, and external force and moment.

4.1.1. Mathematic Model

Entire equations are used to describe every motion in Simulink model. There are four parts in mathematic model, input part, kinematics part, dynamics part, and output part. Input part reflects joint, platform, and actuator characteristics and flight dynamics variables. Kinematics part applies several equations to determine attachment coordinate/position in each plate, actuator C.G. and inertia, and actuator kinematic variables. Results of kinematic part are used by dynamics part to calculate actuator driving force in every motion which is shown in output part. Mathematic model is presented on Fig.11 and 13.

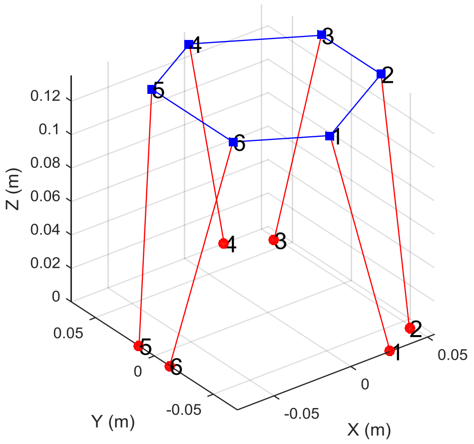

Fig. 11: Hexapod manipulator visualization by using mathematical model in MATLAB/Simulink.

4.1.2. Simscape Model

Kinematics and dynamics part in Simulink model are altered by CAD model in SimScape model. Joints and constraints applied in system should be given from CAD part so that part could substitute kinematics and dynamics model. SimScape model would calculate actuator driving force automatically by using actuator length as input. SimScape model is shown in Fig.12 and 14.

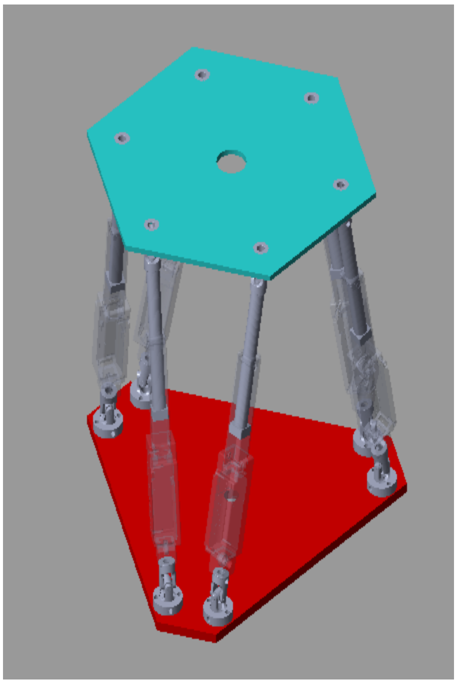

Fig. 12: Hexapod manipulator visualization in SimScape.

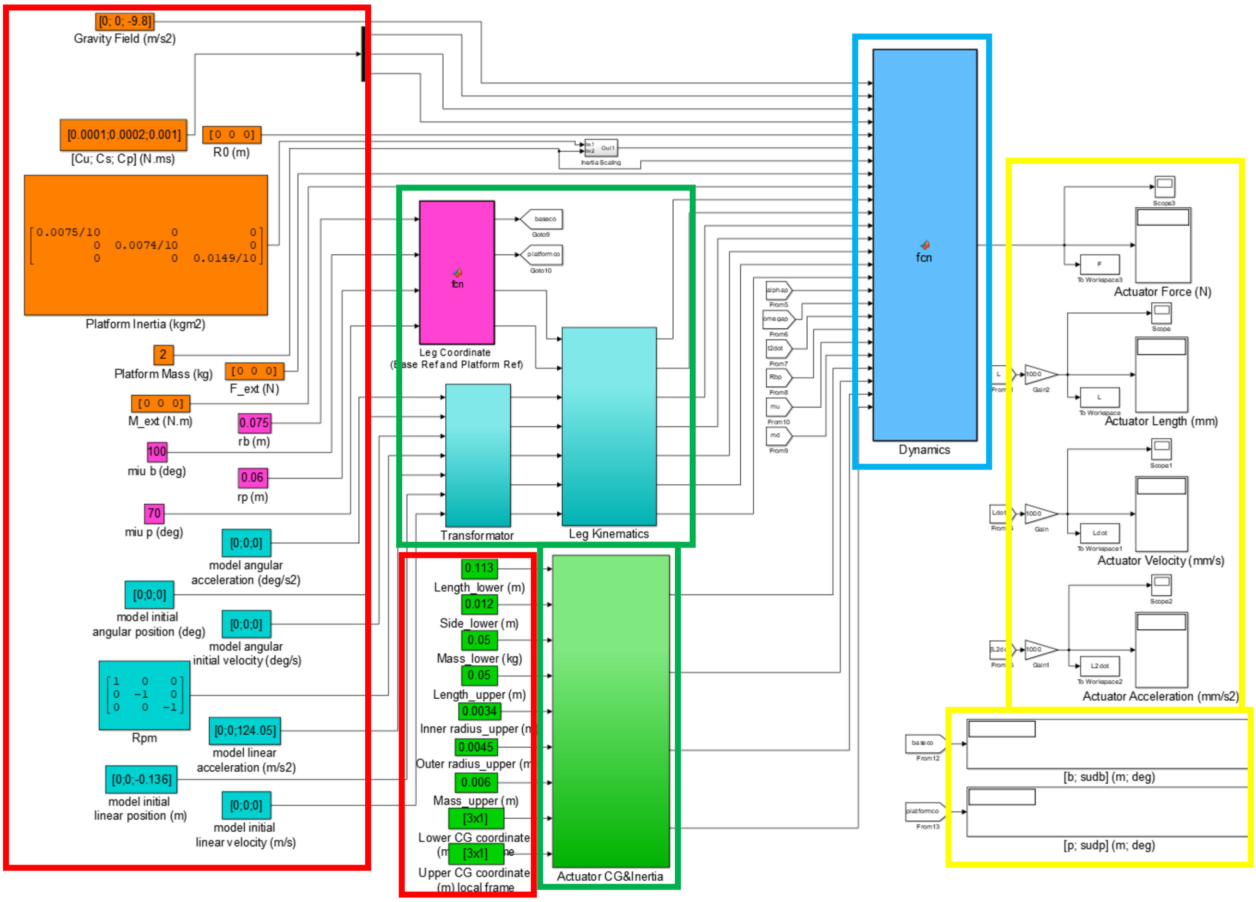

Fig. 13: Illustration of hexapod manipulator system block diagram to obtain actuator driving force by using inverse-dynamic method. Red-outlined box: Input; Green-outlined box: Kinematic model; Blue-outlined box: Dynamic model; Yellow-outlined box: Output.

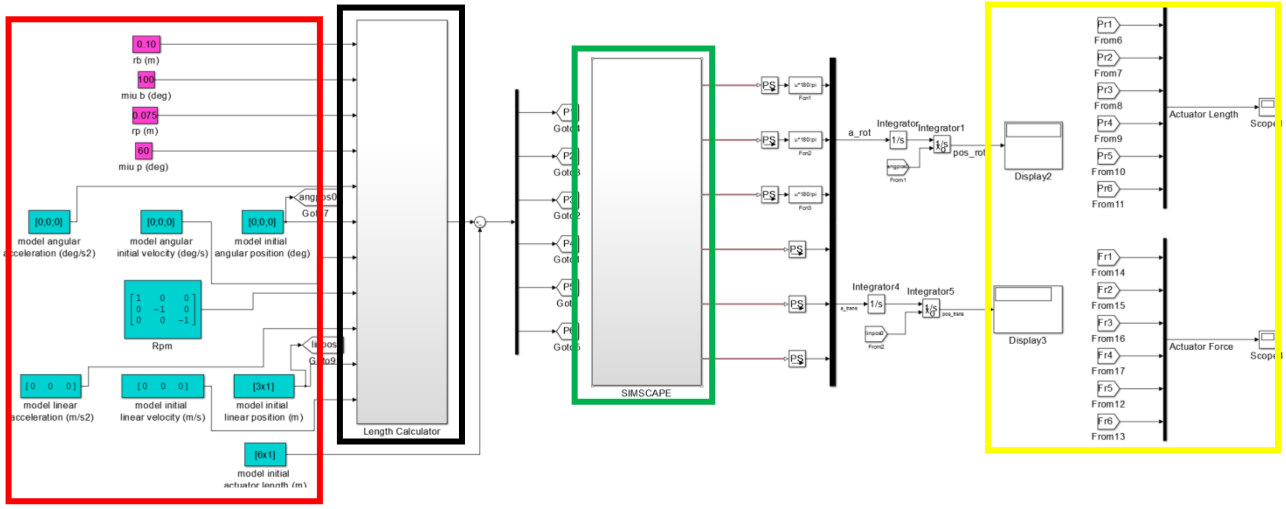

Fig. 14: Hexapod manipulator model in SimScape. Red-outlined box: Input; Black-outlined box: Actuator length calculator; Green-outlined box: Hexapod manipulator model; Yellow-outlined box: Output.

4.1.3. Numerical Model Validation and Case Study

Hexapod manipulator mathematical model by using Dasgupta [3] approach should be validated. In this study, SimScape feature is applied to validate the mathematic model by using CAD model. SimScape model is shown in Fig. 12 and 14. From data in Table 4, the differences between mathematic and SimScape model in terms of final results (displacement and acceleration range) are still acceptable since its value is below 5%.

Table 4: Design Specification Comparison

Parameter	Value in Platform Framework	
	Math model	SimScape model
Load mass (kg)	6	
Init. height (mm)	173.65	
Act. length (mm)	[158,198]	
Platform-plate radius (mm)	75	
Base-plate radius (mm)	100	
μ_b (deg)	100	
μ_p (deg)	60	
Motion range		
X translation (mm)	48.6/-59.1	46.3/-59

Y translation (mm)	54.1/-54.1	51.6/-51.6
Z translation (mm)	20.5/-20.6	20.5/-20.6
X rotation (deg)	15.6/-15.6	15.6/-15.6
Y rotation (deg)	17.8/-18.3	17.8/-18.3
Z rotation (deg)	44/-44	43.7/-43.7
Acceleration performance (g)		
a_x	0.45/-0.26	0.47/-0.27
a_y	0.3/-0.3	0.31/-0.31
a_z	4.81/-2.81	4.71/-2.77

Accuracy of actuator inertia and C.G. calculation part could be one reason why the differences occur. In mathematic model, lower part of actuator is assumed as solid bar and upper part is assumed as hollow cylinder. The reality, lower part is not fully solid bar. In addition, upper part is not attached to the center of lower part but as simplicity, upper part is assumed attach to the center of lower part.

To analyze actuator force, one case study is shown to enhance the quality of manipulator numerical model. These following figures are shown desired trajectory, actuator length, and actuator force.

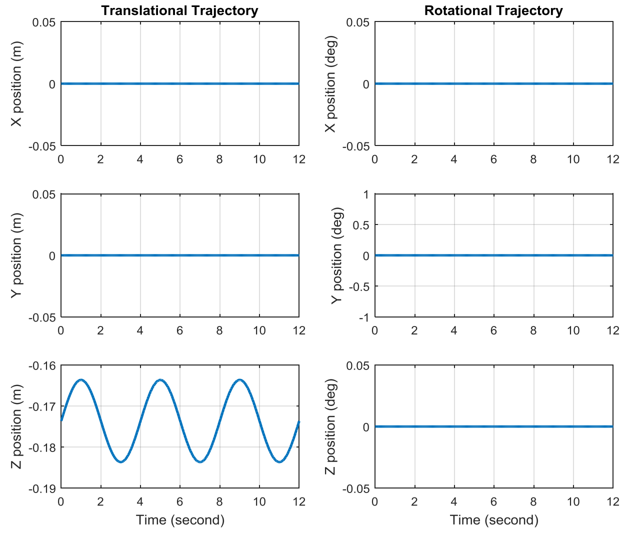

Fig. 15: Heave trajectory with 0.5π rad/s frequency and 0.01 m amplitude.

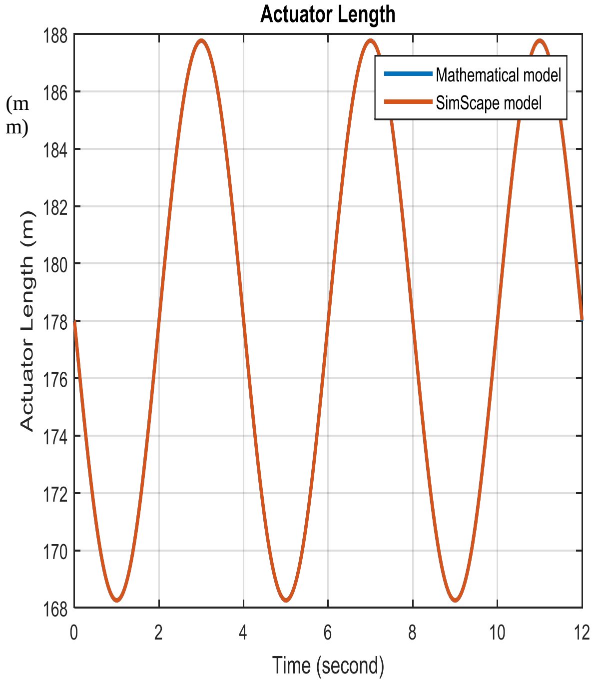

Fig. 16: Actuator length from mathematic and SimScape model.

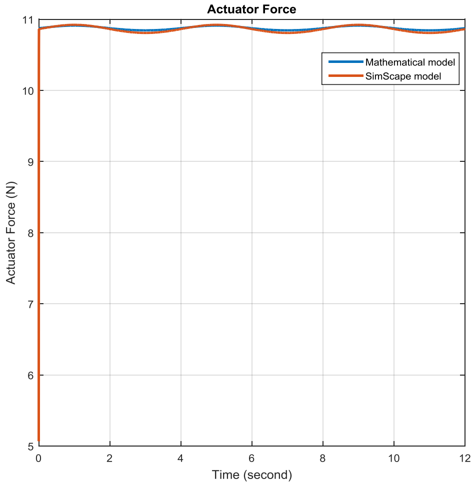

Fig. 17: Actuator force from mathematic and SimScape model.

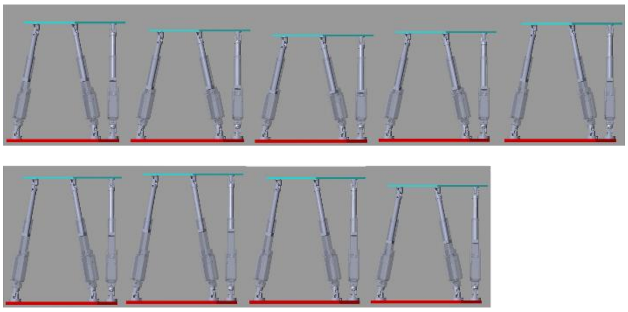

Fig. 18: One cycle of heaving mode time-lapse with time-step = 0.5 s.

From this heaving mode case study, validation process is undergone. In this paper, actuator force and length are denoted as comparison variable. This previous graphic presents actuator length and driving force for heaving motion. The graphic just shows two lines that represent one actuator of each model because the value of every actuator is equal as consequence of similar actuator motion. By observing Fig. 17, differences could be seen since initial time for actuator driving force, but in Fig. 16, which is represented actuator length variable, the differences do not occur. It means actuator length as an input has been same and could not be cause of error. The differences occur as result of different method or assumption to calculate force, such as friction coefficient, accuracy of actuator inertia calculation, and the existence of joint. Those aspects could be the main reason since mathematic model simplify them and need several adjustments to approach the acceptable result.

4.2. Actuation Control Scheme

As mentioned earlier, actuation control scheme used in this study is PID control since its simplicity and feasibility to be implemented. Platform acceleration and attitude would be sensed by IMU and transformed into actuator length variable. Actuator length becomes feedback variable that would be used to gain actuator force and move the platform in accordance with the planned trajectory.

$$F = K_P e(t) + K_I \int e(t)\,dt + K_D \frac{de(t)}{dt} \tag{13}$$

Definition 4.2:

F	Actuator driving force.
K_P	Proportional gain.
K_I	Integral gain.
K_D	Derivative gain.
e(t)	Difference of actual and planned actuator length.

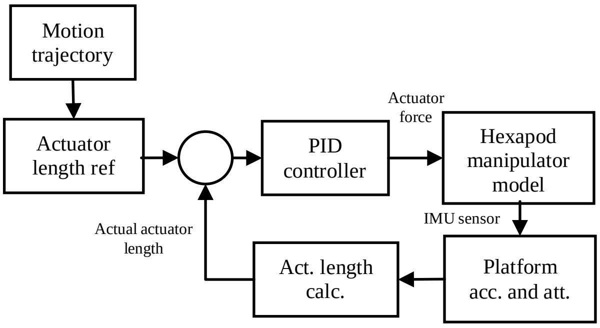

Fig. 19: Hexapod manipulator using PID as control scheme.

By using controlling concept as shown by Fig. 19, actuation control scheme could be applied to numerical manipulator model. There are two case studies for control scheme application, i.e. heaving step-input and pitching step-input. These following figures would show input signal, actuator length response, and platform condition in aircraft framework.

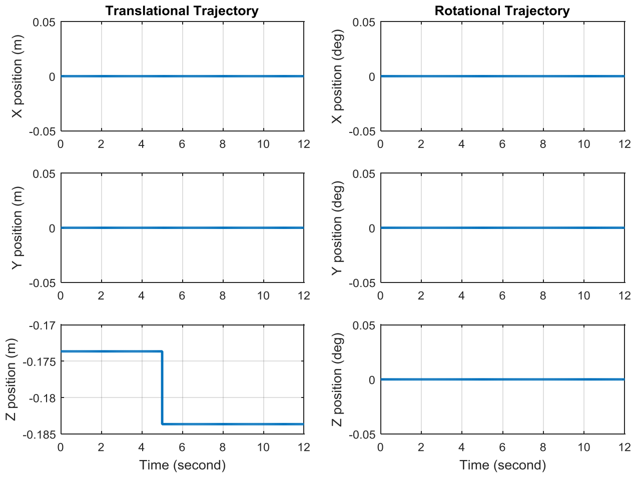

Fig. 20: -0.01 m in Z-axis displacement for controlling test purpose.

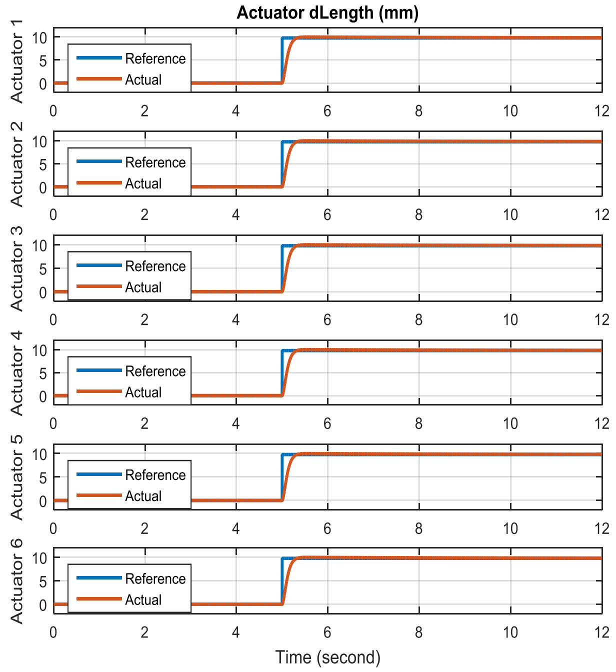

Fig. 21: Actuator length when there is translational displacement in Z-axis.

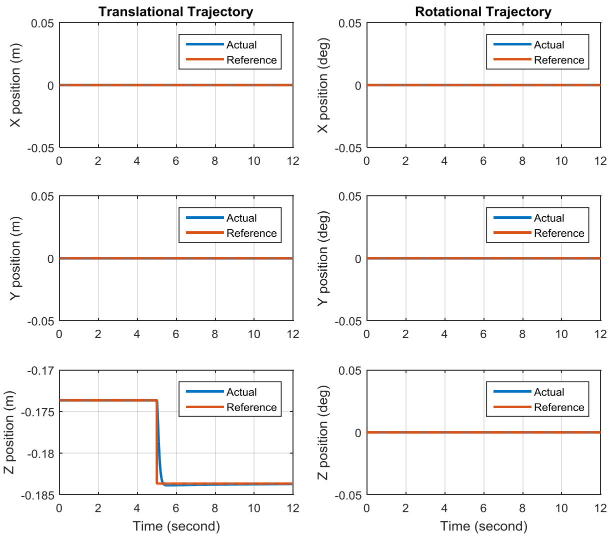

Fig. 22: Linear (left) and angular (right) position based on heaving step-input compared to reference trajectory.

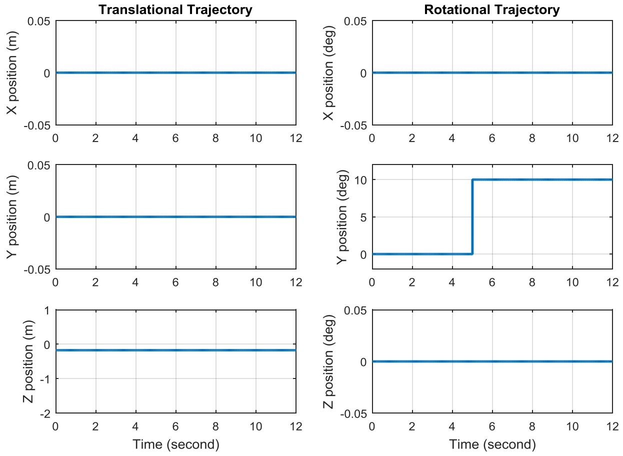

Fig. 23: 10 degrees in pitch rotational axis for controlling test purpose.

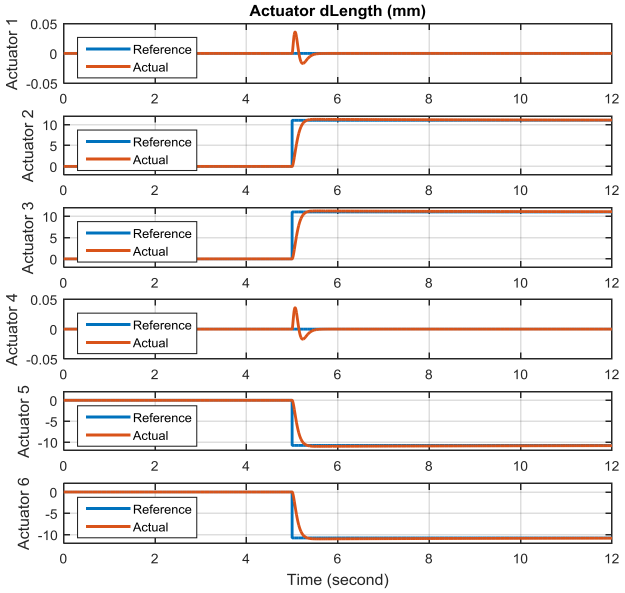

Fig. 24: Actuator length when there is pitch rotation.

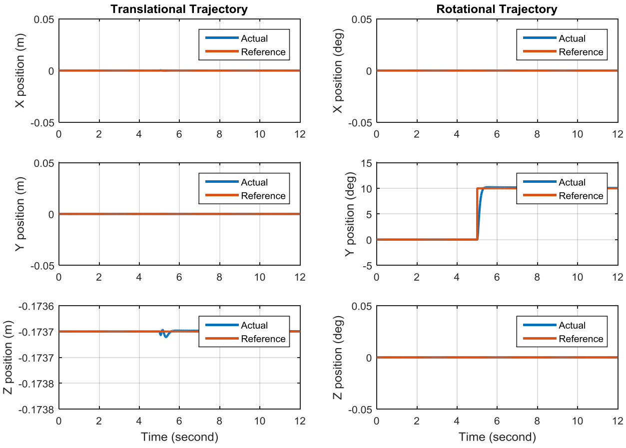

Fig. 25: Linear (left) and angular (right) position based on pitching step-input compared to reference trajectory.

From both case studies, could be seen from Fig. 20 to 25, implementation of PID control scheme is successful to direct manipulator into its destination. Overshoot still occurs in actuator length and trajectory with the occurrence of step signal (translational for heaving mode and rotational trajectory for pitching mode), but it could be removed by retuning PID gain. In addition, pitching case study has error in rotational and translational trajectory that should not be exist in translational trajectory theoretically. However, the value of error in terms of translational trajectory is relatively low in terms of Z translational displacement (lower than 1 mm) compared to its full range of Z translational displacement (20 mm). The occurrence of error in translational displacement could be an additional sign to retune the gain. It could be a theoretical proof of PID implementation to control hexapod manipulator by using actuator length as feedback variable.

4.3. Miniature System Prototyping Process

In this time, hexapod prototype manipulator has achieved its mechanical and electronic system. Its mechanical system is developed by using CAD software to give acceptable accuracy and reality when entering manufacture step. Afterwards, electronic system has two main parts which are responsible to activate the mechanical system, power module part and controller part.

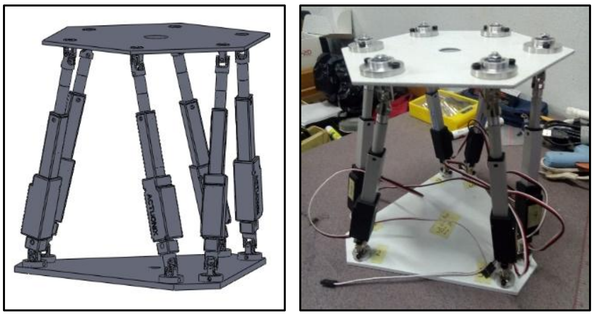

Fig. 26: Illustration of hexapod manipulator design (left) and prototype manipulator (right).

Table 5: Mechanical Design Specification Based on Mathematical Model

Parameter	Value
Load mass (kg)	6
Init. height (mm)	173.65
Act. length (mm)	[158,198]
Platform-plate radius (mm)	75
Base-plate radius (mm)	100
μ_b (deg)	100
μ_p (deg)	60
Motion range (Aircraft Model Framework)	
X translation (mm)	48.6/-59.1
Y translation (mm)	54.1/-54.1
Z translation (mm)	20.6/-20.5
X rotation (deg)	15.6/-15.6
Y rotation (deg)	18.3/-17.8
Z rotation (deg)	44/-44
Acceleration performance (g)	
a_x	0.45/-0.26
a_y	0.3/-0.3
a_z	2.81/-4.81

This current study has reach integration of both parts. Integration between mechanical and electronic system has been conducted and planned to validate hexapod manipulator performance model, displacement range and acceleration performance. This following figure would present the integration of those systems.

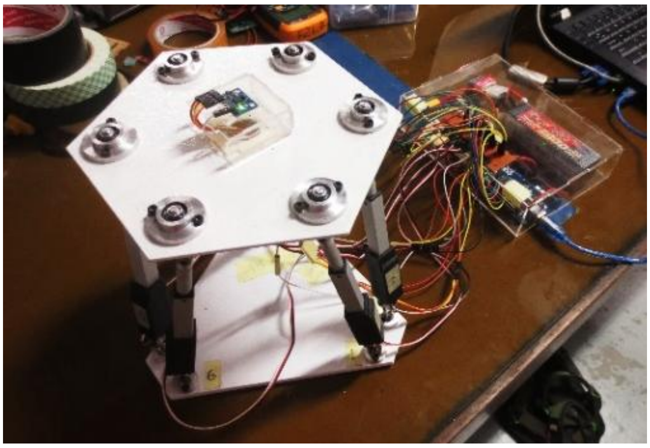

Fig. 27: Integration of mechanical and electronic system.

5. Further Development

5.1. Implementation of Actuation Control Scheme

Arduino is chosen as system actuation controller due to its size and cost. Furthermore, as first development process of motion manipulator, main objective of implementation is to observe and compare manipulator motion in real world with simulation ones. Manipulator trajectory and PID control scheme would be injected into Arduino.

Open-loop control scheme would be used to validate displacement range of prototype manipulator. This type of control scheme just using trajectory-injected Arduino and IMU. While close-loop control scheme would utilize IMU as linear acceleration and rate angular sensor and Arduino as controller. The scope of controller is just to receive/send data from/to computer as data processor. Python language is used to bridge Arduino and computer because of its easiness to communicate to other open-source programs. By using close-loop scheme, acceleration performance validation could be undergone. So, mathematical model assumptions could be reduced in order to obtain acceptable model if compared to prototype manipulator.

5.2. Flight Numerical Simulation and Hexapod Manipulator Integration

By finishing actuation control scheme implementation into prototype manipulator and validating its performance, flight numerical simulation and manipulator integration phase could be done. However, before integration phase is conducted, human-sized manipulator should be developed based on characteristics research in prototype miniature manipulator. Afterward, this full-scale manipulator should be moved according to flight simulation circumstances. Flight dynamics variables are extracted from the numerical simulation and used to actuate the manipulator. Python is used in established communication between flight simulation and instructor post. Hence, data from flight simulation, using the same method as established one, is transferred into manipulator using Python.

6. Conclusion

Currently, aircraft simulator, which is developed by ITB Flight Physics Research Group, consists of aerodynamic and engine model, instructor station, and equations of motion part. The remaining parts are supported by X-Plane, excluding its motion system. The next step to continue this development is developing its motion system. Hexapod manipulator is widely used to reflect aircraft motion in simulator. For this current study, mathematical model has been built and compared to SimScape model. Therefore, validation should be conducted by using prototype manipulator as reference that has same specification as manipulator design in mathematical model. Actuator driving force differences occur in mathematical model comparison as consequences of different assumptions between both models, such as friction coefficient and inertia calculation, also joint existence. Implementation control scheme to numerical model has been performed and the result has achieved its destination trajectory. As future works, actuation control scheme implementation could be used to generate valid range of mathematical model compared to prototype manipulator. Valid range of mathematic model in terms of displacement range and acceleration performance could be obtained by utilizing prototype manipulator as validator equipment. In addition, to start achieving the main goal of Flight Physics Research Group, integration between flight numerical simulation and prototype manipulator should be done which would be continued by connecting human-sized manipulator with flight numerical simulation.

Acknowledgement

This work is part of research funded by the Ministry of Research and Higher Education (Kemenristekdikti) Republic of Indonesia.

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