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The Design of the Longitudinal Autopilot for the LSU-05 Unmanned Aerial Surveillance Vehicle

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Abstract. Longitudinal autopilot design for the LAPAN Surveillance Vehicle LSU-05 will be described in this paper. The LSU-05 is the most recent Unmanned Aerial Vehicle (UAV) project of the Aeronautics Technology Center (Pusat Teknologi Penerbangan – Pustekbang), LAPAN. This UAV is expected to be able to carry 30 kg of payload, four surveillance purposes. The longitudinal autopilot described in this paper consists of four modes, those are Pitch damper, Pitch Attitude Hold, Altitude Hold, and Speed Hold. The Autopilot of the UAV will be designed at four operating speeds, namely 15 m/s, 20 m/s, 25 m/s, and 30 m/. The Athena Vortex Lattice software is used to generate the aerodynamic model of the LSU-05. Non-linear longitudinal aircraft dynamics model is then developed in MATLAB/SIMULINK environment. Linearization of the non-linear model is performed using the linearization tool of SIMULINK. The controller is designed, based on the linear model of the aircraft in the state space form. A Proportional-Integral-Derivative (PID) controller structure is chosen, using root locus method to determine mainly the proportional (P) gain. Integral (I) and derivative (D) gain will only be used if the proportional gain can not achieve the desired target or if an overshoot / undershoot reduction is required. The overshoot/undershoot should not exceed 5% and settling time is less than 20 seconds. The controller designed is simulated using MATLAB and SIMULINK. Preliminary analysis of the controller performance shows that the controller can be used to stabilize the aircraft and to automatize the speed and altitude control throughout the considered speed range.
Keywords: longitudinal, autopilot, PID, UAV

1. Introduction

LSU-05 is an Unmanned Aerial Vehicle (UAV) designed by Pustekbang, LAPAN [1]. The UAV is designed as a multipurpose aircraft. The main mission of the UAV is surveillance. However, it can also be used for aerial photography, disaster evacuation, and as a research platform. The UAV is mainly controlled remotelly, with radio signals from the ground station. It can be controlled manually by a human pilot on the ground, or autonomously using an autopilot system which will be discussed in this paper.

Generic longitudinal autopilot system for this type of UAV consists of altitude-hold/select, speed-hold/select, and a glide-slope control for auto take-off and landing (ATOL) system [2, 3]. However, for semi-automatic control mode, it is necessary to be able to control pitch attitude using the control stick. This pitch attitude control can also serves as the inner loop of either the speed-hold or the altitude-hold control system. The Pitch Attitude Hold is a control system to keep the pitch angle of the aircraft at the commanded value. The Speed Hold is a control system to keep the aircraft at a certain speed, and the Speed Select is a controller to drive the aircraft to go to the commanded airspeed. The Altitude Hold is a system to keep the aircraft at a certain altitude, and the altitude select is a controller that drives the

aircraft to the required altitude. Essentially, the "hold" and the "select" autopilots are the same controller, however, the way of operation is different.

Control systems used on many autopilot systems are PID controller [4, 5, 6]. The PID control system is explained in detail in reference [7]. Several methods are described in sufficient detail such as the root locus method and Frequency-Response method (Nyquist, Bode, Nichols, etc.). In addition to the PID control system, which has been developed in the world is a hybrid control system that is a combination of several control systems such as neural network - PID, neural network - fuzzy logic, fuzzy logic - PID, etc. [8, 9, 10]. Several papers compare the methods [8, 9], the results can be complementary to one another.

In this paper, the controller used was a PID controller with root locus method to get proportional gain. Integral and derivative gain will only used if the proportional gain did not achieve desired target or to reduce overshoot/undershoot. The overshoot/undershoot should not exceed 5% and settling time is less than 20 second. The model of the UAV was linearized model of longitudinal equations motion. It is represented by a state-space model for each operating trim speed. The controller designed will be simulated using MATLAB and Simulink.

2. Modeling of UAV
LSU-05 is a fixed-wing aircraft with tail boom connected to its tail. The UAV is powered with piston engine and 28 inch propeller. As many conventional aircraft, the control surfaces used in this UAV are elevator, rudder, and aileron. For longitudinal motion, the elevator had much effect to this motion. Three view drawing of the UAV is presented on Figure 1.
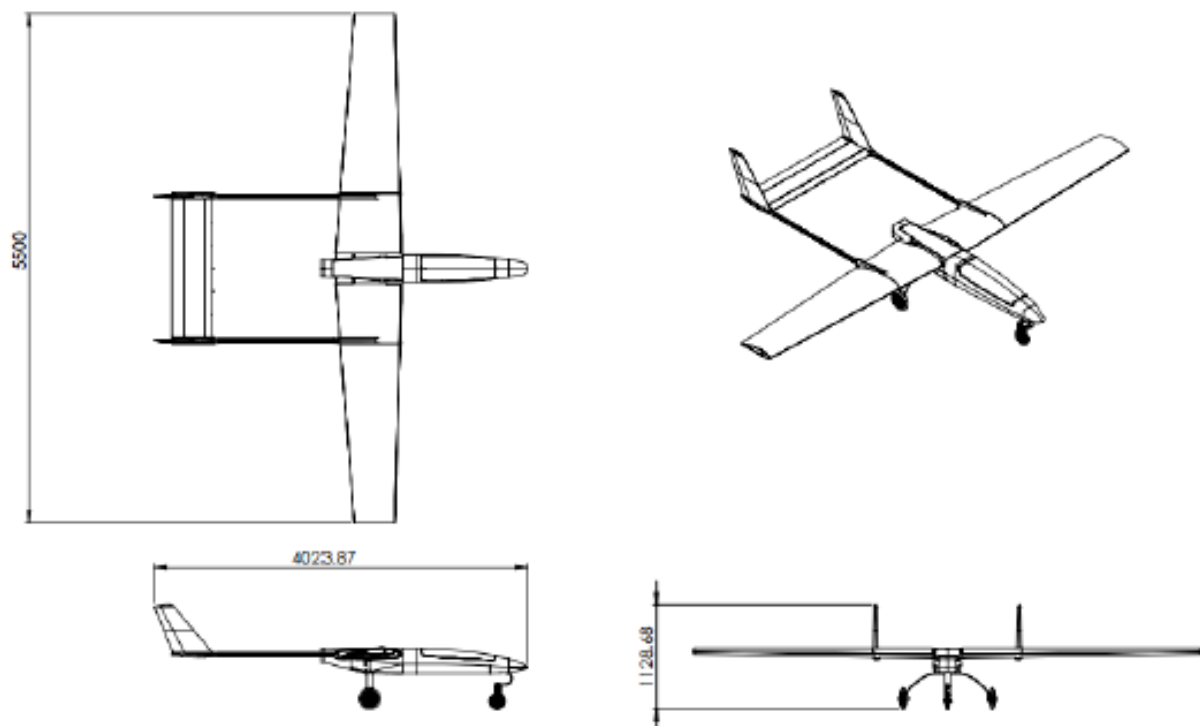

Figure 1 Three-view drawing of LSU-05

The UAV was designed to carry up to 30 kg payload with maximum take-off weight 75 kg. It has 5.5 m wing span and 3.49 m^2 wing area. The UAV configuration is presented in Table 1.

Table 1 UAV configuration

Parameter	Value	Unit
MTOW	75	kg
S	3.4925	m^2
b	5.5	m
c	0.6	m
AR	8.6614	

The aerodynamics characteristics of the aircraft obtained by vortex lattice method. Athena Vortex Lattice (AVL) [11] was used to get aerodynamic coefficients and the derivative of stability and control of the aircraft. Longitudinal aerodynamics characteristics and stability derivatives of the UAV is presented in Table 2.

Table 2 Longitudinal aerodynamics characteristics and stability derivatives of LSU-05

Parameter	Value	Unit
$C_{L\alpha}$	5.568	[per rad]
$C_{m\alpha}$	-1.295	[per rad]
C_{Lq}	9.876	[per rad/s]
C_{mq}	-13.815	[per rad/s]
$C_{L\delta e}$	0.0081	[per deg]
$C_{D\delta e}$	0.0013	[per deg]
$C_{m\delta e}$	-1.36	[per deg]

Aircraft dynamics modeling is described in many references to both longitudinal dynamics and lateral-directional dynamics [12, 13, 14, 15]. The references described how to derive aircraft equations of motion, triming, static and dynamic stability, derivative of stability and control, stability augmentation system [12], and automatic control [14, 15]. To facilitate the design of automatic control systems, the motion equations are linearized by small disturbance theory. This makes the equations can be decoupled into two modes of motion, longitudinal and lateral-directional.

Trim point observed at four operating speed in cruise phase, which is steady straight flight (γ=0). The velocity observed was 15 m/s, 20 m/s, 25 m/s, and 30 m/s. The altitude of operation is 1000 m. Trim condition at each operating trim point is presented in Table 3.

Table 3 Trim condition for steady straight flight (γ=0)

Velocity (m/s)	α (deg)	Thrust (N)	δe (deg)	L/D
30	1.3052	55.84	-4.44	13.16
25	3.3602	43.75	-6.39	16.79
20	7.1262	38.82	-9.96	18.96
15	15.1137	47.5	-17.55	15.78

From Table 3, the optimum operating speed is 20 m/s for maximum range, it has highest lift to drag ratio. The critical speed is 15 m/s, it has high angle of attack (α) which is close to stall condition. From these trim point, the state space for each trim point can be generated from equation (1) and equation (2). The derivations of equations is presented in reference [14]. Matrix A is a state matrix and matrix B is a control matrix. Matrix A consist of velocity component in X-axes (u), velocity component in Z-axes (w), pithc rate (q), and pitch angle (θ). Matrix B consist of elevator deflection (δe) and delta thrust (δT). In many references, delta thrust is modeled in delta throtle.

$$\bar{\dot{x}} = A\bar{x} + B\bar{u} \tag{1}$$

$$\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & 0 & -g \\ Z_u & Z_w & u_0 & 0 \\ M_u + M_{\dot{w}}Z_u & M_w + M_{\dot{w}}Z_w & M_q + M_{\dot{w}}u_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} X_{\delta e} & X_{\delta T} \\ Z_{\delta e} & Z_{\delta T} \\ M_{\delta e} + M_{\dot{w}}Z_{\delta e} & M_{\delta T} + M_{\dot{w}}Z_{\delta T} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_T \end{bmatrix}$$

(2)

The stability of the UAV can be analyzed from the eigenvalues of matrix A. If all eigenvalues are negative, then the UAV is stable. If there is a positive eigenvalue then the UAV is unstable. The eigenvalues of each trim speed is presented in Table 4 and Table 5. For longitudinal motion, the modes of motion can be analyzed in two modes, short period mode and phugoid mode.

Table 4 Eigenvalue, damping, and frequency of matrix A for each trim speed for short period mode

Velocity (m/s)	Eigenvalue	Damping	Frequency (rad/s)
30	-2.52 ± 1.44i	0.869	2.91
25	-2.14 ± 1.25i	0.863	2.48
20	-1.77 ± 1.10i	0.848	2.08
15	-1.43 ± 1.03i	0.811	1.76

It is presented in Table 4, for short period mode, the eigenvalues are negative. The damping for each trim point is positive means the short period mode are damped.

Table 5 Eigenvalue, damping, and frequency of matrix A for each trim speed for phugoid mode

Velocity (m/s)	Eigenvalue	Damping	Frequency (rad/s)
30	0.0152 ± 0.383i	-0.0398	0.383
25	0.0409 ± 0.447i	-0.091	0.449
20	0.0801 ± 0.527i	-0.15	0.533
15	0.1290 ± 0.615i	-0.205	0.628

To make the UAV stable, the phugoid mode must have negative eigenvalue. From Table 5, the eigenvalue of each operating point is positive. The phugoid mode of the UAVs is unstable. It will makes the UAV also unstable, although the short period mode is stable.

3. Autopilot Design and Simulation
This section described the design of basic longitudinal autopilot consist of Pitch Attitude Hold, Altitude Hold, and Speed Hold. The sensors and actuators of the UAV was not modeled in designing of the autopilot.

3.1. Pitch Attitude Hold
Pitch attitude hold is an autopilot to hold aircraft attitude at desired pitch angle (θ). Pitch attitude hold feedback pitch angle (θ) and compare to reference pitch angle. It used pitch damper as inner loop. Pitch damper is a system to control pitch rate (q). As described in previous sections, the UAV is unstable. With pitch damper, the UAV could be stable. The design of pitch damper is presented on Figure 2.
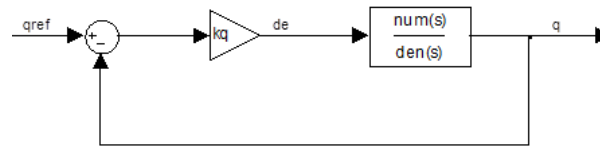
Figure 2 Design of pitch damper with feedback gain kq.

Using root locus method, feedback gain for each trim point is presented in Table 6. The root locus used is negative root locus. The gain is chosen based on location of the pole which has well damping and and miminum overshoot.

Table 6 Feedback gain and damping chosen for pitch damper

Velocity (m/s)	Gain	Damping
30	-0.242	0.775
25	-0.292	0.801
20	-0.277	0.85
15	-0.214	0.999

Pitch damper is used as inner loop for pitch attitude hold. The pitch angle is integration of pitch rate. From the pitch damper designed above, the output pitch rate is integrated with integrator addition to get pitch angle. The pitch angle is fedback to make the closed-loop system. The design of pitch attitude hold is presented on Figure 3.
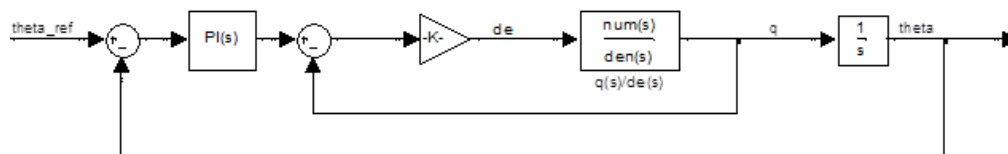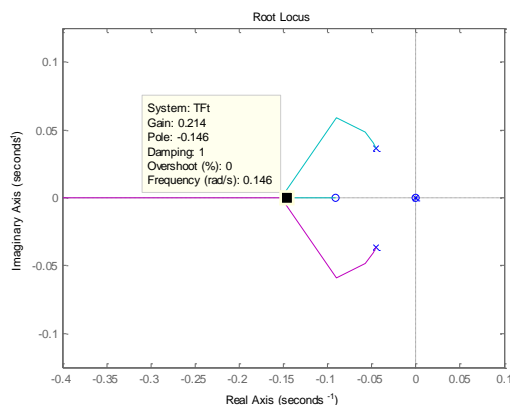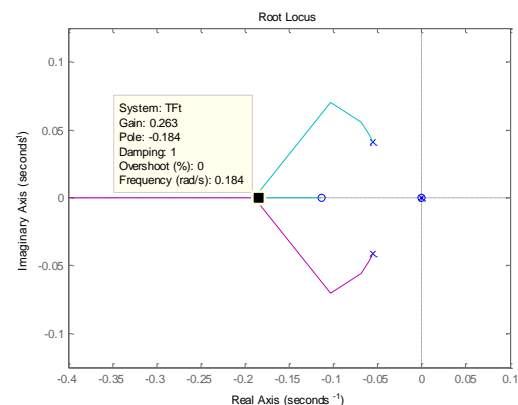

Figure 3 Design of pitch attitude hold with pitch damper as inner loop and PI controller used to control pitch angle.

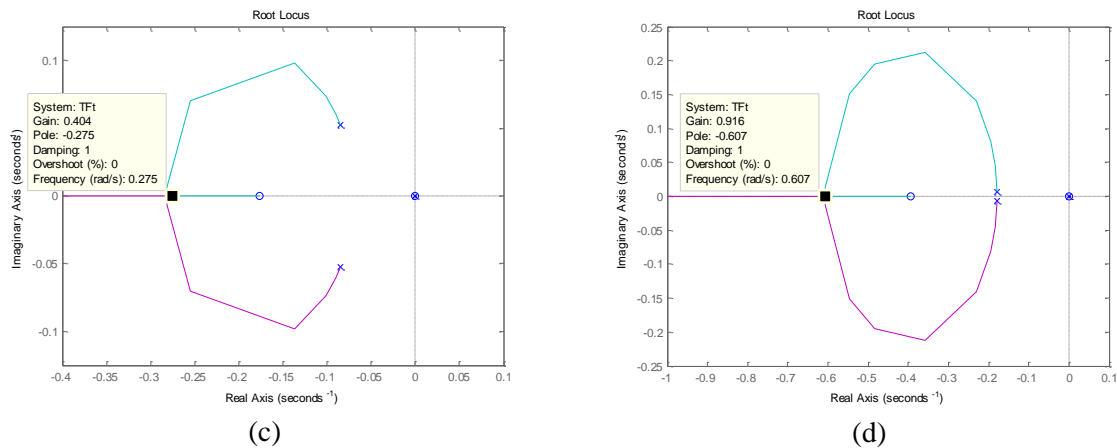Root locus of pitch attitude hold for each operating trim point is presented on Figure 4.

(a)

(b)

Figure 4 Root locus plot of pitch attitude hold at trim point (a) 30 m/s, (b) 25 m/s, (c) 20 m/s, and (d) 15 m/s

From root locus on Figure 4, feedback gain chosen for each operating trim point is presented in Table 7.

Table 7 Feedback gain and damping chosen for pitch attitude hold

Velocity (m/s)	Gain	Damping
30	0.214	1
25	0.263	1
20	0.404	1
15	0.916	1

From Figure 5, the response of system with proportional gain did not satisfy the step input, there are steady state error about 10% to 15 % (dashed). To reduce steady state error, integral gain is added (solid). The integral gains chosen for each trim point are 0.04 of proportional gain for 30 m/s and 25 m/s, 0.06 of proportional gain for 20 m/s, and 0.08 of proportional gain for 15 m/s.
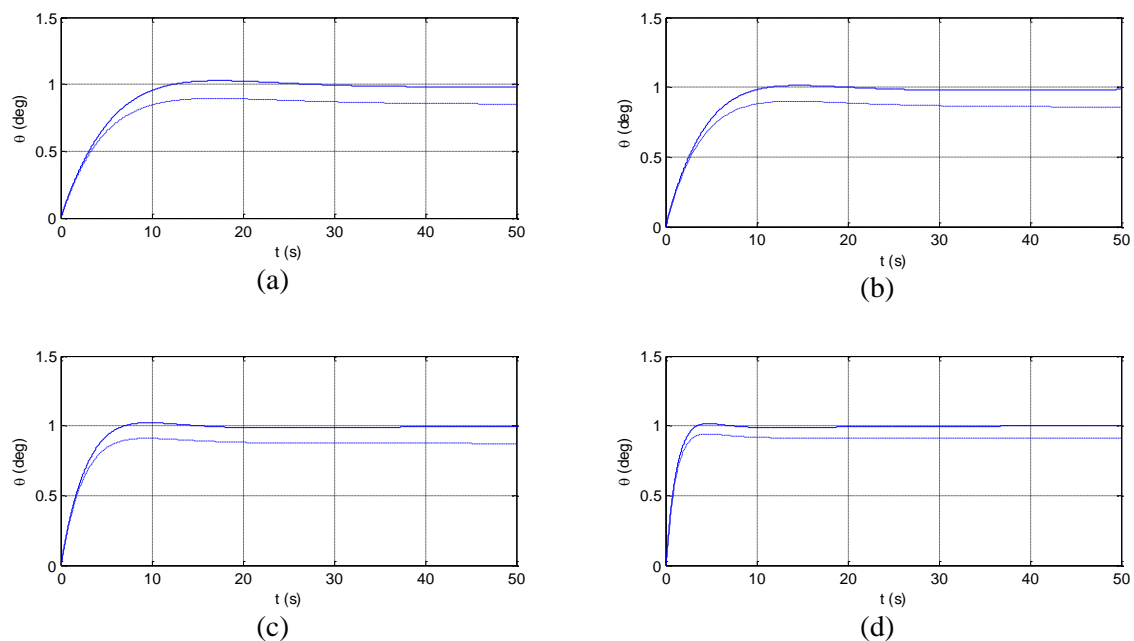
Figure 5 Step response of pitch attitude hold using P gain (dashed) and PI gain (solid)

Step information for each trim point is presented on Table 8. The lower speed can achieved settling time faster than the higher speed. The settilng time for each trim point did not exceed 10 seconds. Settling time treshold was set to 5%. The overshoot of the lower speed is smaller than the higher speed. The overshoot for each trim point is less than 5 %.

**Table 8** Step info of pitch attitude hold for each trim point

Velocity (m/s)	Rise time (s)	Settling time (s)	Overshoot (%)
30	7.5520	9.3564	4.4977
25	6.4381	8.0738	2.8881
20	4.2874	5.3995	2.6497
15	2.0101	2.6115	1.6436

3.2. Altitude Hold

For surveillance mission, altitude hold is very important autopilot. Altitude hold is an autopilot to hold aircraft at certain altitude. To design altitude hold, pitch attitude hold will be used as inner loop. To get better result, the change of altitude must be controlled first. The altitude change (hdot) can be integrated later to get altitude (h). Hdot controller is designed using pitch attitude hold as inner loop. The design of hdot controller is presented on Figure 6.
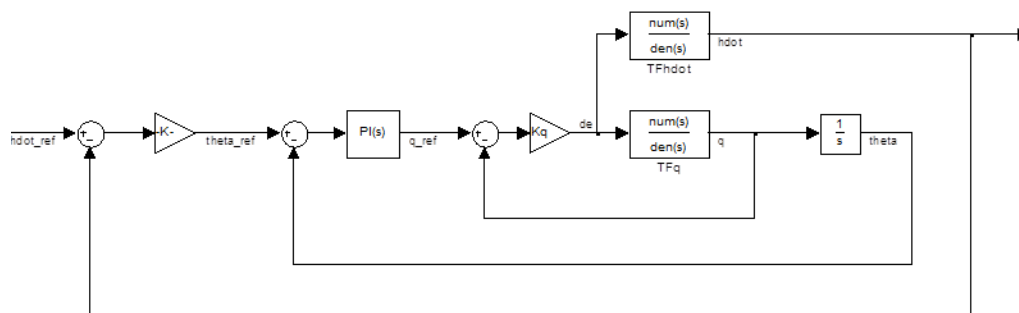
Figure 6 Hdot design with pitch attitude hold as inner loop

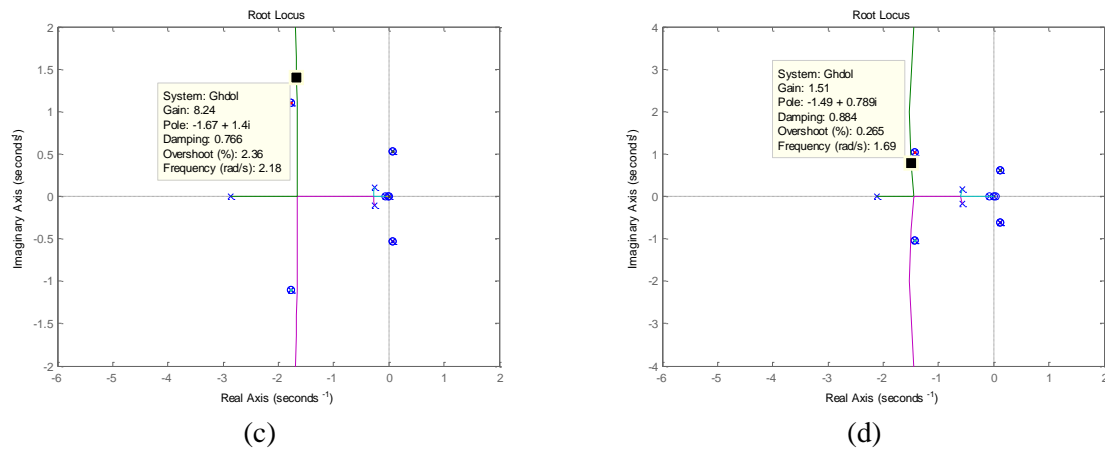Root locus of hdot control for each operating trim point is presented on Figure 7.

(a)

(b)
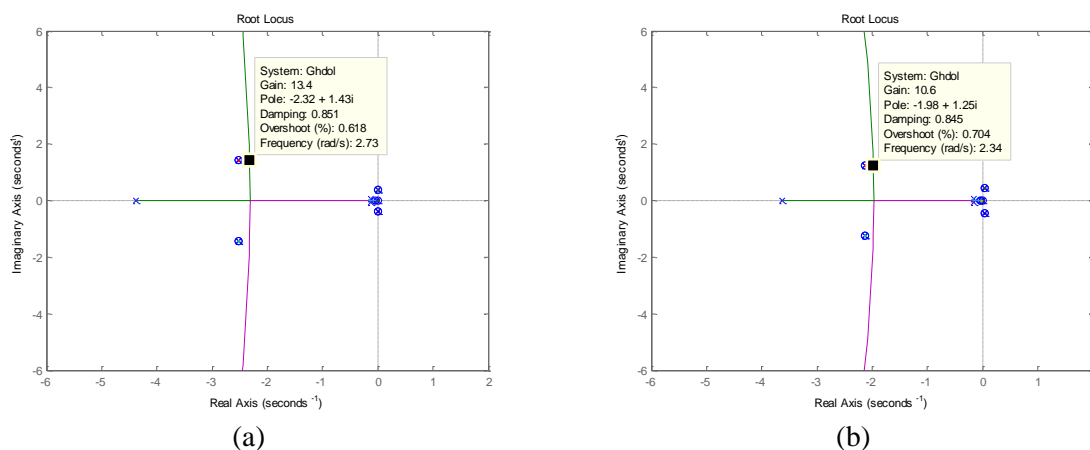
Figure 7 Root locus of hdot at trim point (a) 30 m/s, (b) 25 m/s, (c) 20 m/s, and (d) 15 m/s

From root locus on Figure 7, feedback gain chosen for each operating trim point is presented in Table 9.

Table 9 Feedback gain and damping chosen for Hdot

Velocity (m/s)	Gain	Damping
30	13.4	0.861
25	10.6	0.845
20	8.24	0.766
15	1.51	0.884

Hdot controls designed obove will be used in altitude hold as inner loop. Hdot was integrated to get altitude (h). Altitude is fedback and compare to reference altitude. The design of altitude hold is presented on Figure 8.
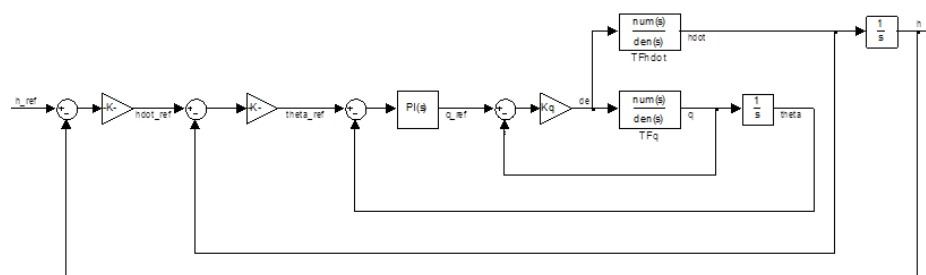

Figure 8 Altitude hold design with hdot control as inner loop

Root locus of altitude hold for each operating trim point is presented on Figure 9.
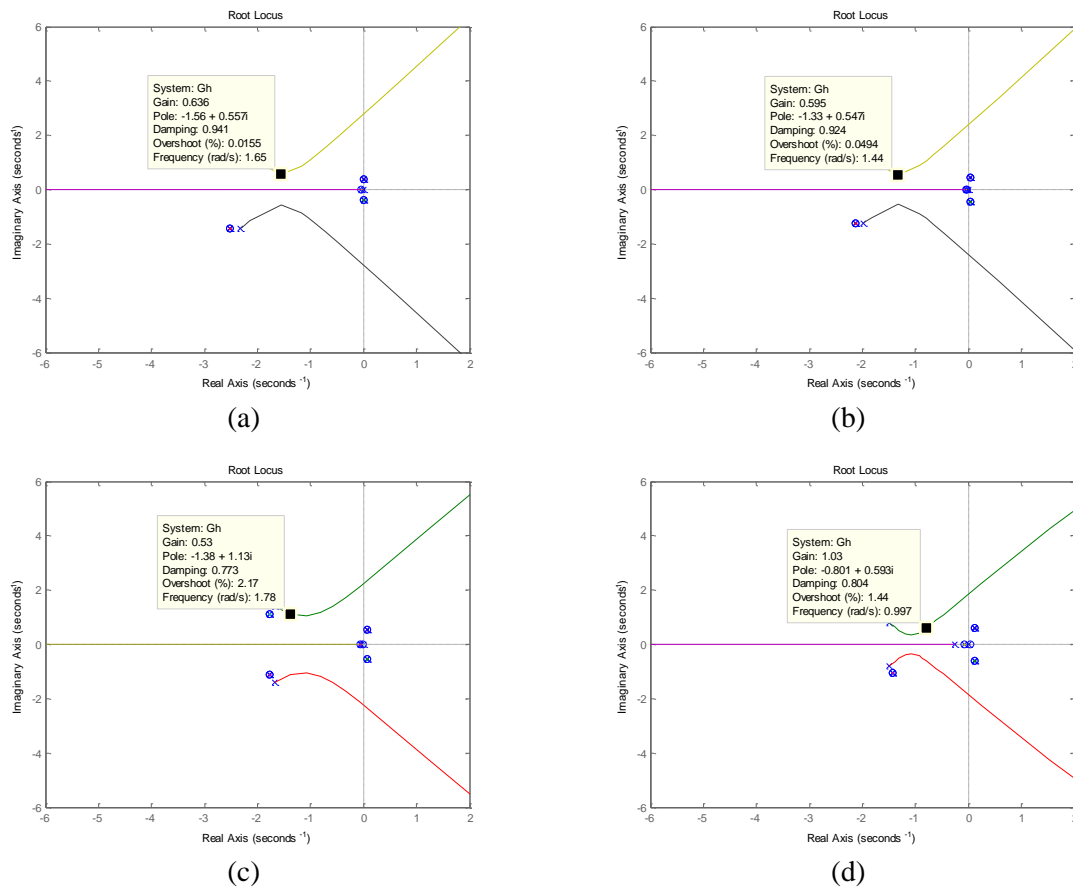
(a)

(b)

(c)

(d)

Figure 9 Root locus of altitude hold at trim point (a) 30 m/s, (b) 25 m/s, (c) 20 m/s, and (d) 15 m/s

From root locus on Figure 9, feedback gain chosen for altitude hold at each operating trim point is presented in Table 10.

Table 10 Feedback gain and damping chosen for altitude hold

Velocity (m/s)	Gain	Damping
30	0.636	0.941
25	0.595	0.924
20	0.530	0.773
15	1.030	0.804

Step response of altitude hold for each trim point is presented on Figure 11.

(a)

(b)

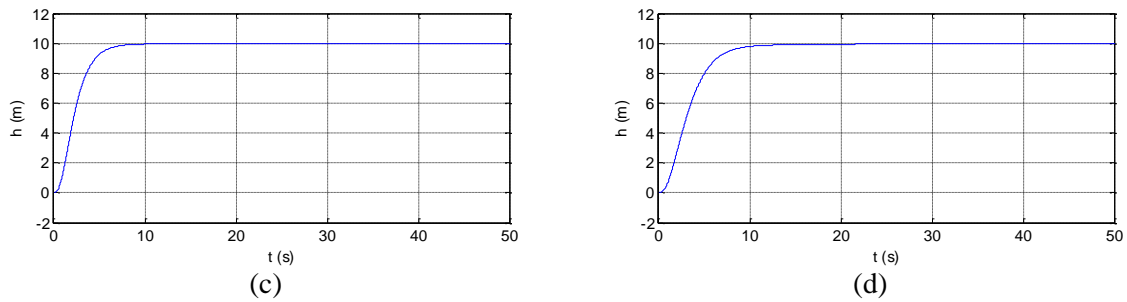(c)   (d)
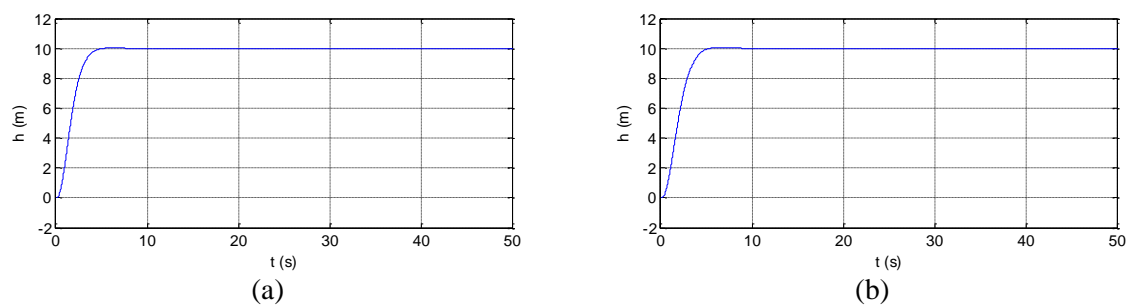
Figure 10 Step response of altitude hold with speed hold on at trim point point (a) 30 m/s, (b) 25 m/s, (c) 20 m/s, and (d) 15 m/s

From Figure 10, altitude holds designed can achieved 10 meters altitude with settling time less than 8 seconds and overshoot less than 0.5 %. The detail information of altitude hold to step response is presented in Table 11.

Table 11 Step info of altitude hold for each trim point

Velocity (m/s)	Rise time (s)	Settling time (s)	Overshoot (%)
30	2.6327	3.9949	0.2311
25	2.7634	4.0694	0.4777
20	3.7004	5.5781	0.0016
15	5.1836	7.6928	0.1720

3.3. Speed Hold

Speed hold is an autopilot to maintain the speed of aircraft at certain value. It is fedback speed and compare to reference speed. The design of speed hold is presented on Figure 11.
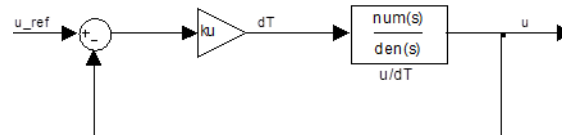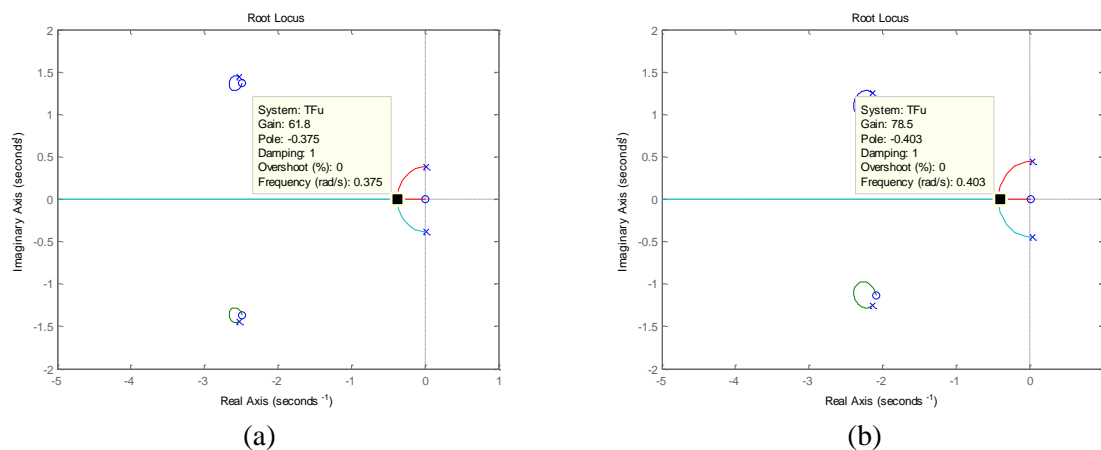

Figure 11 Speed hold design

Root locus of speed hold for each operating trim point is presented on Figure 12.

(a)   (b)

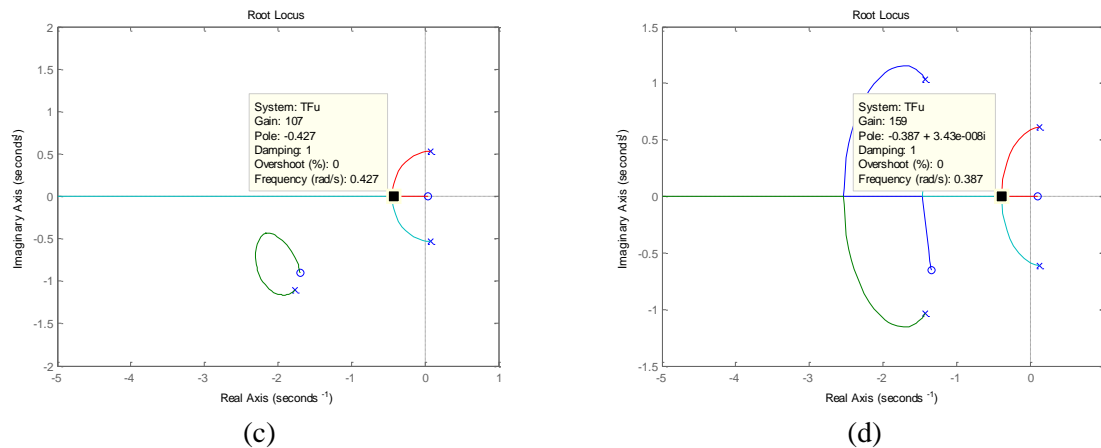(c)   (d)

Figure 12 Root locus of speed hold at trim point (a) 30 m/s, (b) 25 m/s, (c) 20 m/s, and (d) 15 m/s

From root locus on Figure 12, feedback gain chosen for speed hold at each operating trim point is presented in Table 10.

Table 12 Feedback gain and damping chosen for speed hold

Velocity (m/s)	Gain	Damping
30	61.8	1
25	78.5	1
20	107	1
15	159	1

Step response of speed hold for each trim point is presented on Figure 14.

(a)   (b)

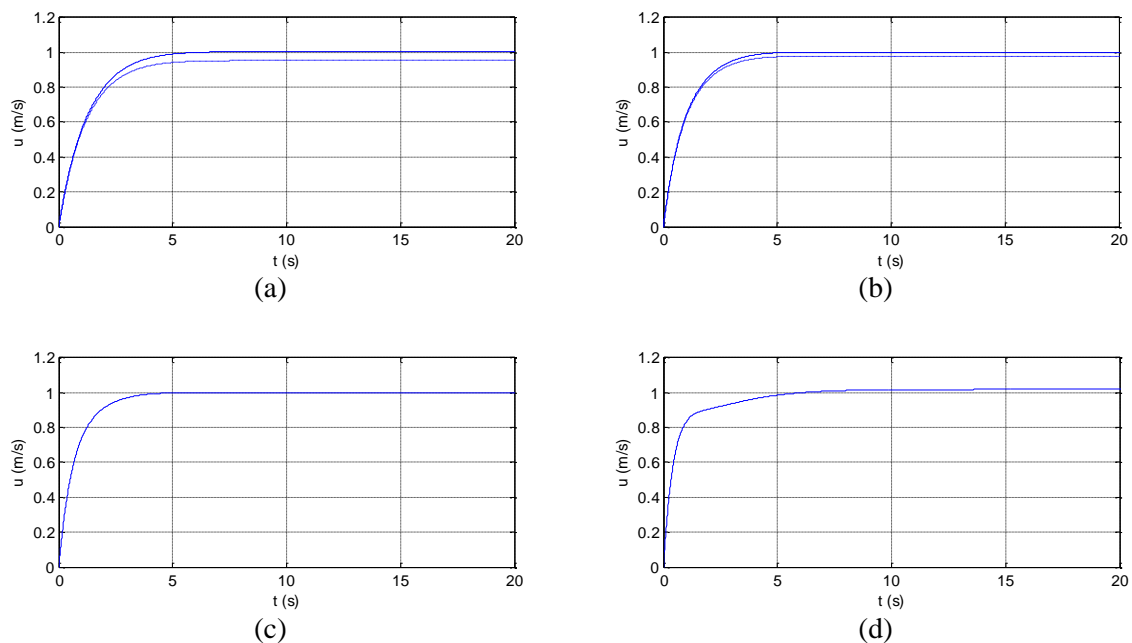(c)   (d)

Figure 13 Step response for speed hold with altitude hold on at trim point point (a) 30 m/s, (b) 25 m/s, (c) 20 m/s, and (d) 15 m/s

Figure 14 shows step response for speed hold with altitude hold on. Step 1 m/s given to system and the system shows well response but there are steady state error with proportional controller only (dashed), integrator is added to the controller to reduce steady state error (solid). The integral gains chosen are 0.045 of proportional gain for 30 m/s and 0.025 of proportional gain for 25 m/s. Settling time for each trim point did not exceed 5 seconds and overshoot is less than 0.5%. The detail information of speed hold to step response is presented in Table 13.

Table 13 Step info of speed hold for each trim point

Velocity (m/s)	Rise time (s)	Settling time (s)	Overshoot (%)
30	2.6807	3.5639	0.3997
25	2.2430	3.0156	0.1289
20	1.7746	2.4813	0.2401
15	2.3015	4.1161	0

4. Conlusions

Longitudinal automatic control for LSU-05 has been designed at trim point 15 m/s, 20 m/s, 25 m/s, and 30 m/s. Pitch attitude hold autopilot used PI controller shown well results, its settling time did not exceed 10 seconds and overshoot is less than 5%. The higher speed needed more time to steady state than the lower speed. Altitude hold autopilot used P controller shown well results, its settling time did not exceed 8 seconds and overshoot is less than 0.5%. The higher speed needed less time to steady state than the lower speed. Speed hold autopilot used PI controller for speed 25 m/s and 30 m/s, while P controller for 20 m/s and 15 m/s. Its settling time did not exceed 5 seconds and overshoot is less than 0.4%. The controllers designed has met design target, which overshoot/undershoot is less than 5 % and setting time is less than 20 seconds.

The proportional gains chosen for pitch attitude hold are 0.214, 0.263, 0.404, and 0.916 for trim point 15 m/s, 20 m/s, 25 m/s, and 30 m/s respectively. And the integral gains chosen for each trim point are 0.04 of proportional gain for 30 m/s and 25 m/s, 0.06 of proportional gain for 20 m/s, and 0.08 of proportional gain for 15 m/s. The proportional gains for altitude hold are 0.636, 0.595, 0.530, and 1.030 for trim speed 15 m/s, 20 m/s, 25 m/s, and 30 m/s respectively. The proportional gains for speed hold are 61.8, 78.5, 107, and 159 for trim point 15 m/s, 20 m/s, 25 m/s, and 30 m/s respectively. The integral gains chosen are 0.045 of proportional gain for 30 m/s and 0.025 of proportional gain for 25 m/s.

Acknowledgment

References

[1]   LSU-05, Pustekbang, LAPAN. URL http://pustekbang.lapan.go.id. Accessed on December 12, 2016
 [2]   Jenie, S.D. and Budiyono, A. 2006 *Automatic Flight Control System,* ITB, Bandung.
 [3]   Hogge, Edward F., 2004 *B-737 Linear Autoland Simulink Model*, Lockheed Martin Corporation, Hampton, Virginia.
 [4]   Eko Budi Purwanto, 2013 *Pemodelan and Simulasi Sistem Kendali Proportional Integral Derivative untuk Kestabilan Dinamika Terbang,* Majalah Sains and Teknologi Dirgantara Vol. 8 No. 2 : pp 48-59.
 [5]   Sufendi, dkk, 2013 *Design and Implementation of Hardware-In-The-Loop-Simulation for UAV Using PID Control Method*, International Conference on Instrumentation, Communications, Information Technology, and Biomedical Engineering (ICICI-BME), November 7-8, Bandung.

[6]   Kada, B. and Ghazzawi, Y., 2011 *Robust PID Controller Design for an UAV Flight Control System*, Proceedings of the World Congress on Engineering and Computer Science Vol II, WCECS, October 19-21, San Francisco, USA.

[7]   Ogata, K., 2010 *Modern Control Engineering*, Prentice Hall, New Jersey.

[8]   Gouthami, E., and Rani, M.A., 2016 *Modeling of an Adaptive Controller for an Aircraft Roll Control System using PID, Fuzzy-PID and Genetic Algorithm.* IOSR Journal of Electronics and Communication Engineering (IOSR-JECE) Volume 11, Issue 1, Ver.II, pp 15-24.

[9]   Nair, M.P. and Harikumar, R., 2015 *Longitudinal Dynamics Control of UAV,* International Conference on Control, Communication & Computing India (ICCC), 19-21 November.

[10] Elsayed, A., 2015 *Design of Longitudinal Motion Controller of a Small Unmanned Aerial Vehicle*, I.J. Intelligent Systems and Applications, 10, pp 37-47.

[11] Mark Drela. AVL. URL http://web.mit.edu/drela/Public/web/avl/. Accessed on February 13, 2017

[12] Hull, D.G. 2007 *Fundamentals of Airplane Flight Mechanics,* Springer, Austin.

[13] Cook, M.V. 1997 *Flight Dynamics Principles,* Elsevier, Oxford.

[14] Nelson, R.C. 1998 *Flight Stability and Automatic Control*, McGraw-Hill, New York.

[15] Allerton, D. 2009 *Principles of Flight Simulation*, John Wiley & Sons Ltd, West Sussex.