PROGRAM BOOK

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Schedule

Thurday, September, 23 2021				
Time	**Agenda**			
	Main Room			
07.30 - 08.00	**Registration**			
08.00 - 09.30	**Opening**			
	Indonesian Raya Song			
	Pray			
	Opening Speech by Chair of ICITACEE 2021			
	Kurniawan Teguh Martono, ST, MT			
	Opening Speech by Head of Computer Engineering Diponegoro University			
	Dr. Ir. R. Rizal isnanto, ST, MM, MT, IPM			
	Opeing Speech by Dean of Engineering Faculty Diponeoro University			
	Prof.Ir. M. Agung Wibowo, MM, MSc, PhD.			
	Opening Speech by IEEE Indonesia Section			
	Dr.-Ing. Wahyudi Hasbi, S.Si, M.Kom			
	Open the event with virtual gong			
09.30-10.00	**Main Speaker 1**			
	Dr. Mohsen Naderpour			
10.00 - 10.30	**Main Speaker 2**			
	Dr Azli Yahya			
10.30 - 11.00	**Main Speaker 3**			
	Dr. Iwan Setiawan., ST., MT			
11.00 - 11.30	**Main Speake 4**			
	Dr. Rifki Ismail			
11.30 - 12.30	**Lunch Break**			
12.30 - 16.00	**Parallel Session**			
	Break Out Room 1	Break Out Room 2	Break Out Room 3	Break Out Room 4
16.00 - 16.30	**Break**			
16.30 - 18.00	**Closing**			

Break Out Room 1

Thursday, September 23, 2021

Time	Paper ID	Title	Presenter
12.30 - 12.45	1570735175	Investigation of Photovoltaic Panel Topology Performance to Feed Electricity in Rural Area	Antika Prasetyaningtyas
12-45 - 13.00	1570735982	Robot-Inclusive Guidelines for Drain Inspection	Matthew Yeo
13.00 - 13.15	1570737132	Implementation of OpenALPR for Detecting Vehicle Licence Plate in Smart Toll Gate	Achmad Hidayatno
13.15 - 13.30	1570748741	Analysist Acceptance of Video Conference at Zoom Application Using Technology Acceptance Model	Brata Wibawa Djojo
13.30 - 13.45	1570730175	Fuzzy Integral Control Design for Boost Converter Based on State-Space Average Model Approach	Adnan Al Tahtawi
13.45 - 14.00	1570735415	Automation Control Design of an Storage Machine Based on Omron PLC System	Lin Prasetyani
14.00 - 14.15	1570736002	Smooth Area and Efficiency Scanning for Mobile Robot Using Double-Scroll Chua Attractor and Artificial Potential Field	Sinta Uri El Hakim
14.15 - 14.30	1570738117	Experimental Study and Modeling of Sloshing in a False Ceiling Robot	Rizuwana Parween
14.30 - 14.45	1570743500	Flexion and Extension Motion for Prosthetic Hand Controlled by Single-Channel EEG	Joga Setiawan
14.45 - 15.00	1570744842	The Effect of Filtering on Sparse Representation-Based Image Reconstruction	Ratri Dwi Atmaja
15.00 - 15.15	1570753077	A Pitch Control System Design for Bicopter UAVs	Nur Uddin
15.15 - 15.30	1570753083	Implementation of Present Counter-Mode Algorithm as a Challenge Value Generator in Color Combo Access Control Prototype	Abiyyu Vindarum
15.30 - 15.45	1570732832	Clustering of Student Perceptions on Developing a Physics Laboratory Based on Information Technology and Local Wisdom	Rudi Susanto
15.45 - 16.00	1570734868	Predicting Online Learning Student Results Using Machine Learning	Aurelius Leander

Break Out Room 2

Thursday, September 23, 2021

Time	Paper ID	Title	Presenter
12.30 - 12.45	1570734869	Stock Prices Prediction Using Machine Learning	Fernando Marchai; William Martin
12-45 - 13.00	1570734889	Detecting Racist and Bad Words Using Text Mining in Social Media	Leonie Christina; Amadeo Willem; Gavin Sukhwir
13.00 - 13.15	1570736203	Challenges and Perceptions in the Use of ICT in Student Assessments During the Covid-19 Pandemic	Sunday Adeola Ajagbe
13.15 - 13.30	1570737297	Influencer Marketing Social Media Influences Brand Awareness and Customer Trust to Increase Purchase Intention (Conceptual Framework Development)	Erick Fernando
13.30 - 13.45	1570737672	Smart Campus Implementation Effects Towards Student Interest in Higher Education: A Systematic Literature Review	Nurma Ayu Wigati
13.45 - 14.00	1570737686	Design and Implementation of Three Application Software Employed in Web Based Rain Gauge Calibrators	Tatik Maftukhah
14.00 - 14.15	1570737848	Threats, Vulnerabilities and Protections in Critical Information Infrastructure	Prasetyo Adi Wibowo Putro
14.15 - 14.30	1570737919	Isolation Forest Based Anomaly Detection: A Systematic Literature Review	Wahid Salman Al Farizi
14.30 - 14.45	1570738142	Performance Comparation for Brain Tumor Segmentation Based on U-Net and ResU-Net Architectural Deep Convolutional Neural Network	Rakha Kahansa Putra
14.45 - 15.00	1570738177	Analysis of Communication Network Reliability Improvement SCADA Based for Pumping Wells Offshore	Sulistiyadi
15.00 - 15.15	1570738189	Factors Influencing Purchase Intention of Cloud Based Food Delivery	Yudi Fernando

15.15 - 15.30	1570738201	Factors Influencing Security, Trust and Customer Continuance Usage Intention of Cloud Based Electronic Payment System in Indonesia	Hary Andriawan
15.30 - 15.45	1570743894	Test Case Update Detection Using Graph Similarity of UML State Machine in Early Development Process	Akbar Noto Ponco Bimantoro
15.45 - 16.00	1570744607	Water Pollution Source Identification Based on Real-Time Monitoring System in Siak River	Evizal Abdul Kadir

Break Out Room 3

Thursday, September 23, 2021

Time	Paper ID	Title	Presenter
12.30 - 12.45	1570746294	Comparing Load-Balancer Algorithms Performance on Virtualized Environment	Richard David Tedja
12-45 - 13.00	1570752492	Sentiment Analysis of Oximeter as Covid-19 Detection Tools on Twitter Using Sastrawi Library with Novelty Technique	Boby Siswanto
13.00 - 13.15	1570752937	Emotions Classification Using Bidirectional Encoder Representations from Transformers	Denis Eka Cahyan
13.15 - 13.30	1570753076	Panoramic Projection of 3D CT Scan Teeth Images	Aziz Fajar
13.30 - 13.45	1570756342	Optimization of OCR in Detecting Research Proposal and Lecturer Community Service Documents Using Thresholding Method	Annisa Yasmin Sumardi
13.45 - 14.00	1570761889	Comparison of K-Nearest Neighbor (K-NN) and Naïve Bayes Algorithm for Sentiment Analysis on Google Play Store Textual Reviews	Mussalimun
14.00 - 14.15	1570732966	Axial Ratio-Bandwidth Enhancement of a Compact L Band Circularly Polarized Antenna Using a Simple Diagonal Slot and Corner Truncation	Subuh Pramono
14.15 - 14.30	1570734627	Combining Time Switching Energy Harvesting and Relay Selection for Energy-Efficient Cooperative Communication Networks	Nasaruddin
14.30 - 14.45	1570735215	Fiber to the Home Access Networks Housing Design in A West Semarang Sub-District	Farah Hana Kusumaputri
14.45 - 15.00	1570736326	An IoT-Based Smart Agriculture System with Locust Prevention and Data Prediction	Md. Ruhul Amin
15.00 - 15.15	1570745129	Automatic Control of Hydroponic Nutrient Solution Concentration Based on Edge and Cloud Computing Using Message Queue Telemetry Transport (MQTT) Protocol	Eka Sari

15.15 - 15.30	1570745142	Implementation of Transfer Control Protocol (TCP) Sockets to Monitor Soil Moisture Using Star Topology on Agricultural Land	Shafa Arfiyani
15.30 - 15.45	1570748346	Analysis of Random Mobility Models on Zone Routing Protocol Performance in Mobile Ad-Hoc Network	Heru Nurwarsito
15.45 - 16.00	1570748697	Development of Multi-Point LoRa Network with LoRaWAN Protocol	Heru Nurwarsito
16.00 - 16.15	1570764919	Design and Analysis of 900 MHz Microstrip Array Antenna for Student Lab Work	Yuli Christyono

Break Out Room 4

Thursday, September 23, 2021

Time	Paper ID	Title	Presenter
12.30 - 12.45	1570727142	Subsynchronous Resonance Analysis of South West Sulawesi Network with Wind Power Integration	Awan Krismanto
12-45 - 13.00	1570733176	Determination of the Maximum Power Capacity of a Power Generation Absorbed by Transmission in Power Systems	Siti Saodah
13.00 - 13.15	1570733966	Design LCL Filter for Single Phase Grid Tie Inverter Using Firefly Algorithm	Irkham; Iwan Setiawan
13.15 - 13.30	1570742583	Development of No Load Power Transformer Model Using Back Propagation Neural Network	Wahyudi Pramono
13.30 - 13.45	1570748726	Design and Implementation of Rooftop off Grid Solar Panel for Household Electricity Loads	Enda Sinuraya
13.45 - 14.00	1570752783	Fault Currents Contribution in Short Circuit Scenario of Conventional Wind Power Plants and DFIG	Langlang Gumilar
14.00 - 14.15	1570754408	An Optimum Tuning Method for DC Bus Voltage Regulation in Double Stage Off-Grid PV Systems	Iwan Setiawan

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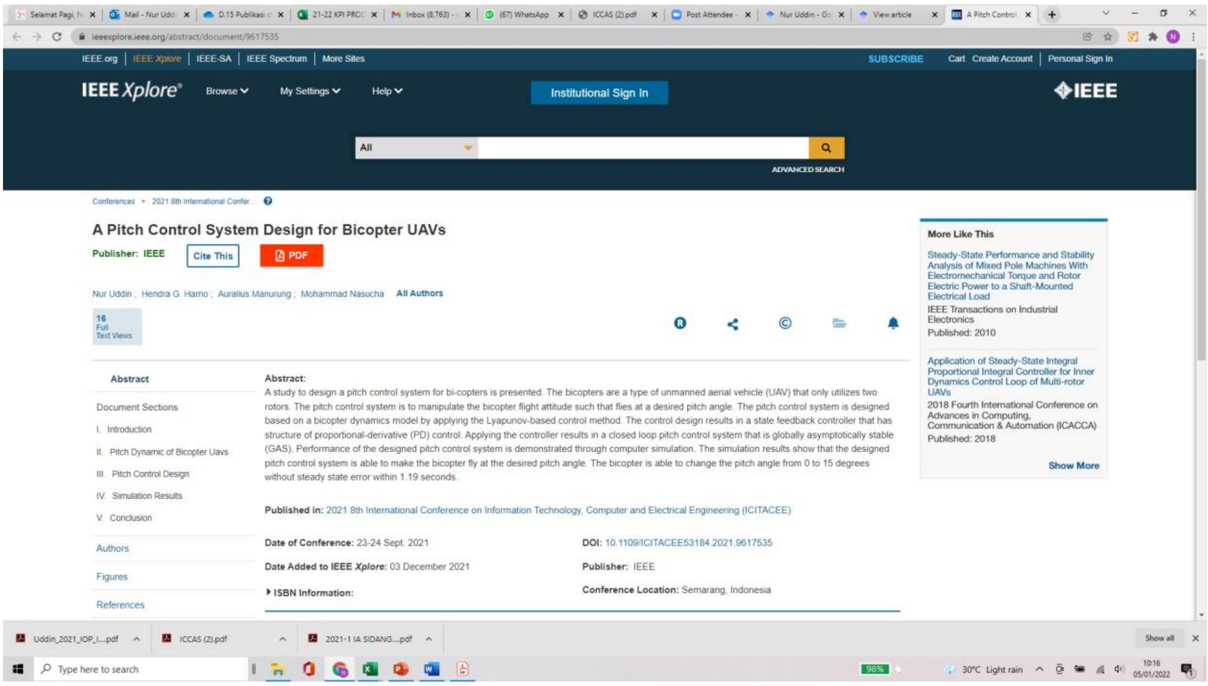

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A Pitch Control System Design for Bicopter UAVs

Publisher: IEEE Cite This PDF

Nur Uddin ; Hendra G. Harno ; Auralius Manurung ; Mohammad Nasucha All Authors

Abstract

Document Sections

I. Introduction

II. Pitch Dynamic of Bicopter Uavs

III. Pitch Control Design

IV. Simulation Results

V. Conclusion

Authors

Figures

References

Abstract:
A study to design a pitch control system for bi-copters is presented. The bicopters are a type of unmanned aerial vehicle (UAV) that only utilizes two rotors. The pitch control system is to manipulate the bicopter flight attitude such that flies at a desired pitch angle. The pitch control system is designed based on a bicopter dynamics model by applying the Lyapunov-based control method. The control design results in a state feedback controller that has structure of proportional-derivative (PD) control. Applying the controller results in a closed loop pitch control system that is globally asymptotically stable (GAS). Performance of the designed pitch control system is demonstrated through computer simulation. The simulation results show that the designed pitch control system is able to make the bicopter fly at the desired pitch angle. The bicopter is able to change the pitch angle from 0 to 15 degrees without steady state error within 1.19 seconds.

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A Pitch Control System Design for Bicopter UAVs

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***Abstract*—A study to design a pitch control system for bicopters is presented. The bicopters are a type of unmanned aerial vehicle (UAV) that only utilizes two rotors. The pitch control system is to manipulate the bicopter flight attitude such that flies at a desired pitch angle. The pitch control system is designed based on a bicopter dynamics model by applying the Lyapunov-based control method. The control design results in a state feedback controller that has structure of proportional-derivative (PD) control. Applying the controller results in a closed loop pitch control system that is globally asymptotically stable (GAS). Performance of the designed pitch control system is demonstrated through computer simulation. The simulation results show that the designed pitch control system is able to make the bicopter fly at the desired pitch angle. The bicopter is able to change the pitch angle from 0 to 15 degrees without steady state error within 1.19 seconds.**

***Index Terms*—bicopter, pitch control, system modeling, control design, Lyapunov-based control**

I. Introduction

Helicopters are flying machines that have been used in transportation for many years. The helicopters are classified a rotary-wing aircraft type. This classification is done based on the wings type, while another type is fixed-wing aircraft [1]. The fixed-wing aircraft has wings that are fixed mounted on the aircraft body. These fixed wings generate lift due to air flow resulted by the aircraft forward motion. On the rotary-wing aircraft, the wings rotate to generate lift. The wings are install on the aircraft body inline to the vertical axis. The rotating wings are known as the blades. Rotation of the blades is driven by the helicopter engines through a rotation mechanism. The set of blades and the rotation mechanism is known as a rotor.

A conventional helicopter has two rotors, the main rotor and the tail rotor [2]. The main rotor has blades with larger and longer size than the blades of tail rotor. The main rotor is vertically mounted close to the helicopter's center of gravity. Rotation of the main rotor results in lift for the helicopter. However, the rotation of main rotor also results in a reaction torque on the helicopter body. This reaction torque makes the helicopter to rotate along the vertical axis and be unstable. The tail rotor is applied to counter the reaction torque and stabilizes the helicopter. The tail rotor is placed horizontally and a certain distance to the helicopter's center of gravity. The longer distance results in less required torque of the tail rotor to counter the reaction torque. Since the lift of helicopter is generated by the blades rotation, the lift can be generated without any movement of the helicopter. This makes the helicopter to be able to do hovering and vertical take-off and landing (VTOL). Hovering is a steady flight condition at constant position and orientation. The abilities for hovering and VTOL become the advantages of helicopter compared to the fixed-wing aircraft. However, the rotor mechanism and mechanical parts make complexity in the helicopter dynamics [3]. This makes flight control development of the helicopter become a difficult problem.

A quadcopter was developed as a UAV that utilizes four rotors. Each rotor consists of a propeller and a high-speed electric motor. The four rotors are installed diagonally on the quadcopter body. The diagonal configuration allows to generate moments on the quadcopter by manipulating the lift of each rotors. The moments are required by the quadcopter to maneuver. Since the lift generated by the propeller is a function of the rotational speed, the lift manipulation can be done through controlling the motor speed. This makes the quadcopter dynamics to be simple as a function of the speed of the four motors. Controlling the quadcopter is done through controlling the rotors speed. This is much simpler than controlling the helicopter. The quadcopter gets a lot of attention in control system community in particularly in developing the flight control, for examples in [4]–[7]. More advanced studies present a development autonomous system by applying the [8]–[11].

The quadcopter becomes the most popular UAV type at this current time. The quadcopters are applied in many sectors, for examples: surveillance [12]–[14], goods delivery [15]–[17], and infrastructure inspection [18]–[23]. The infrastructure inspection may be carried in a narrow space such that the flying vehicle need to be slim and small. A quadcopter has a transverse structure, either cross configuration or plus configuration. This configuration makes the quadcopter has a wide dimension. Eliminating two rotors of the quadcopter results in a slim flying vehicle that only uses two rotor. This vehicle is known as the bicopter [24], [25]. The bicopter is different to conventional helicopter, where the bicopter has two rotors for generating lift while the conventional helicopter has only one rotor to generate lift and another rotor is for stabilization. Moreover, the bicopter has less weight and low power consumption.

Some studies on developing a bicopter have been presented. Modeling the bicopter dynamics and designing an altitude

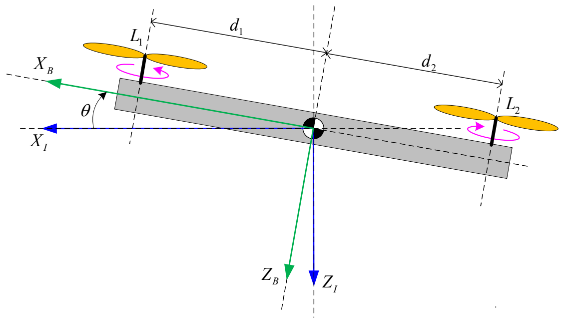

Fig. 1. Bicopter model.

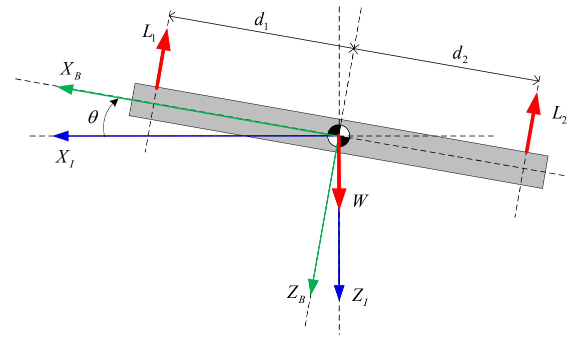

Fig. 2. Free-body diagram of the bicopter model.

control using PID control method was presented in [24]. The altitude control is to make the bicopter fly at a desired flight level. The designed altitude control was evaluated through computer simulation and verified experimentally. A research work to construct a bicopter was also presented in detail by [25]. This research work included an aerodynamics analysis to attain ideal propellers and control design for the bicopter. The result shows that the constructed bicopter was able to fly stable including hovering by carrying a significant payload. The bicopter showed similar levels of efficiency and maneuverability to a common quadcopter and other multirotors types. Another study on developing altitude control for bicopter is also presented in [26]. This study resulted in a closed loop system that is global asymptotically stable.

This paper presents a development of pitch control system for bicopter. The pitch control system is to make the bicopter fly at a desired pitch angle. The pitch control is a part of attitude control system. The pitch control system is developed through the following steps: modeling the bicopter dynamics, design the pitch control system, and performance evaluation through simulation. The modeling is to obtain dynamics equations of the bicopter that will be applied as a model in designing the pitch control system. It is done by applying the Newton's second law of motion, where the bicopter is represented in a free body diagram. This modeling is presented in Section II of this paper. The pitch control system is designed by applying the Lyapunov based control method as presented in Section III. This control method is selected in order to achieve a global asymptotic stability of the closed loop pitch control system. Performance of the designed pitch control system is demonstrated and evaluated through computer simulation. This simulation is presented in Section IV. Finally, the pitch control system development is concluded in Section V.

II. Pitch Dynamic of Bicopter UAVs

A. Dynamics Equation

A model of bicopter is shown in Figure 1. The bicopter has two rotors that located at the front and rear of the bicopter body. Both rotors rotate to generate lift for the bicopter. The rotations have an opposite direction to eliminate moment effect. Two coordinate systems are applied to represent the bicopter motions, i.e., inertial and body coordinate-systems. The inertial coordinate system is a fixed frame coordinate system. Meanwhile, the body coordinate system sticks on the bicopter body such that it changes for any movement of the bicopter. For a simplification, this study only considers the bicopter motions in two dimensional space X and Y axes. Therefore, the inertial and body coordinate-systems are represented by $X_IY_IZ_I$ and $X_BY_BZ_B$, respectively, as shown in the Figure 1.

Assuming both inertial and body coordinate systems are initially identical, where the origin of both coordinate systems are located at the same point and all of the axes are inline. Let the bicopter to move such that the body coordinate system deviates from the inertial coordinate system. Calculating the deviation with respect to the inertial coordinate system results in three independent variables that can be expressed as x, z, and θ. The x and z represent the translation motions of bicopter along the X_I and Z_I axes, respectively. Meanwhile, the θ represents the angular motion of bicopter that is known as the pitch motion. These three variables describe the position and orientation of bicopter with respect to the inertial coordinate system. The position and orientation of an object are commonly known by a term of posture. Therefore, posture of bicopter in the two dimensional frame can be defined as follows:

$$\xi := \begin{bmatrix} x \\ z \\ \theta \end{bmatrix}, \tag{1}$$

where ξ is the posture of bicopter, x is the position of bicopter along the X_I axis, z is the position of bicopter along the Z_I axis, and θ is the pitch angle that represent orientation of the bicopter along the Y_I axis. The bicopter motions are indicated by any change on the posture values.

This study assumes that only three forces work on the bicopter. They are the lift of front propeller L_1, the lift of rear propeller L_2, and the weight of bicopter W as shown in a free-body diagram in Figure 2. The free-body diagram shows the three working forces and the two coordinate systems of the bicopter. The three forces works in neither same direction nor same point. This may result in translation and rotation motions on the bicopter. These motions can be determined by calculating the resultant force and the resultant moment.

The Figure 2 shows that both propeller lift are not parallel to the bicopter wight. The lift are parallel to Z_B axis, while the weight is parallel to the Z_I axis. These indicate that the lift and the weight are in a different linear space. In order to calculate the resultant force, all of the forces have to be in the same linear space. This is done by projecting the forces into the inertia coordinate system such that results in the following equations:

$$\Sigma F_x = -(L_1 + L_2)\sin\theta \quad (2)$$
$$\Sigma F_z = W - (L_1 + L_2)\cos\theta \quad (3)$$

where ΣF_x is the resultant force along the X_I axis and ΣF_z is the resultant force along the Z_I axis. Both resultant forces drive translation motions of the bicopter along the X_I and Z_I axes.

The resultant moment of the bicopter is calculated with respect to the bicopter's center of mass. The calculation result in as follows:

$$\Sigma M_y = L_1 d_1 - L_2 d_2 \quad (4)$$

where ΣM_y is the moment along the Y_I axis, d_1 is the distance of the front propeller to the center of mass, and d_2 is the distance of the rear propeller to the center of mass. This resultant moment causes the bicopter to rotate with rotational axis Y_I and results in the pitch motion.

While the resultant force and resultant moment are known, the bicopter dynamics can be derived by applying the Newton's second law as follows:

$$m\ddot{x} = \Sigma F_x \quad (5)$$
$$m\ddot{y} = \Sigma F_y \quad (6)$$
$$I_y\ddot{\theta} = \Sigma M_y \quad (7)$$

and through a substitution result in:

$$m\ddot{x} = -(L_1 + L_2)\sin\theta \quad (8)$$
$$m\ddot{z} = mg - (L_1 + L_2)\cos\theta \quad (9)$$
$$I_y\ddot{\theta} = d(L_1 - L_2) \quad (10)$$

where m is the mass of bicopter, I_y is the pitch inertia of bicopter, and g is the gravity acceleration. The (8) to (10) are the bicopter dynamic equations in two dimensional space that is the longitudinal space. The equations can be explicitly represented by the motion variables as follows:

$$\ddot{x} = -\frac{1}{m}(L_1 + L_2)\sin\theta \quad (11)$$
$$\ddot{z} = g - \frac{1}{m}(L_1 + L_2)\cos\theta \quad (12)$$
$$\ddot{\theta} = \frac{d}{I_y}(L_1 - L_2). \quad (13)$$

In the longitudinal space, the bicopter has three degree of freedom (3-DOF) motions, i.e., 1) translation motion along the X_I axis expressed by variable x, 2) translation motion along the Z_I axis expressed by variable z, and 3) rotational motion along the Y_I axis expressed by variable θ.

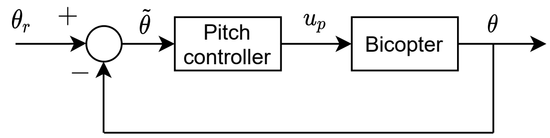

Fig. 3. Block diagram of the bicopter's pitch control system.

B. Equilibrium Point

Let a bicopter is initially flying stationary at a position (x_0, z_0) and a pitch angle θ_0 such that the posture is expressed as follows:

$$\xi(0) = \begin{bmatrix} x(0) \\ z(0) \\ \theta(0) \end{bmatrix} = \begin{bmatrix} x_0 \\ z_0 \\ \theta_0 \end{bmatrix}, \quad (14)$$

where $\xi(0)$ is known as the initial posture. The stationary flight is a flight condition where posture of the vehicle is constant. This implicates that the initial posture of bicopter is an equilibrium point. Define lift of both propeller at the initial condition as follows:

$$L_1(0) = L_{10} \quad (15)$$
$$L_2(0) = L_{20}. \quad (16)$$

Therefore, the bicopter dynamics at the initial condition can be described as follows:

$$\ddot{x}_0 = -(L_{10} + L_{20})\sin\theta_0 = 0 \quad (17)$$
$$\ddot{z}_0 = mg - (L_{10} + L_{20})\cos\theta_0 = 0 \quad (18)$$
$$\ddot{\theta}_0 = d(L_{10} - L_{20}) = 0. \quad (19)$$

Solving the (17) to (19) results in:

$$\theta_0 = 0 \quad (20)$$
$$L_{10} = L_{20} = \frac{1}{2}mg. \quad (21)$$

The L_{10} and L_{20} are the lifts of front and rear propellers for flying stationary. This stationary flight is also known as hovering.

III. Pitch Control Design

Assuming the bicopter is flying at a pitch angle θ. The bicopter is then desired to change the flight attitude from the current pitch angle θ to a new pitch angle θ_r which is also known as the reference pitch angle. A pitch control system is introduced to the bicopter such that the bicopter can reach the desired pitch angle. Design of the pitch control system is presented as follows.

A block diagram of the pitch control system is shown in Figure 3. Deviation of the current pitch angle to the reference pitch angle is defined as follows:

$$\tilde{\theta} = \theta - \theta_r \quad (22)$$

where $\tilde{\theta}$ is known as the pitch angle error. According to (13), the second derivative of (22) with respect to time is given as follows:

$$\ddot{\tilde{\theta}} = \frac{d}{I_y}\left[(L_1 - L_{1_r}) - (L_2 - L_{2_r})\right] \tag{23}$$

where L_{1_r} and L_{2_r} are the lifts of front and rear propellers for the reference pitch angle. The (23) is known as the pitch-angle error dynamics.

Assume that relations of the lift of both flight attitude are defined as follows:

$$L_{1_r} = L_1 + u_p \tag{24}$$

$$L_{2_r} = L_2 - u_p, \tag{25}$$

where u_p is the control lift. The control lift expresses the amount of lift that needs to be increased by the front propeller but decreased by the rear propeller simultaneously in order to reach the desired pitch angle. Substituting (24) and (25) into (23) results in:

$$\ddot{\tilde{\theta}} = -\frac{2d}{I_y}u_p \tag{26}$$

which is an explicit expression of the pitch-angle error dynamics as a function of the control lift.

A proper control lift needs to be determined such that the (26) is asymptotically stable. The asymptotic stability implicates that the pitch-angle error is vanish as time goes to infinity. This results in the bicopter's pitch angle to approach and reach the reference pitch angle.

The asymptotic stability can be achieved by applying a states feedback control. The states feedback control can be design by applying one of the available control design methods. In this study, the state feedback control is designed by applying the Lyapunov-based control method and described as follows [27].

Define new variables $e_1 = \tilde{\theta}$ and $e_2 = \dot{\tilde{\theta}}$, such that the following equations can be established to represent the pitch-angle error dynamics (26):

$$\dot{e}_1 = e_2 \tag{27}$$

$$\dot{e}_2 = -\frac{2d}{I_y}u_p. \tag{28}$$

For the (27) and (28), define the following positive definite function as a Lyapunov function candidate:

$$V = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2. \tag{29}$$

A time derivative of V along to the trajectories of (27) and (28) is given as follows:

$$\dot{V} = e_1 e_2 - \frac{2d}{I_y}e_2 u_p. \tag{30}$$

According to the Lyapunov stability theorem, the pitch-angle error dynamics is asymptotically stable if for the V positive definite, it has $\dot{V}$ negative definite. The (30) has only one manipulated variable to make $\dot{V}$ negative, that is the control lift u_p. Now, define u_p as follows:

$$u_p = \frac{I_y}{2d}\left[(1 + k_1)e_1 + k_2 e_2\right] \tag{31}$$

and substitute (31) into (30), it results in

$$\dot{V} = -k_1 e_1 e_2 - k_2 e_2^2. \tag{32}$$

Negative definiteness of (32) can be approached by applying the Young's inequality as follows:

$$\dot{V} = -k_2 e_2^2 - k_2 e_1 e_2 \tag{33}$$

$$\leq -k_2 e_2^2 - k_1\left(\frac{e_1^2}{2} + \frac{e_2^2}{2}\right) \tag{34}$$

$$= -\frac{k_1}{2}e_1^2 - \left(k_2 + \frac{k_1}{2}\right)e_2^2, \tag{35}$$

where the $\dot{V} \leq 0$ is resulted by $k_1 > 0$ and $k_2 > -0.5k_1$. Therefore, the pitch-angle error dynamic is asymptotically stable by applying the following states feedback control as the lift control:

$$u_p = \frac{I_y}{2d}\left[(1 + k_1)\tilde{\theta} + k_2\dot{\tilde{\theta}}\right], \tag{36}$$

where by $k_1 > 0$ and $k_2 > -0.5k_1$. Substituting (36) into (26) results in:

$$\ddot{\tilde{\theta}} + k_2\dot{\tilde{\theta}} + (1 + k_1)\tilde{\theta} = 0, \tag{37}$$

which is the characteristic of closed-loop pitch control system of the bicopter. Laplace transformation of the characteristic equation (37) is given as follows:

$$s^2 + k_2 s + (1 + k_1) = 0. \tag{38}$$

where s is the Laplace variable. The (38) is a second order system that has the following general form:

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0, \tag{39}$$

where ζ is the damping factor and ω_n is the natural frequency. Through a comparison of (38) and (39), it is found the following relations:

$$k_1 = \omega_n^2 - 1 \tag{40}$$

$$k_2 = 2\zeta\omega_n. \tag{41}$$

The (40) and (41) show that the control parameters k_1 and k_2 in (36) determine the closed loop system characteristic and vice versa. Therefore, both control parameters should be calculated by considering the desired characteristic of closed-loop pitch-control system.

IV. Simulation Results

Simulations are carried out to demonstrate performance of the designed pitch control system. The pitch control system has a state feedback control (36) with two control parameters k_1 and k_2. Both control parameters are determined base on the desired characteristic of the closed loop pitch control system. For this simulation, the desired characteristics are $\zeta = 0.7$ and $\omega_n = 5$. Therefore, the control parameters are calculated according to (40) and (41), and results in $k_1 = 24$ and $k_2 = 7$. The Table I provides information about the bicopter parameters for the simulation. These parameters include mass, moment inertia, and location of the both rotors on the bicopter structure.

TABLE I
BICOPTER PARAMETERS

Parameter	Symbol	Value	Unit
Mass	m	2	kg
Moment inertia	I_y	0.2	kg.m^2
Distance of propeller 1 from c.g.	d_1	0.2	m
Distance of propeller 2 from c.g.	d_2	0.2	m

Note: c.g. is center of gravity.

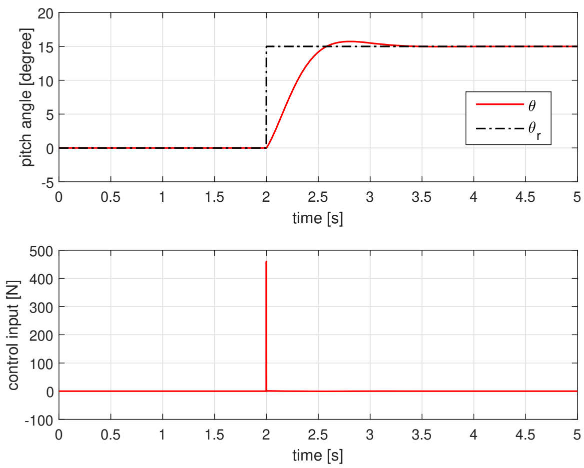

Fig. 4. Time response of the bicopter pitch control system.

Scenario of the simulation is described as follows. The bicopter is initially flying stationary at flight altitude 5 meter, where position and orientation of the bicopter are fixed. The bicopter posture at the stationary flight is given as follows:

$$\xi(0) = \begin{bmatrix} x(0) \\ z(0) \\ \theta(0) \end{bmatrix} = \begin{bmatrix} 0 \\ -5 \\ 0^\circ \end{bmatrix}. \tag{42}$$

The posture shows negative value due to the flight altitude and the Z_I axis has an opposite direction. After flying for two seconds, the bicopter is desired to change the pitch angle from 0° to 15°.

Performance of the pitch control system is evaluated based on a time response of the pitch motion and the required control input. Evaluation of the time response includes the steady-state error, rise time, overshoot, and settling time. The steady-state error is a deviation of the system response to the desired response at steady state. The rise time represents a required time to increase the system response from 10% to 90% of the steady-state response. The overshoot represents a percentage ratio of the overshoot to the value of steady-state response. An overshoot 5% is commonly applied as the maximum overshoot in control system designs. The settling time is the required time for the system response to reach and remind within a specific error band. The error band 2% is applied in this study.

The simulation is performed through digital computation using a computer. The computation is done with time sampling 1 microseconds. The simulation result in shown in Figure 4. The result shows that the bicopter was able to approach and reach the reference pitch angle with zero steady state error. The time response shows a rise time 0.40 seconds, settling time 1.13 seconds, and overshoot 4.86%. This response is quite good and acceptable for the bicopter. However, the Figure 4 shows that the required control input for the pitch motion is up to 459.8 Newtons. This required control input is very high compared to lift of each propellers at the stationary flight, which is a half of the bicopter weight or 9.8 Newtons. This required control input is not reasonable and needs to be reduced.

The high control input needs a high-power rotor that implicates to higher electric-power consumption. Moreover, the high-power rotor usually has large size and heavy. The control input needs to be small as possible in a reasonable range value. There is no a specific definition of the reasonable range value, but a control input less than the half of bicopter weight is expected in this study.

Considering (36), it is shown that the control input has a state feedback from the time derivative of the pitch-error, $\dot{\tilde{\theta}}$. This time derivative represents the pitch-error rate. While the pitch reference is a step function, the time derivative is very high at the step time and therefore the control input. In order to minimize the control input, the pitch-error rate needs to be bounded. Define a limit for pitch error rate of the bicopter as follows:

$$-360 \leq \dot{\tilde{\theta}} \leq 360, \tag{43}$$

where the minimum rate is -360 degree per seconds and the maximum rate is 360 degree per seconds.

Applying the rate limit and running the second simulation result in time responses as shown in Figure 5. The pitch time-response has a zero steady-state error with a rise time 0.43 seconds, settling time 1.19 seconds, and overshoot 4.56%. The pitch-time response at the second simulation is slightly slower than at the first simulation, but a little bit better at the overshoot. Remarkably, the control input at the second simulation is much less than the control input at the first simulation, where it is only up to 3.2 Newtons.

The result of second simulation is more reasonable for the bicopter, where the pitch time response is quite good and comparable to the first simulation result but requires much less control input. Figure 6 shows a comparison of the bicopter's pitch time-responses by applying a rate limiter and without rate limiter in the pitch controller. This result shows a benefit of applying a rate limiter in the pitch controller to minimize the required control input without decreasing the control performance significantly.

V. CONCLUSION

A design of pitch control system for bicopter has been presented. The pitch control was designed by applying the Lyapunov-based control method. It resulted in a controller that has a structure of proportional-derivative (PD) control. Applying the controller results in a closed-loop pitch control system

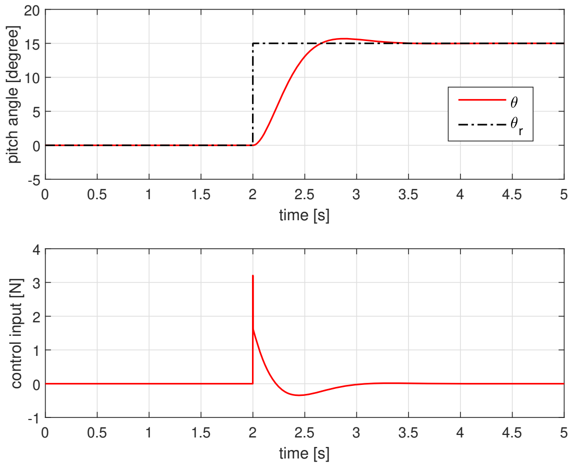

Fig. 5. Time response of the bicopter pitch control system with a rate limiter.

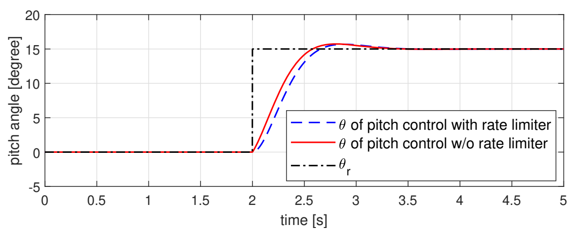

Fig. 6. A comparison of the bicopter's pitch-angle time-response of using pitch controllers with and without a rate limiter.

that is globally asymptotically stable (GAS). This stability is proved by the Lyapunov's stability theorem. The designed pitch control system was demonstrated in computer simulation. The simulation results show that the pitch controller needs a rate limiter to minimize the control input. The designed pitch control was able to change pitch angle of the bicopter from $0°$ to $15°$ within 1.19 seconds by requiring maximum control input 3.2 Newtons. This result shows that the designed controller has an acceptable performance and feasible to be implemented.

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