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An Experimental Procedure for Design and Construction of Monocopter and Its Control Using Optical and GPS-Aided AHRS Sensors

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***Abstract*—**Monocopter is a single-wing rotary flying vehicle which has the capability of hovering. This flying vehicle includes two dynamic parts in which more efficiency can be expected rather than other Micro UAVs due to the extended area of wing compared to its fuselage. Low cost and simple mechanism in comparison to other vehicles such as helicopter are the most important specifications of this flying vehicle.

In the previous paper we discussed the introduction of the final system but in this paper, the experimental design process of Monocopter and its control algorithm has been investigated in general. Also the editorial bugs in the previous article have been corrected and some translational ambiguities have been resolved.

Initially by constructing several prototypes and carrying out many flight tests the main design parameters of this air vehicle were obtained by experimental measurements. Eventually the required main monocopter for this project was constructed. After construction of the monocopter in order to design, implementation and testing of control algorithms first a simple optic system used for determining the heading angle. After doing numerous tests on Test Stand, the control algorithm designed and timing of applying control inputs adjusted. Then other control parameters of system were tuned in flight tests. Eventually the final control system designed and implemented using the AHRS sensor and the final operational tests performed successfully.

***Keywords*—**Monocopter, Flap, Heading Angle, AHRS, Cyclic, Photo Diode**.**

I. INTRODUCTION

MONOCOPTER is a kind of rotary flying vehicle which uses a single wing for flight. The main idea for building this flying vehicle has been brought from the maple seed. When this seed falls down from the maple tree, it flies precisely and regularly like a small helicopter till it comes down on the ground. In this state, the heavier part which contains the seed has the role of rotary axes and center of gravity while the extended part operates like a wing or a propeller in which a small lift force can be produced by this rotating system and it lands slowly like a glider.

Generally in monocopter design the main parameters of design such as wingspan, thrust to weight ratio, angle of incidence, airfoil, flap area, length of motor strut and etc. need to be determine. For this purpose in the most similar projects it has been used the classic Process of design and performing the wind tunnel tests and also CFD[1] simulation code. But in this project due to the lack of access to this equipment, these parameters were calculated through the trial and error method experimentally. So the cost and duration of the air-vehicle's system design was greatly reduced. However the cost of different flying models and the tests are much less than the cost of wind tunnel tests.

Thus in the first step of experimental process of dynamic and aerodynamic design procedure resulted to construction of initial prototype of monocopter. In the next steps the monocopter flight control challenges was propounded. There are two important challenges in controlling of monocopter; determination of heading angle at any instant and also control algorithm and timing control inputs. In the next step for implementing and testing the control algorithm, a simple hardware was designed for indicating the heading angle of monocopter trough the optic sensors and a light source. Thereby the control algorithm and timing of applying control inputs were implemented and tested with performing the several experimental tests and flight tests. And in the final step the more advanced flying vehicle was constructed with some changes which applied to aerodynamic design of flying vehicle (using the low Reynolds No. airfoil, winglet and wing twist implementation) and with adding the AHRS as a fast compass to the system, the final control system implemented and tested.

In addition this paper with simple expression and far from using the advanced dynamic equations or complex control methods, and also with presenting the several tables containing the main dimension of flying vehicle, has been able to be useful for operational construction of monocopter and educational purposes.

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[1] Computational Fluid dynamic

Fig. 1 Monocopter systems constructed

II. Prototype Monocopter with Optical Control

As it shown in Fig. 2 there are three types of Monocopters. The first type is the MIT University's model. In this figure the engine has placed straight across the wing [7]. And the 2nd one which is the most complex type belongs to Lockheed Martin Company. And the 3rd one is Maryland University's model [5]. In this project we resemble this one. This figure was chosen because of its simplicity compared to other models.

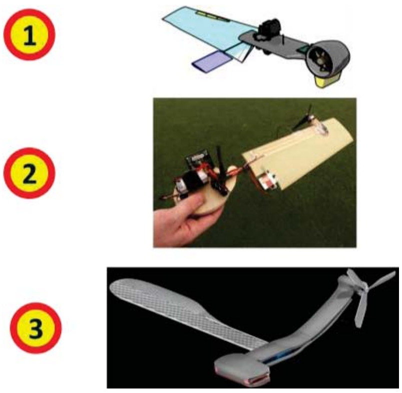

Fig. 2 Monocopter Types

This air vehicle consists of one main wing, a flap and its servomotor, a fly-bar, a brushless motor, motor speed control system, battery, flight computer system and motor strut (Fig. 3). The motor strut in this system causes the main masses to be farther than the center of gravity [3]. Also, if the distribution of masses in the monocopter is far from center of gravity, the amount of gyroscopic force in the system will increase and therefore the system stability will increase [2], [3]. The fly-bar in this system is tuning the distance of center of gravity and aerodynamic center which cause the cone angle decreases [1], [4].

A brushless DC electrical motor with the maximum of 800 g thrust has been employed as propulsion and so, a high speed electrical servomotor has been installed on the single existed flap of the system. And this monocopter has been designed and constructed in such a way that the rotational speed in hovering is about 5 cycles per second In this project, a new framework has been used in which a light source is used as the reference of the heading angle.

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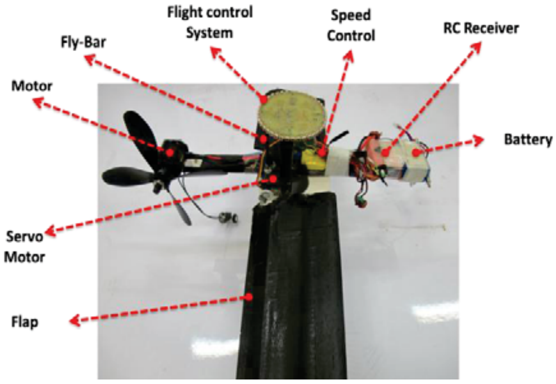

Fig. 3 Equipment configuration in the system

Besides, it should be noted that the main target in selecting this system is its simple hardware rather than the hardware in digital compass. Otherwise, the sensor fusion of digital compass system, as the first effort of designers in monocopter control, could reduce the work speed and efficiency. So in the first stage, we have decided to present this new approach in order to test the control methods of monocopter system.

For this purpose, a 40-arrays of photo diode has been installed and the sensors output data has been measured by an Xmega64 microcontroller using five 8×1-multiplexer. This processor unit calculates the direct of the light source position related to the system by selecting the maximum value among the measured data of the sensors. In this processor, the control commands which are applied by the pilot are received in the form of PWM signals via the radio control receiver. Then, due to the direction of the applied command, a sector of circular path in which the flap commands should be applied is computed. Therefore in an appropriate time instant, the command required for servo-flap is calculated and applied to the servomotor as a PWM signal. Fig. 4 illustrates the electronic circuit of the flight computer.

So, the pilot applies the commands for moving left, right, upward and downward and commands for motor speed (Throttle) with radio control. The throttle command is applied directly from radio control to the speed control system and control the flight height manually. The other commands are received by flight computer in which appropriate control operations are performed considering these commands. The schematic of system hardware is depicted in Fig. 5.

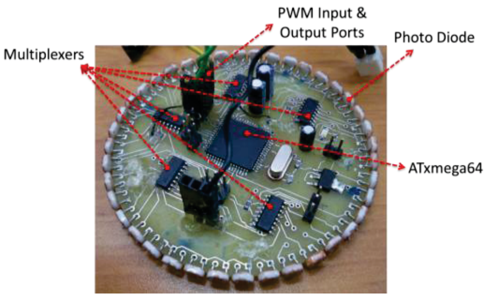

Fig. 4 Circular-shaped avionic PCB of optical prototype of monocopter

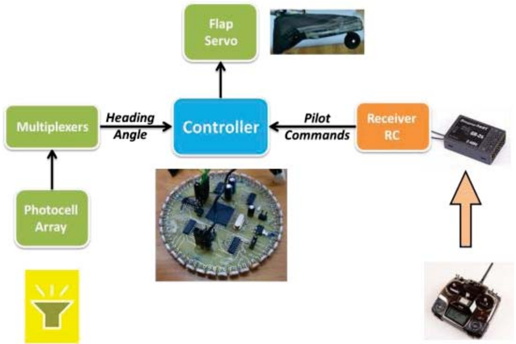

Fig. 5 Schematic of system hardware

The flapping mechanism in monocopter is very similar to the helicopter cyclic system. In some systems such as helicopter, when the command is applied to one side of the flap, the system is inclined to the opposite side.

For assessing the flapping mechanism, several tests have been carried out on the stand and effectiveness of commands and system performance was fully tested (See Fig. 6). It was found that the effectiveness of control commands is exactly similar to the helicopter cyclic system [7], [8].

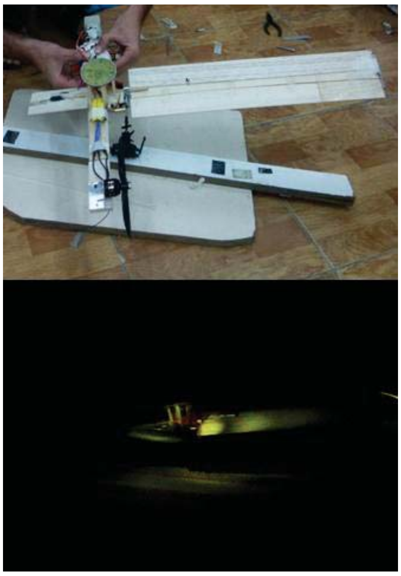

Fig. 6 The performed tests on the stand

Considering the commands which are applied by the pilot and the heading angle of the system, the flying vehicle flap will be activated in special interval while it will not be active in other states. The main consideration in this control method is the transition time of the servo-flap. So in the higher rotational speed, the system may completely loose its performance.

It was discovered in the flight test of monocopter system that due to the complex nature of gyroscopic dynamics, there is a Phase lag in the system. The value of this Phase lag is the function of moment of inertia and the rotational speed of flying vehicle [3], [4], [8].

As shown in Fig. 7, if the external light source be located in front of the pilot and at the same time the forward commands be applied by the pilot with the stick, the monocopter will flaps in an arc of 60 degrees at 12 o'clock of the pilot and will not be active in other states. It is obvious while the pilot applied the left ward commands to the stick, the monocopter will flaps at 9 o'clock of the pilot. That's because of the 180 degrees of phase lag compared with the helicopter cyclic system.

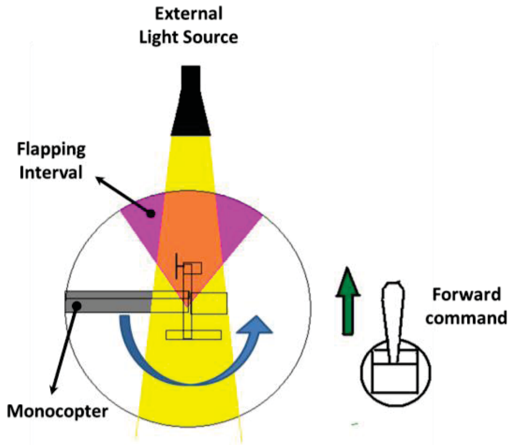

Fig. 7 The schematic of phase difference of commands in the system

In the next charts detailed explanation about monocopter control rules would be provided.

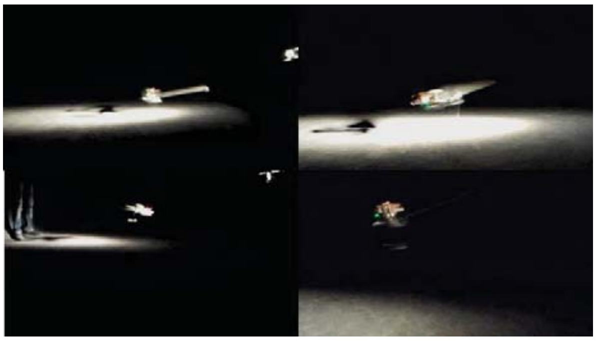

Fig. 8 Prototype Monocopter with Optical control system flight tests

III. CONSTRUCTION OF THE MAIN FLYING VEHICLE

After constructing the initial prototype of monocopter and performing the flight tests and its control algorithm test, and also due to the obtained designed points & results, we decided to build an advanced prototype of monocopter which its requisites are increasing the static stability of the system and improving of its aerodynamic design. The purpose of the designing this system was the design and construction of the prototype which could carry on the final avionic payload with lower angular velocity than the rate gyroscope's saturation.

For building this Air-vehicle the Balsa wood and the carbon fiber spar have been used. Due to effect of wind speed on the flying vehicle wing and flying vehicle dimension, the Low-Reynolds No. airfoils have been employed [9], [12]. Due to the high relative length of wings and great difference of linear speed between two wings and also for linearization of lift force along the wings, the 25 degrees of twist has been considered for the main wing in final design.

TABLE I
DIMENSIONAL CHARACTERISTICS OF FLYING VEHICLE

Frame Length	151 Centimeters
Wing span	81.5 Centimeters
Wing width	12-19 Centimeters
Fly-bar length	21 Centimeters
Fly-bar width	19 Centimeters
Flap width	3.5-9 Centimeters
Flap length	64 Centimeters
Stabilizer length	75 Centimeters
Weight	1210 gr

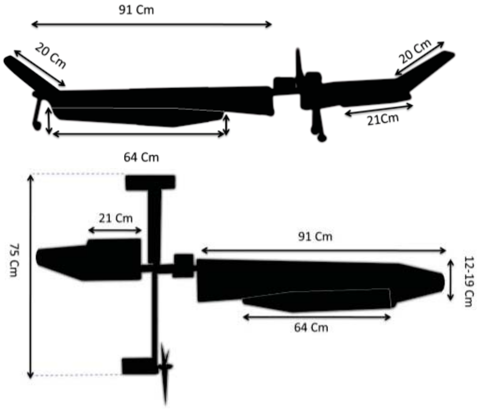

Fig. 9 Three-dimensional plan of flying vehicle

A brushless DC electrical motor with the maximum of 1.6 kg thrust force has been employed as a forward driving force in this system. The average rotational speed of this system is about 950 degrees per second. This rotator motion will produce a little gyroscopic force due to the distribution of masses and moment of inertia in the system. On the other hand this factor increases the system stability and also causes the influence of some nonlinear parameters in the system control.

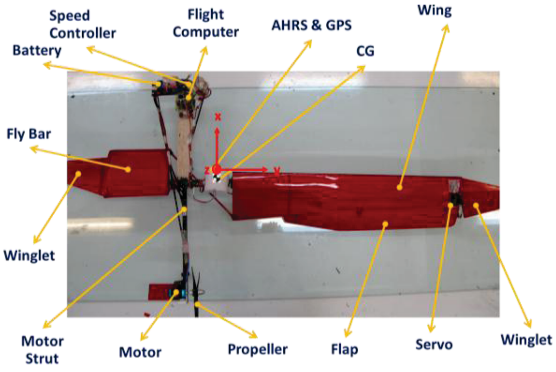

Fig. 10 Equipment configuration in the system

The setting of the center of gravity in this flying vehicle is an important and precise factor. If the center of gravity of the system is further away from fly bar, the cone angle of flying in the system will increase (See Fig. 11). In this circumstance, the system stability will increase in one hand and in the other hand, the system controllability will decrease. In addition, the lift of wing, area and standing angle of winglets will be effective in determination of flying cone angle in the flying vehicle [10], [11], [6].

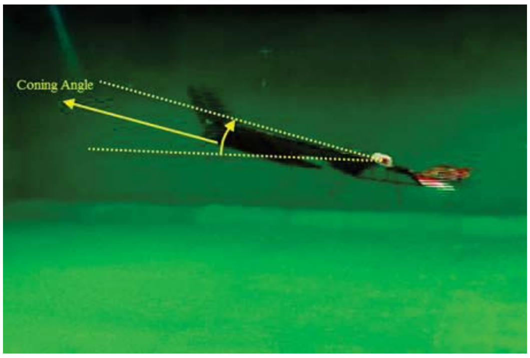

Fig. 11 The flying cone angle

In this system, an actuator has been used which is installed on the single existed flap of the system. For this purpose, a high speed electrical servomotor has been used. This servomotor (Align DS520) is the product of Align Company and specifically is used for control of unmanned helicopter's tail in which the commands are received with the frequency of 250 Hz and the response time of the system for 60 degrees of rotation is 70 milliseconds. Therefore, due to this fact that the required angle of flap deflection in this system is about 20 degrees, it can be expected that this rate of change applies in the time of about 30 milliseconds. This time range is one of the fundamental restrictions of the control of rotator systems.

IV. AVIONIC HARDWARE

The hardware of the avionic system is composed of a MTi_G[2] MEMS GPS aided AHRS for measuring the attitude angles, heading and position of flying vehicle, a flight computer, an RC radio control receiver and RF modem for monitoring and data acquisition.

The flight computer is constituted of SAM7256 ARM microcontroller and ATxmega64 microcontroller. The task of flight computer is the generation of control commands for flying vehicle and the communication management among all systems. The control commands which are applied by the pilot in the ATxmega64 microcontroller are received in the form of PWM signals via the radio control in the flight computer. These commands are transmitted to the ARM microcontroller. The ARM microcontroller receives the data such as attitude angles, heading and the flying position from AHRS and GPS via a serial port. Then, considering the commands which are applied by the pilot, appropriate control algorithms are performed by ARM microcontroller. So, the PWM command required for servo-flap is calculated and generated in an appropriate time. Finally, the required data for system

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[2] A MEMS GPS aided AHRS that manufactured by **xsens**.

monitoring in ATxmega64 microcontroller is collected and then transmitted to the ground station via the short-range RF modem of 900 MHz with 38400 baud rate (see Fig. 13).

The ground station (Fig. 12) is also composed of an RF modem, an interface circuit including an ATxmega64 microcontroller and a personal computer (PC). The ATxmega64 microcontroller is communicated with the avionic system via an RF modem and receives the flight information. Then, it sends this data to the PC. In addition to data saving, the implemented software in the PC can display some information visually by a GUI. This software was implemented in C#.net programming environment which provides the possibility of data communications between the user and the avionic system.

So the pilot applies the control commands for moving towards left and right or up and down and commands for motor speed (Throttle) with radio control. The throttle command is applied directly from radio control to the speed control system. The other commands are received by flight computer in which appropriate control operations are performed considering these commands.

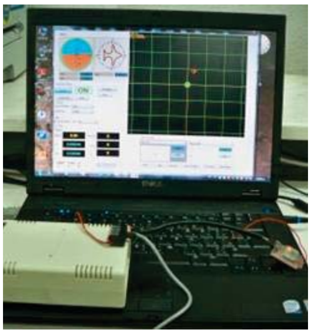

Fig. 12 The ground station

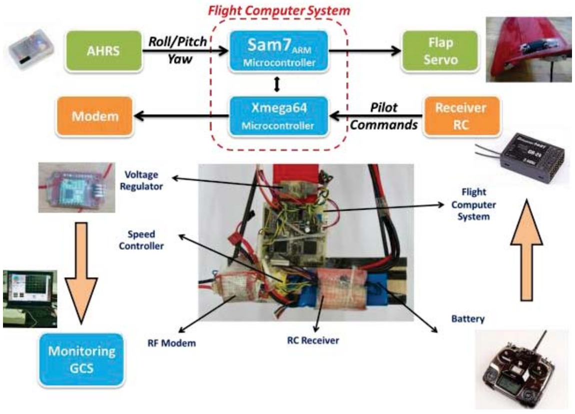

Fig. 13 The schematic of system hardware

V. CONTROL THEORY

As stated before the most important factor in monocopter control is the identification of heading angle of flying. In this system, AHRS and GPS have been used for this purpose. This structure acts as a very fast compass which gives the data such as attitude and heading angles to the flying vehicle [1].

Considering the commands which are applied by the pilot and the heading angle of the system, the flying vehicle flap will be activated in special times while it will not be active in other states. The main considerations in this control method are the constraints of rate gyroscopes; the data updating rate of sensors system and the required transition time for the flap's servo since only 40 milliseconds exists for commands applying in each cycle [1].

In AHRS, the rate gyroscopes with 1200 degrees per second and 18 g linear acceleration input are used. So in the monocopter design, it should be considered that the maximum of system angular velocity should not exceed this amount. For considering this fact, the flying system was designed and constructed in such a way that it could fly with less angular velocity than this range, so that the stability will be achieved. Also, AHRS in the flying vehicle must be installed as possible to the nearest place to the center of rotation so that the minimum linear centripetal acceleration will be applied to the system.

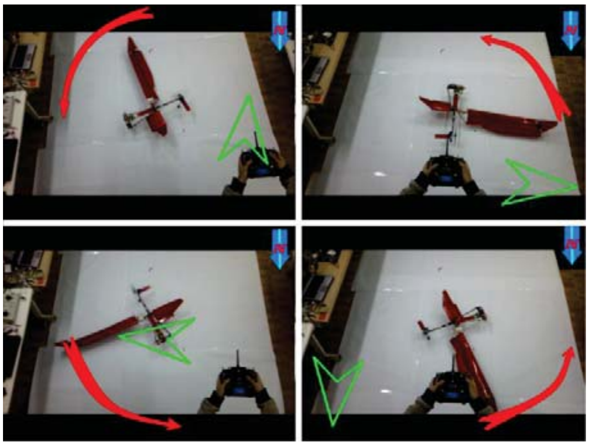

Fig. 14 The schematic of commands phase lag in the system

For instance in the main system, in the state in which the pilot stands to the south ward, in order to be able to interpret the commands, if the commands to the top position is applied to the stick, the flap command must be applied on the second quarter of trigonometric circle. That's because of the 270 degrees of phase lag compared with the helicopter cyclic system.

Also, when the command to the left position is applied by the pilot, the flap command must be applied on the third quarter of the trigonometric circle. The commands to the down and right positions are also applied to the flap in accordance with the phase lag. (See Fig. 14).

Fig. 15 illustrates the main control structure of system. The bottom block of diagram, indicates the role of pilot in the system. The Roll and Pitch axis control commands in the inertial coordinate system are applied by the pilot to the Control Rules1 block. This block includes the main control rules of monocopter which has been implemented as some nonlinear conditional rule. These rules due to the applied commands from the pilot and received feedback from the heading angle indicate the flap actuator position Fig. 16. The existed relay symbol in the block diagram represents that the flap actuator commands applied in fully deflection. And it has three states; up, down and zero. The dynamic model of flap actuator has been shown in servo dynamic block.

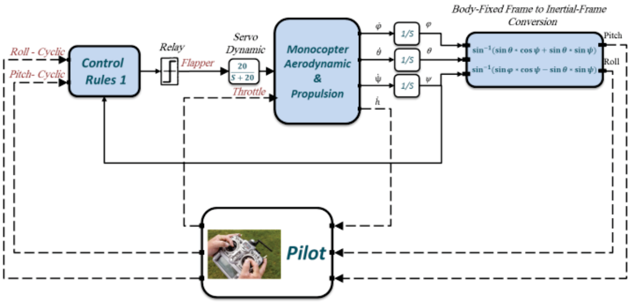

Fig. 15 The main control structure block diagram

The flap actuator commands which applied on the monocopter dynamic model caused the attitude angle changes in the body coordinate system.

Due to continuous rotating of body during the flight, this information will not be interpretable for the pilot who is an outside observer. The conversion of body coordinate system to inertial coordinate system (1) is done by the control unit and it causes the system to be interpretable or observable for the pilot.

$$\begin{aligned}\theta_{inertial} &= \sin^{-1}(\sin\theta_b * \cos\psi_b + \sin\theta_b * \sin\psi_b)\\ \psi_{inertial} &= \sin^{-1}(\sin\varphi_b * \cos\psi_b - \sin\theta_b * \sin\psi_b)\end{aligned} \tag{1}$$

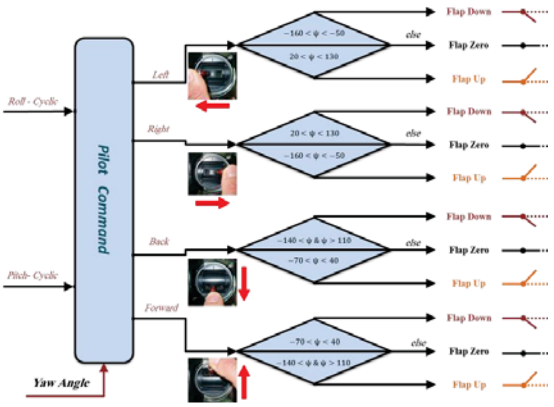

Fig. 16 Nonlinear conditional rules of control structure

The equations of this coordinate conversion have been illustrated in block diagram. The pilot with observing the Roll and Pitch angles in inertial coordinate system applies the control commands thus the Roll and Pitch control loops are implemented. Rotational speed and height of monocopter is controlled by the throttle command.

VI. PROJECT DESCRIPTION

In this project, after preparing the air-vehicle and the hardware of control system, the presented control algorithm was implemented on the system and the control parameters were set by using several tests. As referred in previous sections, this system is hovering with the average rotational speed about 950 degrees per second. Increase and decrease in rotational speed causes the lift force of the flying vehicle to increase and decrease and consequently, increases and decreases the height of flying. Therefore, as the rotational speed is directly proportional with the thrust force of the motor, the pilot can regulate the height of the system by setting the throttle command.

It should be noted that due to the limitations of actuator transition time, the overgrowth in angular velocity can drive out the system from controllability and on the other hand the undergrowth of this parameter may threaten the flying vehicle stability and robustness.

The illustrated curve in Fig. 17 shows the rotational speed of the monocopter in a short flight. Also, the variations of yaw angle of flying vehicle are shown in Fig. 18. This curve indicates the rotational motion of the flying vehicle that causes the yaw parameter to vary permanently between -180 and +180 degrees.

The points A and B in Fig. 17 represents the time when the pilot has applied the control command. So during this time span, the drag force increased in some time intervals of the flying due to the flap angle variation and subsequently, the rotational speed of the system has also decreased. In the curve of Fig. 19, the roll and the pitch parameters are illustrated during the flight. It can be deduced from this data that the AHRS system operates well and it is not in a malfunction situation. It can be observed that in control command, the flying vehicle pitch angle variation (which represents the angle of attack in the wing) increases. Gradually, this variation grows till the command is interrupted and the system returns to the stable flight state. The existence of the delay in control response of this parameter is due to the dynamic lag of the system which is creates because of the stability of the gyroscopic motion and the large size of the flying vehicle. The acceleration variations in X-axis and Y-axis are mostly due to existence of center-oriented acceleration. This factor mostly effects on the Y-axis (the axis of wing frame). As seen in Fig. 20, the maximum of this parameter is less than 2 (g) which is somewhat due to error of AHRS emplacement.

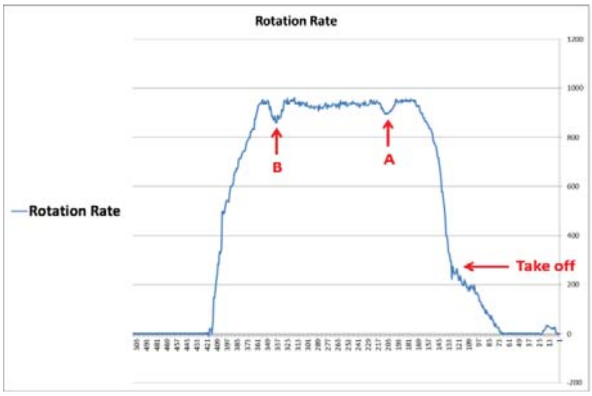

Fig. 17 The curve of system rotational speed variation

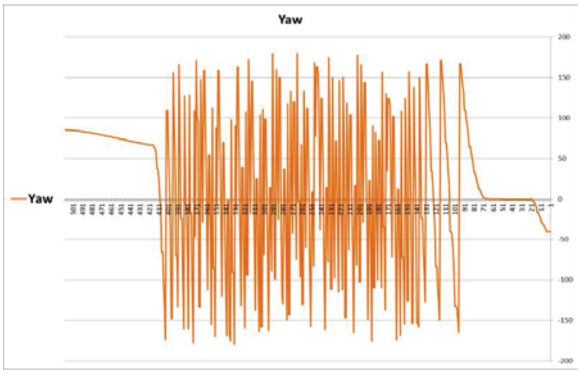

Fig. 18 The curve of system yaw angle variation

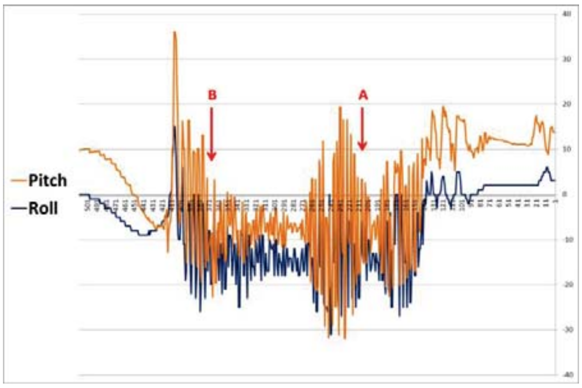

Fig. 19 The curves of system roll and pitch angles variation

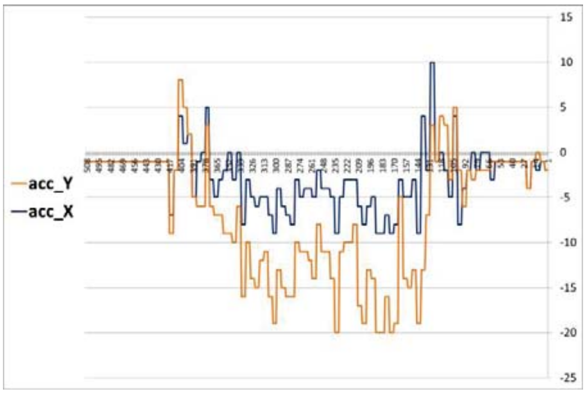

Fig. 20 The curves of linear acceleration variations

VII. CONCLUSION

- It should be noted that due to the limitations of actuator transition time, the overgrowth in angular velocity can drive out the system from controllability and on the other hand the undergrowth of this parameter may threaten the flight system stability and robustness.
- It was observed that rotation's speed variation changed the amount of system phase lag.
- Using of wing-lets which is installed on both tips of wing and Fly-bar is increasing the lift force by collecting air disturbances at the wing tip and also increases the lateral stability.

VIII. REMARKS AND SUGGESTIONS

In order to extend and develop this system and in continuation of the activities which carried out previously, for instance with upgrading the AHRS attitude angle measurement system and increasing the saturation of rate gyroscope, the control loops of roll and pitch angles could be implemented (which are flight cone angle and wing angle of attack, respectively). If these parameters are controlled, the flight stability can be provided without using any fly-bar. Thus, with fly-bar and motor strut omission, it will be possible to build smaller and faster samples. Then this system design will be more similar to the system which is constructed by Lockheed Martin Company. Since this model is naturally unstable, the implementation of angles control loops is essential for its stabilization [13], [14]. The sample of this flying model has been built for completing the pervious investigations and its inherent instability was observed.

In performed flight tests, the accuracy of GPS operation observed by the ground control station in flying state and it was found that there is the possibility of the implementation the GPS guidance loops. Therefore it could be possible to implement the monocopter fully autonomous flight.

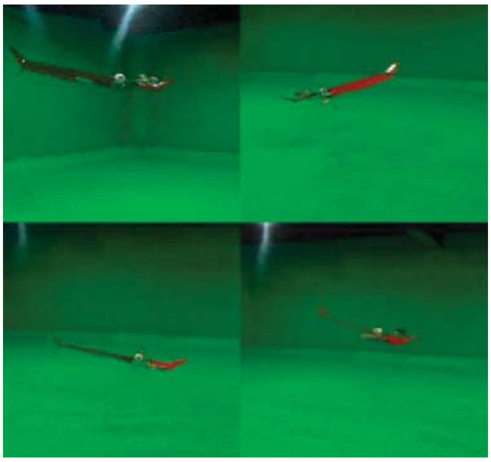

Fig. 21 The main monocopter system which controlled by AHRS in flying state

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