Last updated on April 5, 2018

ROBUST ADAPTIVE CONTROL DESIGN FOR UNMANNED HELICOPTER TREX-600E AT HOVER AND POSITION TRACKING

Klayli Jaafar, Salarieh Hassan[1], Alasty Aria [2]
Dept. of Mechanical Engineering,
Sharif University of Technology,
Tehran, Iran
jaafar.klayli@mech.sharif.ir

***Abstract*— This project presents a nonlinear robust control design method for TREX-600 unmanned helicopter. The control objective is to let the helicopter hover and track some pre-defined time-varying positions. The proposed controller employs feedback linearization process to realize the dynamic decoupling control and applies adaptive sliding mode control to compensate for the parametric uncertainties and external disturbances. The global asymptotical stability is proved via Lyapunov stability analysis. The performance and robustness of controller is evaluated through numerical simulation in the presence of parametric uncertainties and unknown disturbances. A 4-DoF tester is used to carry out real flight tests and a necessary electronic unit is implemented for real flight experiences. The results is compared with those of linear controllers.**

***Keywords*—sliding mode; Robust Control; Adaptive Control; feedback linearization; RC helicopter; Lyapunov stability; Hover, Waypoint Tracking.**

1. INTRODUCTION

Miniature unmanned vehicles (MUVs) are becoming popular due to their compact size, high maneuverability and high size-to-payload ratio. This is especially true with Vertical Takeoff and Landing (VTOL) vehicles due to their distinct capabilities to maneuver in any direction and to hover, even in highly confined areas [1]. From all classes of MUVs, miniature unmanned helicopters (MUHs) have advantages over fixed-wing UAVs because they take-off and land vertically, they do not require a runway, and they have the ability to hover and fly in low altitudes [2]. However, the control of MUHs is a challenging problem due to a large number of states and parameters, unknown nonlinearities, and couplings in their dynamics that make it important to design robust nonlinear controllers. Since the number of inputs are less than degrees of freedom (DoF), MUHs are considered underactuated systems. Therefore, Robustness is one of the critical issues which must be considered in the control system design for such high-performance autonomous helicopter, since any mathematical helicopter model will unavoidably have uncertainty due to the empirical representation of aerodynamic forces and moments [3].

Arlinghaus has derived a 13-state dynamic model of TREX-600 MUH using the Extended Kalman Filter (EKF) where a novel, state of the art hybrid PID/LQR controller is developed and compared with a full state Linear Quadratic Regulator (LQR). The hybrid controller uses a proportional position, PID velocity outer loop coupled with an inner loop LQR for attitude control [4]. Tao considered an adaptive PID control strategy of TREX-600 14-state model at hover and postion tracking [5]. Miranda has linearized the nonlinear model of TREX-600 about hover conditions and has designed a PD controller for hover and trajectory tracking [6]. . In spite of its proven robustness, the Sliding Mode Control (SMC) suffers from the inherent disadvantage of high-frequency oscillations of the control signal known as chattering [7]. This problem makes the implementation of SMC impossible for electromechanical systems as high-frequency oscillations can actuate unmodeled dynamics of the system and cause mechanical wear in it. However, evolution of SMCs of second as well as higher order conquered this problem of chattering to a large extent [8]. Some algorithms, which propose a solution to the above control problem, have been presented in [9]. Because the high order SMC requires complex calculations, a chattering free sliding mode control (CFSMC) based on adjusting the sliding condition can be obtained from Lyapunov stability theorem.

Feedback linearization (FBL) is an approach to nonlinear control design in which a nonlinear state feedback control law is applied that, in principle, cancels all system nonlinearities. However, to perform FBL, the system nonlinearities must be completely known, including their derivatives up to some order depending on how they enter the dynamics. This is a potential problem in flight control since the aerodynamic forces and moments cannot be modeled precisely. To achieve robustness against such model errors, the combination of FBL and SMC (FLSMC) is proposed to augment the FBL controller [10].

This work presents the development of a control strategy for the RC helicopter TREX-600 that is capable of hovering and, in

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[1] Corresponding author. Tel: (+98) 21- 66165538
E-mail address: salarieh@sharif.edu
[2] Corresponding author. Tel: (+98) 21-66165504
E-mail address: aalasti@sharif.edu

the future, waypoint following. Real flight tests will be implemented and the results will be compared of those of linear robust controller based on H∞.

The remainder of the paper is arranged as follows. Section 2 describes the dynamic model and the parameters of the system are specified. In Section 3, the candidate technique to control the model is carried out. In section 4, the RC helicopter tester is studied and explained. Finally some conclusions are presented in section 5.

2. DYNAMIC MODEL

The helicopter TREX-600 is shown in Fig.1 and its parameters are shown in Table 1. The RC helicopter mathematical model can be derived from [11]. There are many methods to model a RC helicopter which are: an analytical method, an approximated model with considering the flapping angles, and a simple method without considering flapping dynamics. The first method is too complicated that makes the control design impossible, but it is a suitable frame to test the control performance, and the third method is trivial and not effective. Therefore, in this thesis the second method will be used along with the system (parameters) identification. It is worth mentioning that the flapping dynamic can be neglected at hover. The helicopter can be considered as a rigid body that has 6 DoFs, but there are subsystems which affect the whole dynamics of the helicopter: tail rotor, main rotor, and Heading Hold Gyro (HHG). The influential subsystem is the main rotor and its flapping angles under the cyclic movement. Gyro and tail rotor are also a subsystem that add a state to the system. After the modeling process, a 17-state variable dynamic model is obtained. The model diagram is shown in Fig.2. In this figure, it is obvious that the helicopter has four control inputs: 3 servo motors for the swash plate and one servo motor for the pitch angle of the tail rotor. Furthermore, the brushless motor is controlled by the speed controller which is also controlled by a throttle input. In the beginning of real tests, the system identification will be based on the results of [12], but after that the parameters will be evaluated and modified using the results of real tests.

As a matter of fact, flapping angles are unknowns and have to be estimated. Consequently, a Kalman filter, estimator, is added to the model which will be simulated in MATLAB/SIMULINK software. This simulation will be applied to the analytical dynamic model as it is more realistic.

Figure 1. TREX-600 RC Helicopter

Table 1. TREX-600 main parameters

Gear ration: Motor: Main Rotor: Tail Rotor	Tail Rotor	Main Rotor Diameter	Main Rotor Propeller length	Width	Height	Length	Mass
1:8.61:3.85	260 mm	1347 mm	600 mm	210 mm	319 mm	1160 mm	2840 gr

In this thesis, the tester of [13] will also be used for preliminary real flight tests, but it needs some enhancement elaborated upon in the fourth section. Furthermore, required sensors and a microcontroller to implement the control algorithm will be designed and installed. The process of modeling, control, and verification is shown in Fig.3.

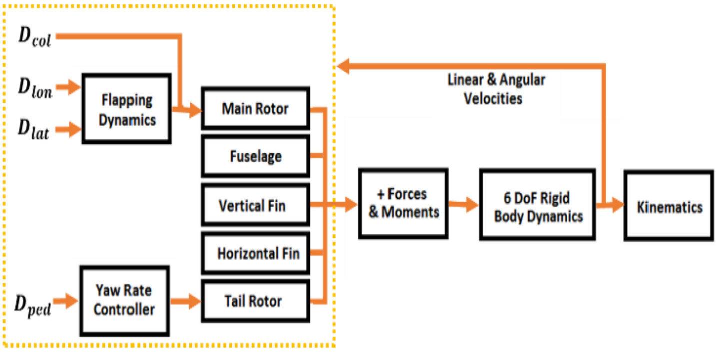

Figure 2: Dynamics model diagram including the 4 input signals

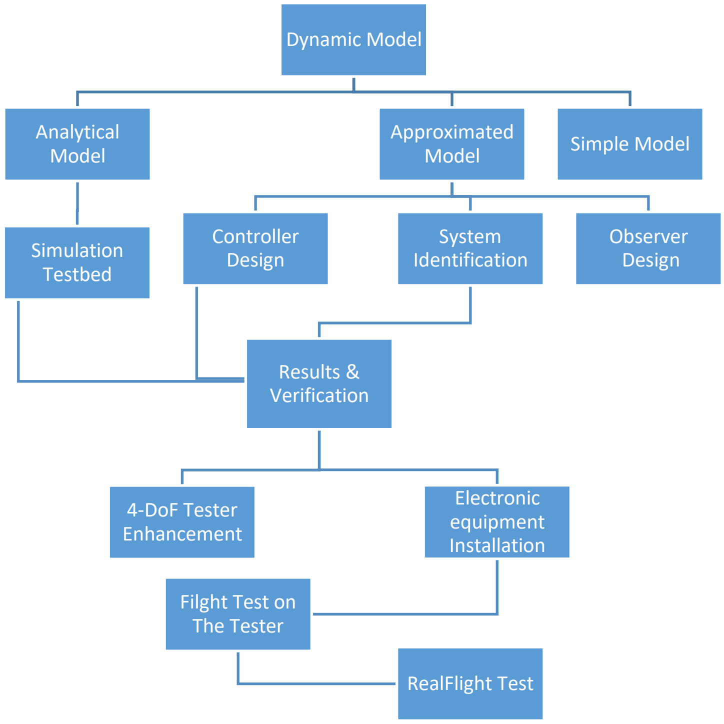

Figure 3: The main steps of the present thesis

3. CONTROL DESIGN (NOT FINISHED YET)

3.1 Control Objective

The primary flight control objective is to design the four control inputs for the TREX-600 MUH to hover and to track a reference position (waypoint tracking), while keeping the stability of the closed-loop dynamics.

3.2 Control Design

The best algorithm to control a RC helicopter is to divide the whole dynamics into two parts: one part consists of the fast dynamics and the second part is the slow dynamics. Generally, an inner loop for fast, rotational dynamics and an outer loop for slow, translational dynamics will be considered (Fig.4). The inner loop plays an important role in the stability of the system and then a robust control must be considered for it.

To do so, there are 3 proposed methods: the first is a stochastic controller to control the nonlinear dynamics with the stochastic disturbance, but this method is not easy and can take more time that is already little. The second method is what explained below and in the abstract. The problem of this method is the presence of chattering because of using the sliding mode controller which is not smooth. The third method that I prefer has the same idea of the second one but a Slotine controller is used instead the sliding mode controller. This substitution, to ensure the stability of closed-loop, needs more mathematic and algebra analysis, so it is not an easy task.

3.2.1 FEEDBACK LINEARIZATION

The main idea of FBL strategy is to modify the system structure, so that the closed-loop control system transformed into a fully or partly linear one in which linear control techniques can be applied.

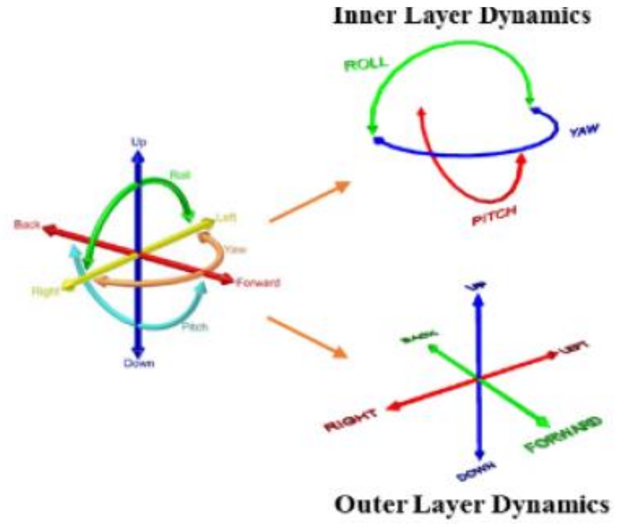

Figure 4: Layered Dynamics for cascade control

For the underactuated helicopter dynamic model, the relative degree of the system (r) is not equal to the system dimension (n), then the system is not fully feedback linearizable and there are (r-n)-D zero dynamics. To solve this problem, the dynamic extension procedure will be used.

3.2.2 SLIDING MODE ADAPTIVE CONTROL (SMAC)

In this section the translational position tracking error and its high order derivative will be defined and sliding surfaces will be considered. Control and adaptive laws are designed and the the global asymptotic stability is proved by a suitable Lyapunov function.

4. RC HELICOPTER TESTER

The objective of having a tester is to improve the safely and to have a second source of data for the validation stage. The tester of [13] is a 4-DoF tester which simulates pitch, yaw, roll, and heave motion of helicopter. Two encoders were used to measure pitch and roll angles and a potentiometer was used to measure the heave motion. Two torque converters designed by pulleys and belts were used to improve the resolution of encoders (Fig.5). But, this tester had many problems that are listed below:

- The calculations of torque converters were wrong. Actually, there is no need to such mechanical converters (for a quadrature encoder, every cycle or revolution has 4 count).

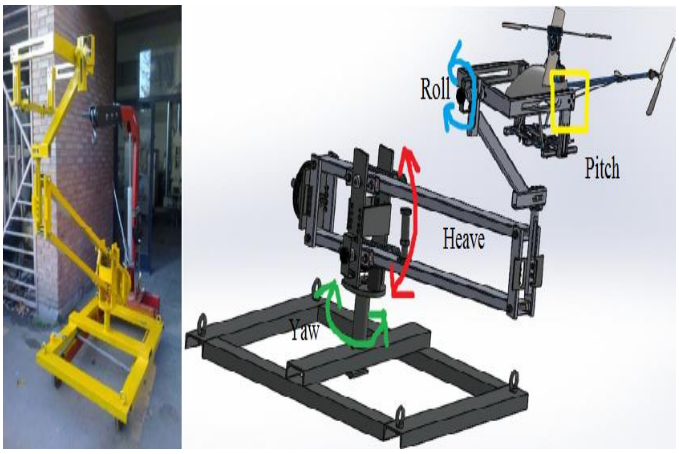

Figure 5: The RC Helicopter Tester of [13]

- There is no sensor to detect the motion of yaw and to measure it.
- The potentiometer of heave motion is not mechanically installed.
- The flexible coupling of pitch encoder has tough “shaft misalignment”.

These problems were solved by the following steps:

- The structure of the tester has been enhanced by removing the mechanical converters which add another dynamics to helicopter being tested.
- Installation of the two potentiometers in order to detect the yaw and heave motion.
- Lubrication of ball bearings.
- Adding big rubber casters to make the tester mobile.

An Arduino board has been used to measure all the 4 motions. The enhanced tester is shown in the figure 6.

For a real flight test, and because the helicopter has no sensor (other than the HHG) and no control unit, a control and some necessary sensors like GPS, accelerometers, and gyroscopes unit must be added to the helicopter. In this work, a Raspberry Pi 3 as the control board, an Atxmega128a1 IC as the PWM generator, and the SNav-ADM[3] system of SDRA Co, Ltd Company as the inertial measurement unit (IMU). These components are shown in Fig. 7. By using MATLAB/SIMULINK, the model must be run in external mode, I mean on the Raspberry Pi 3, which in turn is connected via Wi-Fi to the computer, and via pins to the designed PCB of Atxmega128a1. A button is considered on the RC controller to switch between manual and automatic modes. Now, we, I and M. H. Khalesi, a PhD student, are working on Hardware-In-the-Loop Simulation (HILS) after getting desired results from the Software-In-the-Loop Simulation (SILS).

Figure 6: The enhanced tester

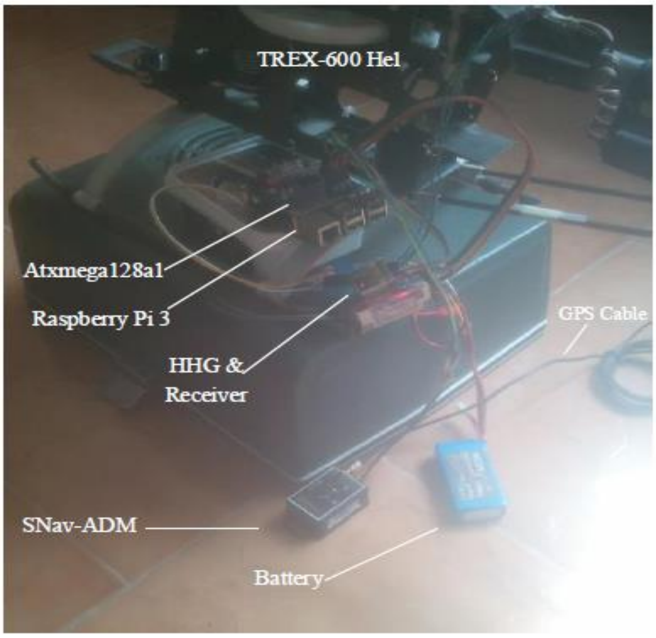

Figure 7: The electronic unit being tested

5. CONCLUSION

In this paper, control problem of a RC helicopter TREX-600 is developed via FLSMC. First an approximated dynamic model is derived and then the system identification and controller design is carried out. The performance of controller is evaluated by numerical simulations and real flight tests using a 4-DoF tester. The tester has many problems that must be solved and the necessary electronic unit to control the helicopter will be implemented. The results of the designed controller will be compared with respect to the results of other controllers like $H\infty$ controller.

ACKNOWLEDGEMENT

I would like to acknowledge and extend my gratitude to Professor Hasan Salarieh and M. H. Khalesi for the opportunity to work on this project.

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