Test Bed for Unmanned Helicopters' Performance Evaluation and Benchmarking

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***Abstract*— This paper presents an experimental test bed for the development and evaluation of autonomous helicopter controllers. The developed system is a custom laboratory construction which involves a small electric powered helicopter mounted on a flying stand, equipped with the set of sensors needed for real-time flight monitoring and control. Special attention has been paid to the safety of the test bed, as helicopter performance during test flights can be monitored, from a close distance, without the risk of accidents. This setup works indoors, regardless weather conditions, and can be used for performance evaluation and benchmarking of unmanned helicopters' stability, control and autonomy issues. To validate the use of this setup, a fuzzy logic based autopilot has been developed. The ability of this controller to perform autonomous hovering along with altitude control is evaluated and test results are presented and discussed.**

I. Introduction

Nowadays unmanned helicopters are an essential part in the field of experimental robotics. After years of development, the market of VTOLs includes vehicles of various types, sizes and operational capabilities that satisfy almost any needs [1]. Their advanced abilities (flexibility, aerobatic maneuvering, hovering) along with the multiple potential applications (both civil and military) have led many scientists to deal with the problem of autonomous navigation of these vehicles. The control of these vehicles remains a challenge for research teams that propose from time to time novel control techniques.

Recently, there has been a lot of discussion about the performance evaluation and benchmarking for intelligent robots [2]. The robotics society aims to find ways of building test beds where experiments on various fields of robotics will be accompanied by performance evaluation and benchmarking. The reason for this is that we need a way to compare different approaches. As unmanned helicopters are by far intelligent robots, it would be desirable to build a test bed where various control techniques for unmanned helicopters would be evaluated.

This paper presents a prototype test bed for unmanned helicopters, designed and developed in the Intelligent Systems & Robotics Laboratory of Technical University of Crete. This test bed has been primarily built in order to fill the gap between simulation runs and actual experimentation on real vehicles. Moreover, this setup can be used for performance evaluation and benchmarking of unmanned helicopters. In Section II, we analyze these two aims of our work.

II. Motivation

The development of autonomous navigation systems for unmanned helicopters is a difficult and high cost procedure. In this cost, except from the equipment needed (helicopter, sensors, telemetry systems etc) one should add the cost of crashes and damages that appear during experimentation. Since helicopters are very unstable and difficult to control systems, experimentation on real vehicles often result in crashes. For this reason, the development of an autonomous navigation controller involves numerous tests in a simulation environment. In this environment, controllers are evaluated for their ability to control efficiently the helicopter. If the simulation results are encouraging, the controller may be tested on the real vehicle.

The above procedure meets two difficulties. At first, the simulation environment cannot simulate the helicopter's navigation in detail. As a result, a controller that seems to work satisfactorily in the simulation may be inappropriate for the navigation of the real vehicle in a real environment. The second problem is that even if the controller is evaluated in simulation, first tests in the real vehicle are the most dangerous, since it is difficult to predict the controller's response in the case of (unexpected) disturbances. As a result, it would be desirable to test the controller in a real vehicle without having the danger of crashing and destroying the equipment.

In the past years, there have been proposed ways of testing controllers in a real vehicle safely. In the literature we meet two approaches. At first we meet mechanical constructions that simulate a real helicopter [3-5]. These mechanical constructions do not use real helicopters but

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simplified models able to emulate the dynamics and kinematics of a real vehicle.

Further in the literature, we meet systems that use real helicopters for the experiments [6, 7]. In these systems, a mechanical construction holds the helicopter in a stable position allowing only small and safe movements. Using mechanical limitations, the helicopter is able to move only in one or two axes and within limits. As a result the helicopter cannot take any dangerous orientation or collide to the ground. Both works have the disadvantage of allowing only two degrees of freedom in the helicopter movements.

Concerning the aspect of performance evaluation and benchmarking for unmanned helicopters, there has been presented some work [8], but we do not meet in the literature any test bed that works as a complete evaluation system for unmanned helicopters.

The motivation of this work/paper is the construction of a laboratory test bed where small helicopters can be safely (for both humans and the equipment involved) used indoors for experimental validation without limitations in helicopters' movement (6 degrees of freedom). Indoor flying gives the ability for continuous tests regardless of weather conditions. Another motivation is that the suggested test bed minimizes the need for experienced helicopter pilots within the research group.

Moreover, our aim is to build a complete setup for benchmarking on control techniques of unmanned helicopters. This work will lead on a comparison through evaluation of various control approaches for unmanned helicopters. Since we use an electric power helicopter, this setup can be used for evaluation performance along with helicopter's autonomy.

III. ARCHITECTURE

The architecture of our test bed can be divided into three parts:

- Customized Flying Stand
- Customized Helicopter with Avionics
- Ground Control Station

A. *Helicopter Flying Stand*

For the unmanned helicopter mounting, a customized Whiteman [9] flying stand is used. The flying stand is all aluminum construction with ball bearings to allow smooth and easy movements to the helicopter (Fig. 1). The important with this construction is that allows the helicopter to move and rotate in all axes (6 degrees of freedom). The same flying stand has been used for other purposes in [10, 11], but it was not used as a test bed for control experiments.

The stand lets the helicopter move naturally without any constraint around a 2.1m diameter circle, flying forwards, backwards or sideways. A gas strut is used to counterbalance the weight of the stand. As a result the helicopter does not lift any extra weight.

Since the test bed is designed for indoor experiments, a positioning system must be developed in order to know helicopter's position (both horizontal and vertical) during testing. To avoid developing high cost indoor positioning and localization vision systems [12], we take advantage of the rotary movement of the central shaft of the stand. The stand and consequently the helicopter move around a circle (planar rotation at Fig. 1) with a rotation angle which may easily be monitored. For this reason, we reconstructed the central shaft of the flying stand installing a rotational encoder (odometer unit) on it (Fig. 2a). This encoder initializes its position to zero and then gives signed numbers that denote the actual position relative to the initial position. Positive numbers denote rotation to the left while negative numbers denote rotation to the right side. The use of this sensor gives us the ability to know at each time instant the planar (horizontal) position of the helicopter.

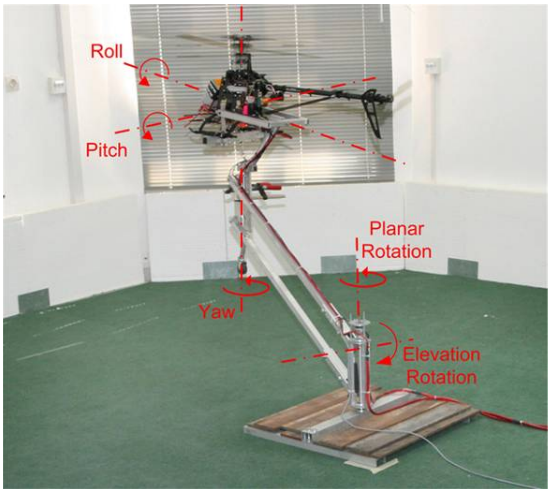
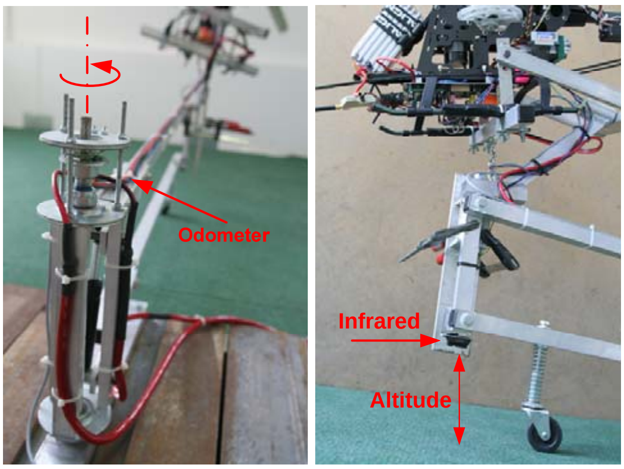


Fig. 1. The suggested test bed and its rotation axes.



a) b)

Fig. 2. Customized flying stand details: a) Odometer for planar positioning, b) Infrared sensor for altitude measurement.

Moreover, we need to know the altitude (vertical position) in which the helicopter flies. The flying stand gives the ability to the helicopter to fly to a maximum height of 60cm. To monitor the actual altitude we use an infrared distance sensor mounted at the lower part of the bracket that holds the helicopter, as it is shown in Fig.2b. This sensor gives altitude readings with accuracy less than 1cm, which is far better than the accuracy of outdoor altimeters or GPS.

B. *Helicopter and Avionics*

The VTOL that we use in our test bed is a customization of the commercially available RC helicopter T-REX 600 Carbon Fiber edition, constructed by Align Corporation. This is a 50-size helicopter designed for competition aerobatics, able to make difficult maneuvers and move precisely in the 3D environment. The greatest characteristic of this helicopter is that it has electric power system so there is no need for fuel gas, and therefore it does not produce any exhaust gasses during its operation, which is important for indoor testing. The technical specifications of the T-REX 600 helicopter are listed in Table I.

TABLE I
TECHNICAL SPECIFICATIONS OF THE T-REX 600

Length	1200 mm
Height	405 mm
Main Blade Length	600 mm
Main Rotor Diameter	1350 mm
Tail Rotor	240 mm
Engine	Align 600XL Brushless motor
Weight	1610 g
Payload	2 kg
Autonomy	15 min (hovering)

This helicopter has been heavily customized in order to be ready for experimental use. In what follows we describe the additional equipment and avionics we put on board.

1) *Inertial Measurement Unit (IMU)*

This unit gives the orientation of the helicopter. The commercial product MTi from Xsens Motion Technologies has been used. The MTi is a miniature, gyro-enhanced Attitude and Heading Reference System (AHRS). Its internal low-power signal processor provides drift-free 3D orientation, calibrated acceleration, rate of turn and earth-magnetic field data. The unit consists of 3D gyroscopes, accelerometers and magnetometers and also outputs the 3 Euler angles (roll, pitch and yaw). For the communication between IMU and control station a USB-serial data and power cable is used.

2) *Digital Switch*

This is the interface that manages the switching from manual to autonomous flight. Manual flight is controlled remotely by a human operator, while autonomous flight is supervised by a Central Processing Unit (CPU). Switching between manual and autonomous flight is an important operation because it allows the human tester to regain manual control at any time instant during experimentation. This function might be very useful in case of failure or insufficient controller behavior.

3) *Servo driver/controller*

RC servos are the actuators used to control the motion of the helicopter. In manual operation, the onboard receiver gets the transmitter commands and sends the appropriate signals to servos in order to accomplish the operator’s input. In order to send such signals from the control station to the servos, a servo driver is needed. For that reason an OOPic microcontroller is used, which translates control signals from the ground station to RC servo signals and drives the servos. Further, the OOPic reads the input from the localization system (x-y position, altitude) and sends it to the control station.

4) *Communication System*

A wireless communication system has been established between the control station and the OOPic microcontroller. Having 2 receiver/transmitter units (one on the helicopter and one on the ground station) and by using the Bluetooth protocol, we obtain two-way communication between the serial port of the OOPic and the serial port of the control station.

5) *Power System*

T-REX 600 has high power consumption. During hovering, the electric motor needs about 50A current of 25V. Normally in these helicopters, LiPo batteries are used. These batteries have high capacity and the ability to sustain big currents. With this consumption and with a high capacity LiPo battery, T-REX can perform hovering for about 15 minutes. To overcome this limitation in the duration of experiments, the test bed is provided with constant power supply. For this reason we use a power supply of 24V that through wires gives continuous current to the helicopter. However, the use of batteries for experimentation is possible, in order to have the ability to perform experiments on evaluating performance along with autonomy. This is critical, since a helicopter flying outdoors cannot have unlimited power supply and autonomy must be taken into account in the control procedure.

C. *Ground Control Station*

Since our test bed works indoors and we can have all the signals through wireless communication (expect from the IMU), there is no need to put any processor unit onboard. For this reason we use portable CPU which serves as the “control station”. Because of this solution, the helicopter has fewer payloads to lift, while the control station has increased processing power able to run control algorithms at high speeds. This station also serves as the monitoring unit during experiments. All sensor data are collected and evaluated in real time, while they are saved for offline evaluation and cross reference.

D. *Connection of the subsystems*

Figures 3 and 4 show the interconnections of the test bed. Odometer and infrared sensor are mounted on the stand and they are connected to the OOPic through wires which do not block the movements of the stand. OOPic, IMU and Bluetooth modem are mounted on the bottom of the helicopter fuselage. The only wired connection between helicopter and control station is the one with the IMU.

Moreover wires are used for the power supply of the helicopter as may be seen in Fig. 3. These wires also do not block the rotation of the stand.

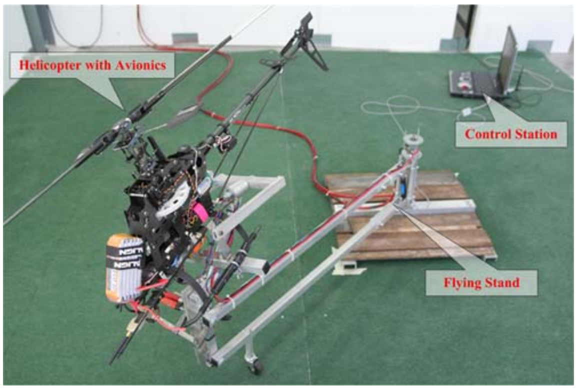


Fig. 3. The complete helicopter flight control test bed.

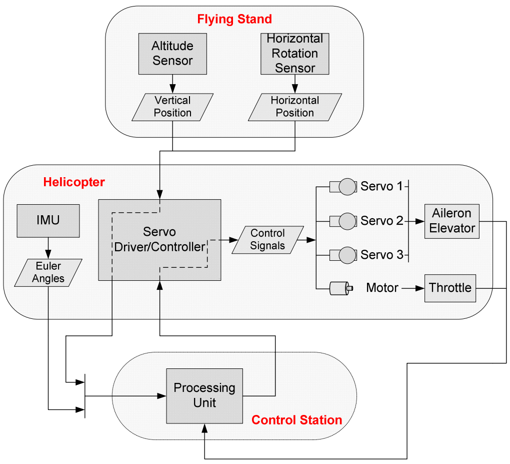


Fig.4. Connections between subsystems.

IV. Safety

Safety is a very important issue that must be carefully considered when handling model helicopters. A model helicopter is potentially a very dangerous piece of equipment since it's rotor blades may spin at over 1.700 rpm. Even the most experienced pilots might make a mistake or experience various failures that may cause severe property or physical damage and in the worst case serious injuries. When a helicopter crashes, several parts break and spread all over the crash area.

The potential hazard is even bigger when using unmanned helicopters for autonomous navigation. The use of a control system in the phase of development involves risks of insufficient control that may result in unexpected behavior, and even if a safety pilot is standby to take control of the vehicle, accidents may be difficult to avoid. For this reason, safety was carefully taken into account in the development of the test bed.

In our case, the experimental test bed is designed to work indoors. Even though the helicopter is attached on the flying stand, which holds it in safe positions, we want to increase test bed's safety by securing appropriately the test bed area. For this reason a safety cage was built around the test bed area, so as to protect the human operator and people monitoring the experiments (Fig. 5). The cage is made of unbreakable glass that permits clear view of the test bed area. In the unlikely event of an accident or a malfunction where the stand fails to hold securely the helicopter, the safety cage will prevent any helicopter part to get outside the cage area.

This setup contributes to the safety of the test bed. It is the first test bed for unmanned helicopters that allows safe monitoring from short distance with clear view of the helicopter flight, movements and reaction to control commands. Further, operator has the ability to directly confirm sensor readings. As an extension, this setup can also be used for scenarios of faulty operation towards the development of new tools for detection, isolation and prevention of malfunctions.

Fig. 5. View of the safety cage.

V. Experimental Validation

In order to validate the appropriateness of the developed system as a flight control test bed, we started experimentation through the developing of easy-to-implement controllers. Since the test bed is a complex system and requires analytical study in order to derive an accurate dynamical model, we experimented with a fuzzy controller which does not require mathematical modeling. Fuzzy logic offers a modeling framework that allows for simple knowledge representation of the helicopter pilot controls in terms of IF-THEN rules. Therefore, fuzzy controllers may be developed very fast and they are capable of imitating human operators, as we have observed in the past [13-15].

A fuzzy controller of the Mamdani type has been designed and implemented (Fig. 6) in the MATLAB environment. The objective of this controller is to keep the helicopter at "hovering" at predefined positions subject to wind and other disturbances. Each position is defined by horizontal and vertical coordinates. Its design was based on the knowledge extracted from an experienced model helicopter pilot. According to acquired information the heuristic controller's inputs are the *roll* and *pitch* angles at every time instant, as well as the *position error*, *change of* *position error*, and *altitude error*.

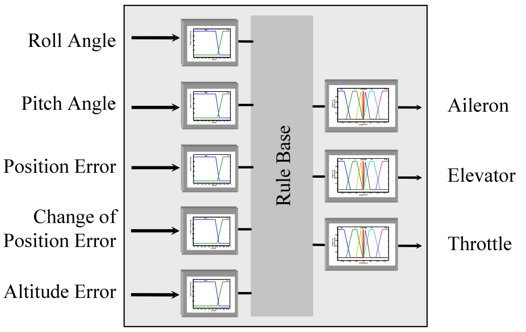


Fig. 6. Fuzzy Controller.

The first two inputs of the fuzzy controller, *roll* and *pitch* angles, are measured by the IMU in real time. The third input, *position error*, is defined as the difference between the current horizontal position and the target horizontal position (position error = current position – target position). *Position error* represents how far the helicopter is from the target point. The next input in the fuzzy controller, *change of position error*, represents how the position error changes and if the helicopter reaches the target point or moves away from it. This input is defined as the difference (in odometer units) between the previous position error and the current position error (change of position error = previous position error – current position error). The last input, *altitude* error, is also calculated as the difference between the current and the target altitude (altitude error = current altitude – target altitude). The outputs of the fuzzy controller are the changes of roll and pitch angles (*Aileron* and *Elevator* movements respectively) and *Throttle* change.

The control objective in the experiments performed was the stabilization of the helicopter at a specific point (defined by horizontal and vertical coordinates). After take-off the controller already has the target coordinates at which will hover the helicopter. Then checks the actual horizontal position first and second the actual altitude in order to drive the helicopter to the desired horizontal and vertical position. After some iterations in which the helicopter hovers at the target point, the controller lands it.

Monitoring of the input/output parameters for two test cases may be seen in Fig. 7 and 8. In these figures *Roll* and *Pitch* values are measured in degrees, while *Position Error* and *Change of Position Error* are measured in odometer units. *Altitude error* is measured in cm. *Elevator*, *Aileron* and *Throttle* values are measured in control signals (values that OOPic accepts as input and automatically translates into servo signals).

In **Test Case 1** (Fig. 7) the ability of the controller to perform autonomous take-off and keep the helicopter hovering in a predefined vertical position is evaluated. The helicopter is placed on the desired horizontal position by the human operator and then the autopilot takes over. The target altitude is set at 22 cm. The autopilot has to take-off the helicopter and reach the target altitude (vertical position), while keeping the helicopter steady in the horizontal position.

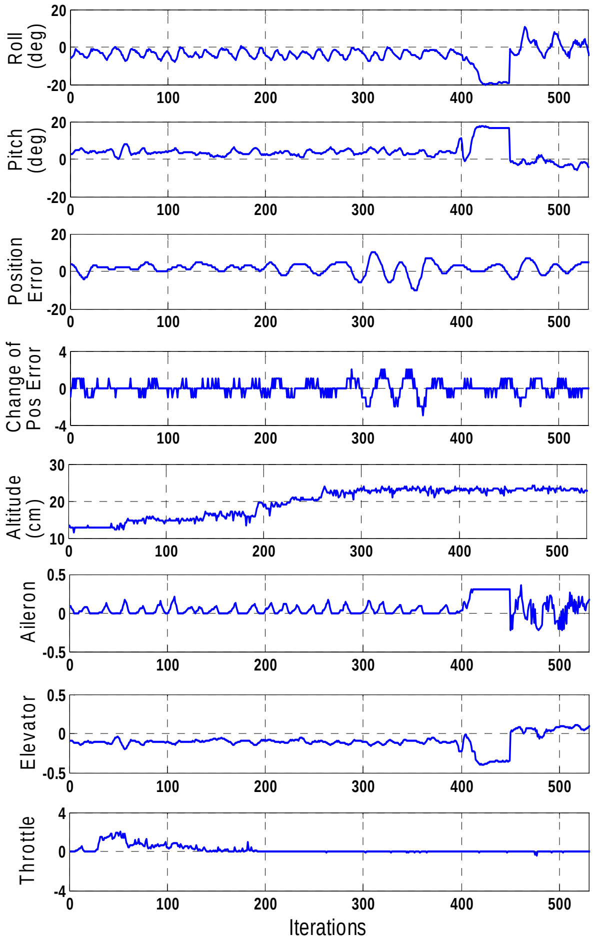


Fig. 7. Parameter's monitoring for the **Test Case 1**.

As it can be seen in Fig. 7, the helicopter is placed on the desired horizontal position. The controller keeps roll and pitch angles close to zero and gradually increases throttle, in order to increase the altitude and reach the targeted one. When the target altitude is reached, few oscillations around the horizontal position occur but the controller manages to hold the helicopter hovering in the desired position. Through this test case we observed that the controller manages to successfully accomplish its mission subject to the disturbances (air circulation inside the safety cage) that occur due to the indoor position of the test bed.

In Fig. 8, we present the results of **Test Case 2**. In this test case, the initial horizontal position of the helicopter is different from the desired one and the controller's ability to drive the helicopter to the desired position (vertical and horizontal), and then land it autonomously, is evaluated.

The helicopter is placed manually to a random position and then the fuzzy autopilot gains control of the helicopter. The target of the autopilot is to move the helicopter to the initial position and in 20 cm altitude. It is clear that the autopilot drives the helicopter to the target point by moving it to the desired horizontal position at first and then by raising the altitude until the targeted one has been reached. After a few iterations that the target position has been reached, the controller reduces the throttle and lands the helicopter. Small oscillations occur while the autopilot tries to keep the helicopter in stable position.

VI. Remarks

Some remarks after extensive experimentation with the suggested flight control test bed are summarized in the following.

First, regarding the functionality of the test bed, it proved that the test bed can be used indoors aiding the fast development of flight controllers. The test bed performed well even for aggressive tests (for recorded experiments check: www.dpem.tuc.gr/robolab/testflights). Further, as all experiments have been safely done it important to emphasize on the safety issues of the experimental test bed. Even when testing of aggressive flight controllers gave extremely agile maneuvers, the test bed proved safe for humans and equipment involved.

Moreover, the test bed proved that it can be used for performance evaluation and benchmarking. Human operators have the ability to collect and process data, either online or offline. Test bed is designed to be expandable and new features (more sensors, special benchmarking programs) can be easily added.

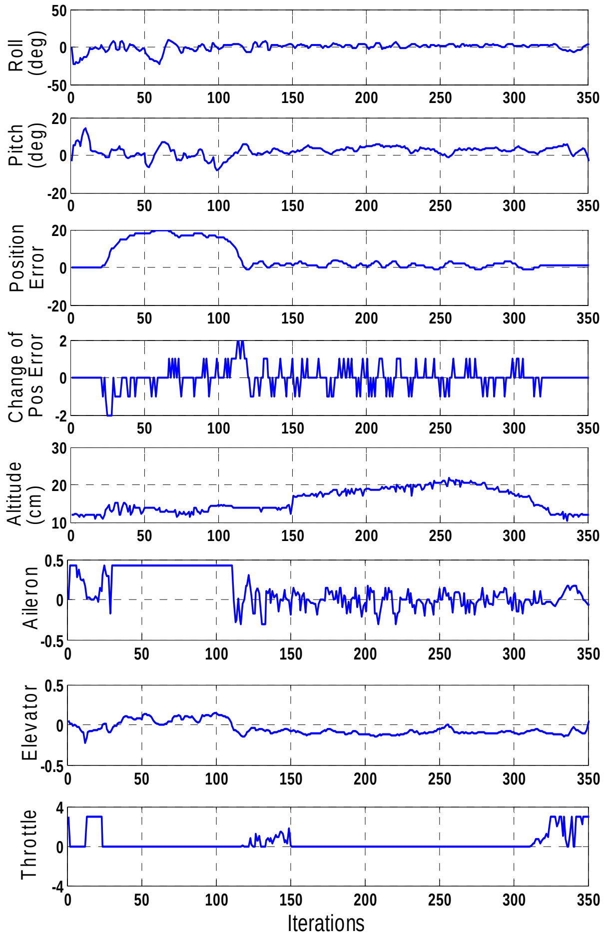


Fig. 8. Parameter's monitoring for the **Test Case 2**.

VII. Conclusion

In this paper we introduced a custom experimental test bed for safe evaluation and benchmarking of autopilot/flight controllers for unmanned helicopters. The test bed works indoors and is independent of power supply. The first experimental results show that this setup works well. The development of controllers is done on a real helicopter and not in simulation, so we can have direct and reliable results. Humans monitoring the flight have the ability to have clear view of the test bed from a short distance.

Future work, involves development of other kinds of controllers which will be tested and evaluated on the test bed. This work will lead to a comparison of controllers based on their efficiency and ability to control successfully an unmanned helicopter.

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