An Experimental Test Bed for Small Unmanned Helicopters

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Abstract: This paper introduces a custom experimental test bed for the evaluation of autonomous flight controllers for unmanned helicopters. The development of controllers for unmanned helicopters is a difficult procedure which involves testing through simulation at first, and then actual experimentation on real vehicles. As simulation cannot accurately represent the exact real flight conditions and the dangers involved in them, the suggested test bed fills the gap between simulation runs and experimental flights. The developed system involves a small helicopter mounted on a flying stand, equipped with a set of sensors for real-time flight monitoring and control. For demonstration purposes, the test bed has been used for design and validation of a fuzzy logic based autopilot, able to perform hovering and altitude control. Experimental results are presented and commented for various test cases.

Key words: unmanned helicopters, experimental test bed, aerial robotics, flight control, fuzzy control

1 Introduction

During the last decades, Unmanned Aerial Vehicles (UAVs) have dominated the scene of mobile robotics since they offer a platform able to successfully accomplish various aerial missions, both military and civil, such as surveillance, traffic management, land management, border patrol, search and rescue, and much more. Unmanned helicopters (aka. VTOL UAVs for Vertical Take-Off and Landing UAVs) are the most flexible flying machines among the variety of UAVs, as they have the ability to take off/land vertically as well as to perform aggressive maneuvers and hovering, which gives them the advantage of effective observation from various positions. These advantages, along with the continuous evolution of robotic vehicles' technology, have led to a remarkable growth in the market of unmanned helicopters, which nowadays includes vehicles of various types, sizes and operational capabilities [1].

During the last years, small scale (about 1500 mm in length) helicopters are preferred for autonomous systems design and experimentation due to their expendability and low cost. The development of autonomous navigation systems for unmanned helicopters is a difficult and expensive procedure. Apart 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, experimentation on real vehicles often results in crashes. High cost is one of the reason the research on unmanned helicopters focuses on small rotorcrafts, usually small size commercially available "Radio Controlled" (RC) helicopters, which are low budget platforms suitable for experimentation and research of control systems [2, 3].

As mentioned, insufficient control may result to unexpected behaviors and crashes. For this reason, the design of an autonomous navigation controller begins with numerous tests in a software-based 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 a real vehicle.

It is known that the simulation procedure has drawbacks. At first, simulation cannot imitate helicopter's navigation in detail, including all possible environmental disturbances. Therefore, a controller that seems to work satisfactorily in a simulation environment may be not sufficient in the real environment. Moreover, independently of any simulation evaluation, first/initial tests with a real vehicle generally are the most dangerous, since a lot of unexpected problems may arise at this time. As a result, it would be desirable to test the controller on a real vehicle but in a safe environment, without having the danger of crashing and destroying the equipment or harm people that monitor the flight.

In the past years, there have been proposed ways of testing controllers on a real (not simulated) vehicle. Normally, there is a mechanical construction where a real helicopter (or a simplified model of it) can fly indoors without crashing or harming the humans involved in the experimentation. In [4], a custom helicopter-like construction whose degrees of freedom are reduced (Figure 1a), is used for the design and evaluation of a flight stabilization controller. In [5], a mechanical construction is used to emulate the flying behavior of a helicopter. The experimental setup consists of a base on which a long arm is mounted that carries the helicopter body (Figure 1b). Two motors with propellers mounted on the helicopter body can generate the force that causes the helicopter body to lift off the ground. A similar test bed is also used in [6].

Further in the literature, we meet systems that use real helicopters for the experiments. In [7] and [8], a mechanical construction holds the helicopter in a stable position allowing only small and safe movements (Figures 1c and 1d respectively). Using mechanical limitations, the helicopter is able to move in only one or two axes and within limits. As a result, the helicopter cannot take any dangerous orientation or collide to the ground.

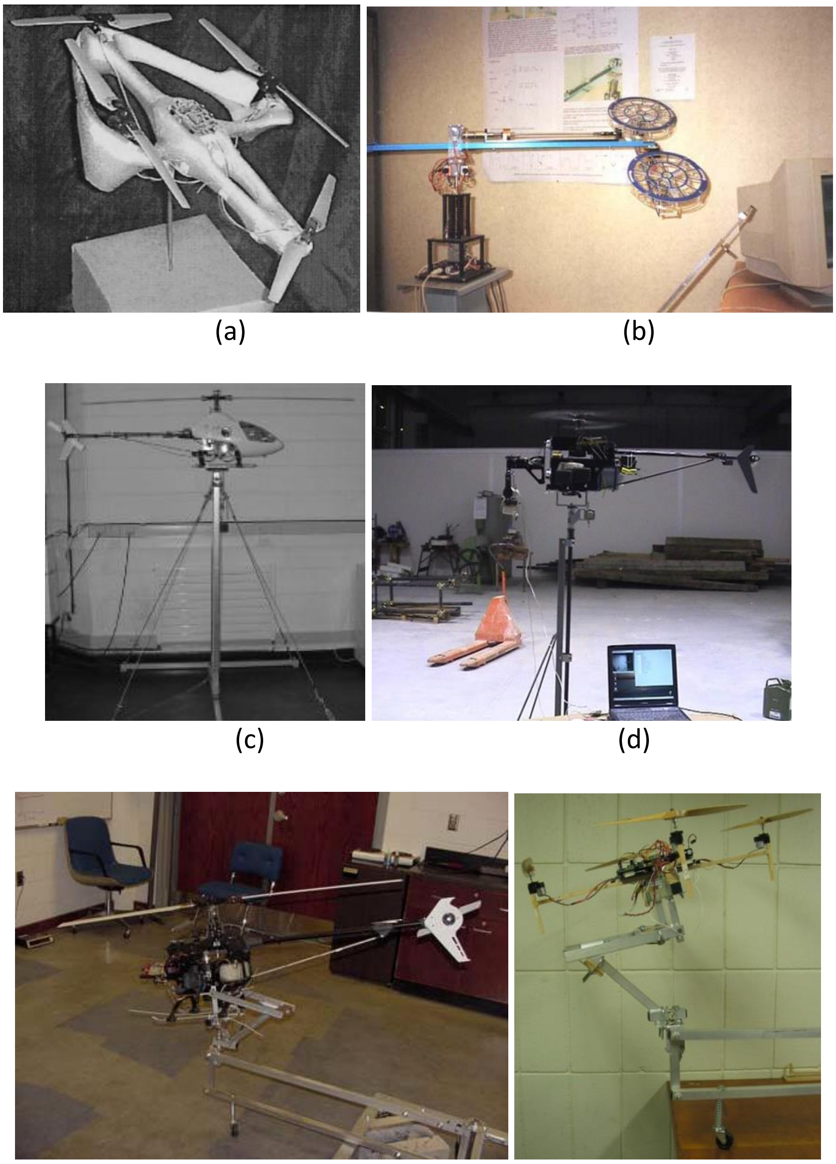
Another mechanical construction used in the literature is the Whiteman flying stand [9]. This construction allows free movement in all axes (5 degrees of freedom). It was first introduced in [10], where it has been modified to limit motion to the vertical plane and used for a set of hover experiments. In [11], a gas powered radio controlled helicopter is placed on a similar stand, in order to determine and evaluate flight characteristics and lifting capabilities with various payloads (Figure 1e). In [12], the stand is used in order to develop and evaluate a quadrotor (Figure 1f). The stand was modified to allow quadrotor's rotation about pitch and roll axes. The modified stand proved not suitable for the attempted experiment because of its size and weight. It should be noted that in both [11] and [12], the Whiteman stand was not used for the development of a flight control test bed.

In the above references, either a helicopter emulation construction is used or a real helicopter with reduced degrees of freedom. In both cases, the developed controller covers only partially the control of the vehicle in one or two axes and it is not sufficient to fully control a helicopter in real conditions.

In this paper we propose an experimentation test bed for the flight control of small helicopters. The system we suggest can be safely (for both humans and the equipment involved) used indoors for experimental validation, allowing 5 degrees of freedom in helicopters' movement. Indoor flying gives the ability for continuous tests, regardless of weather conditions. The suggested test bed also minimizes the need for experienced helicopter pilots within a research group. Regularly, flying small helicopters requires pilot training which stems research efforts towards autonomous helicopter flights.

In this paper we also propose a fuzzy controller for the altitude and hovering control of an unmanned helicopter. The controller was developed using the proposed test bed and is able to stabilize the helicopter in desired positions (each position is defined by horizontal and vertical coordinates). Except from hovering at a desired altitude, the tasks of autonomous take-off and landing are also considered here. The development of this controller was a secondary action, mainly to evaluate and validate the proposed test bed. However, it turned out that the controller itself contains significant innovation towards the autonomous indoor flight.

In the literature, altitude control is a part of an autonomous navigation controller [13, 14], where a subsystem dedicated to altitude control cooperates with other subsystems in order to navigate the helicopter. In [15] an adaptive approach is proposed for altitude control for an unmanned helicopter which utilizes rotor revolutions to track altitude commands. Significant work has been done also in the field of autonomous landing problem for unmanned helicopters [16, 17].



(a) (b)

(c) (d)

(e) (f)

Fig. 1 Pictures of test beds presented in the literature

This paper is organized as follows. In Section 2 we describe the suggested experimental test bed. Main parts and systems of the test bed are presented together with the way this test bed works. In Section 3, we present a simple fuzzy controller which was designed for validation and experimentation on the suggested test bed. In Section 4, experimental results are presented and remarked. At last, a conclusion is derived and future work on the subject is suggested.

2 Experimental Test Bed

The laboratory test bed consists of three basic parts; a customized flying stand, a customized small helicopter and a control unit (Figure 2).

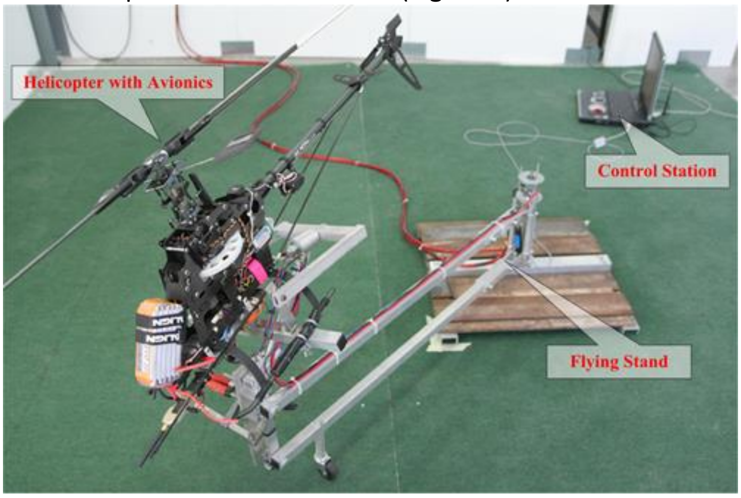


Fig. 2 The proposed experimental test bed.

2.1 Helicopter Flying Stand

The flying stand is a mechanical construction able to hold the helicopter, allowing full movements (5 degrees of freedom) while protecting it from damaging and crashing. It is a customized construction based on the commercially available mechanism by Whiteman Industries, that it is used by inexperienced pilots for flight training. A small electric helicopter is mounted on the stand as shown in Figures 2, 3 and 4.

The stand is all aluminum construction with ball bearings to allow smooth and easy movements to the helicopter. Friction at the joints is considered negligible. As a result, the helicopter can 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 so the helicopter does not lift any extra weight. In Figure 3, rotations as well as the Euler angles of the helicopter are presented.

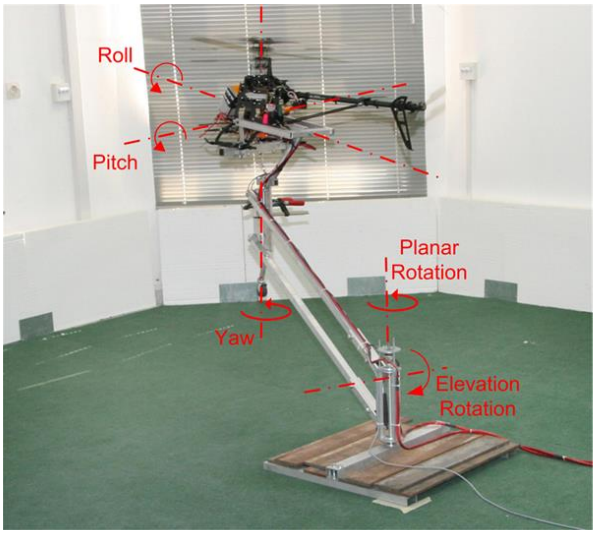


Fig. 3 Euler angles and rotation axes.

2.1.1 Kimematics

In this section, we present the forward kinematic equations of the stand using the Denavit-Hartenberg convention. Using this equations, position and orientation of the helicopter (end-effector) can be calculated.

The flying stand (Figures 3, 4) has five revolute joints. Each joint rotates around an axis and the synthesis of all rotations provides the final position of the end-effector, which in our case is the place where the helicopter is mounted on the stand. In Figure 4, a right side view of the stand is presented. Based on this view, the coordinate frames attached to the center of each revolute joint are presented in Figure 5. As it can be derived from Figures 4 and 5, dimensions presented in Figure 5 are not the actual ones, but a relevant clear view of each frame is presented, since in the stand the distance between these frames is very small. Frame 5 is the frame of the end effector. Parameters L_1, L_2, L_3, L_4, L_5 are known system constants that represent the length of each link, while parameters ϑ_1, ϑ_2, ϑ_3, ϑ_4, ϑ_5 represent the rotation angle of each joint. Angles ϑ_3, ϑ_4, ϑ_5 correspond to the yaw, roll and pitch angles of the helicopter, respectively. The stand allows full rotation of the yaw angle while it constraints roll and pitch angles between -40° and 40°. The four parameters of the Denavit-Hartenberg convention (link length a_i, link twist α_i, link offset d_i, joint angle ϑ_i), applied to the stand, are presented on Table 1.

Fig. 4 Right side view of the test bed

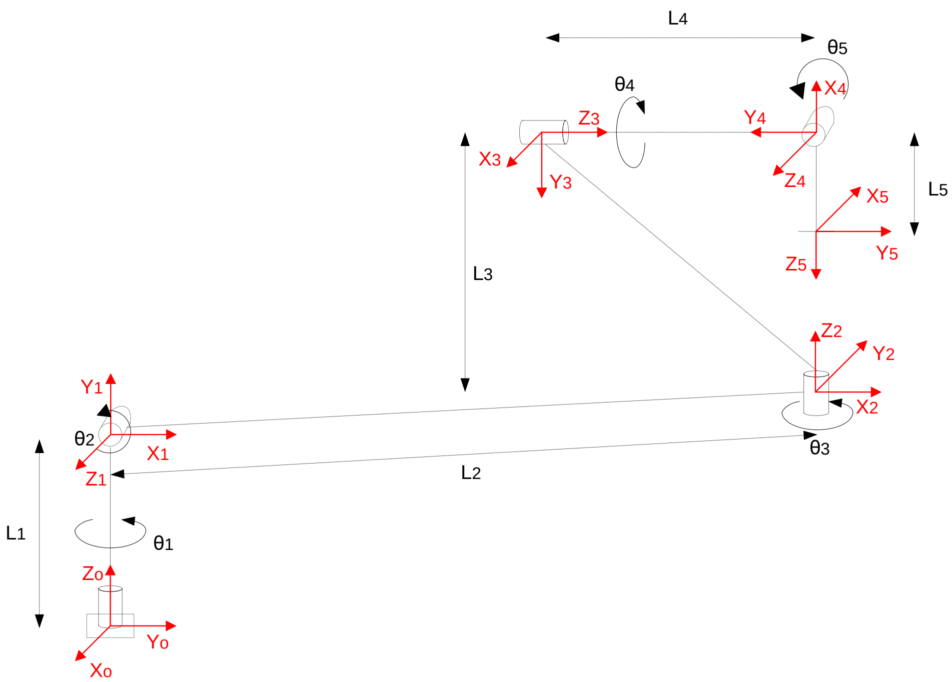


Fig. 5 Coordinate frames attached to revolute joints

Table 1 Denavit-Hartenberg Link Parameters

Link	a_i	α_i	d_i	ϑ_i
1	0	90^O	L_1	ϑ_1
2	L_2	-90^O	0	ϑ_2
3	L_3	-90^O	L_4	ϑ_3
4	0	-90^O	L_4	ϑ_4
5	0	90^O	L_5	ϑ_5

According to the Denavit-Hartenberg convention, the homogeneous transformation matrices A_i for each link are the following:

$$A_1 = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ \sin\theta_1 & 0 & -\cos\theta_1 & 0 \\ 0 & 1 & 0 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix},\ A_2 = \begin{bmatrix} \cos\theta_2 & 0 & -\sin\theta_2 & L_2\cos\theta_2 \\ \sin\theta_2 & 0 & \cos\theta_2 & L_2\sin\theta_2 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A_3 = \begin{bmatrix} \cos\theta_3 & 0 & -\sin\theta_3 & L_3\cos\theta_3 \\ \sin\theta_3 & 0 & \cos\theta_3 & L_3\sin\theta_3 \\ 0 & -1 & 0 & L_4 \\ 0 & 0 & 0 & 1 \end{bmatrix},\ A_4 = \begin{bmatrix} \cos\theta_4 & 0 & -\sin\theta_4 & 0 \\ \sin\theta_4 & 0 & \cos\theta_4 & 0 \\ 0 & -1 & 0 & L_4 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$A_5 = \begin{bmatrix} \cos\theta_5 & 0 & \sin\theta_5 & 0 \\ \sin\theta_5 & 0 & -\cos\theta_5 & 0 \\ 0 & 1 & 0 & L_5 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

Then the transformation matrix that gives the position and orientation of the end effector frame expressed in base coordinates, is the following:

$$T_5^0 = A_1A_2A_3A_4A_5 = \begin{bmatrix} r_{11} & r_{12} & r_{13} & d_x \\ r_{21} & r_{22} & r_{23} & d_y \\ r_{31} & r_{32} & r_{33} & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

where, for $c_i=\cos\vartheta_i$ and $s_i=\sin\vartheta_i$, we have

$r_{11} = [(c_1c_2c_3-s_1s_3)c_4+c_1s_2s_4]c_5+(c_1c_2s_3+s_1c_3)s_5$

$r_{21} = [(s_1c_2c_3+c_1s_3)c_4+s_1s_2s_4]c_5+(s_1c_2s_3-c_1c_3)s_5$

$r_{31} = (s_2c_3c_4-c_2s_4)c_5+s_2s_3s_5$

$r_{12} = -(c_1c_2c_3-s_1s_3)s_4+c_1s_2c_4$

$r_{22} = -(s_1c_2c_3+c_1s_3)s_4+s_1s_2c_4$

$r_{32} = -s_2c_3s_4-c_2c_4$

$r_{13} = [(c_1c_2c_3-s_1s_3)c_4+c_1s_2s_4]s_5-(c_1c_2s_3+s_1c_3)c_5$

$r_{23} = [(s_1c_2c_3+c_1s_3)c_4+s_1s_2s_4]s_5-(s_1c_2s_3-c_1c_3)c_5$

$r_{33} = (s_2c_3c_4-c_2s_4)s_5-s_2s_3c_5$

$d_x = [-(c_1c_2c_3-s_1s_3)s_4+c_1s_2c_4]L_5+(-c_1c_2s_3-s_1c_3-c_1s_2)L_4+(c_1c_2c_3-s_1s_3)L_3+c_1c_2L_2$

$d_y = [-(s_1c_2c_3+c_1s_3)s_4+s_1s_2c_4]L_5+(-s_1c_2s_3+c_1c_3-s_1s_2)L_4+(s_1c_2c_3+c_1s_3)L_3+s_1c_2L_2$

$d_z = (-s_2c_3s_4-c_2c_4)L_5+(-s_2s_3+c_2)L_4+s_2c_3L_3+s_2L_2+L_1$

In the transformation matrix T_5^0 the first three entries of the last column are the x, y, z components of the origin O_5 in the base frame. That is d_x, d_y, d_z are the coordinates of the end-effector in the base frame. The rotational part of T_5^0 (r_{ij}, i, j=1, 2, 3) gives the orientation of the frame O_5 relative to the base frame.

Since parameters L_1, L_2, L_3, L_4, L_5 are known constants, the value of parameters $\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4, \vartheta_5$ must be known in order to calculate final position and orientation at each time instant. Therefore, five rotational encoders must be used in order to monitor each of the five ϑ_i (i=1, 2, 3, 4, 5) angles. To simplify the test bed construction, a positioning and orientation system has been developed, where only three encoding sensors are used (Section 2.1.2). As a result, this kinematic analysis is not used in this paper but ongoing and future work involves the use of this model, for the accurate evaluation of the positioning/orientation system installed. It should also be noted that even thought the stand is a robotic manipulator, there are no motors at any joint. The stand moves only by the forces of the end effector, which here is the helicopter.

2.1.2 Positioning and Orientation System

To develop an autonomous flight controller, one needs to know the actual position and orientation of the helicopter. In unmanned helicopters that fly outdoors, mainly GPS (Global Positioning System) sensors are used for this purpose. Such a system cannot be utilized for indoor experimentation, so a reference system must be developed.

In robotics research, several localization systems for indoor experimentation have been developed. Usually these systems involve the use of high cost cameras, where localization is calculated through vision [18]. To avoid these high cost indoor systems, we utilize the rotary movement of the central shaft of the stand. The stand and consequently the helicopter move around a circle (planar rotation at Figure 3) with a rotation angle which may easily be monitored. For this reason, a rotation encoder has been installed on the central shaft of the stand (Figure 6). The encoder initializes its position to zero and then gives signed numbers that denote the current position relative to the initial position. Positive numbers denote rotation to the left while negative numbers denote rotation to the right side. The rotation encoder gives the planar position of the helicopter at each time instant. To facilitate experimentation, we have observed that the accuracy of the rotation encoder should be higher than 0,5 degrees.

Moreover, one needs to know the altitude at which the helicopter flies. An infrared sensor is used to monitor the actual value of altitude. The sensor is mounted at the lower part of the bracket that holds the helicopter, as it is shown in Figure 6. The mounting point has a distance of 10cm from the ground, so the initial altitude in the experiments is 10 cm and not 0 cm. The accuracy of the altitude readings is less than 1cm, which is far better than the accuracy of outdoor altimeters or GPS.

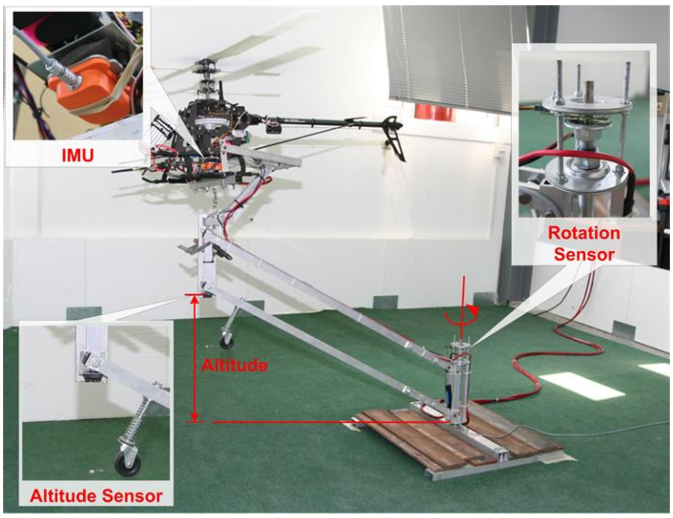


Fig. 6 Positioning sensors.

Using the above two sensors, final position of the helicopter can be easily monitored during the experiments. Orientation of the helicopter is what needed in order to have a complete reference system and make calculations during the experiments. For this reason, an Inertial Measurement Unit (IMU, Figure 6) is used. This sensor is mounted on the helicopter and provides its orientation (Euler angles) at each time instant. Further information about this unit is provided in Section 2.2.1.

2.2 Helicopter and Avionics

The VTOL used for experiments 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. One major characteristic of this helicopter is that it has electric power system so there is no need for fuel gas. Therefore, it does not produce any exhaust gasses during its operation, and makes it ideal for indoor testing. The technical specifications of the T-REX 600 helicopter are listed in Table 2.

Table 2 Technical specifications of the T-Rex 600 VTOL

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	3 kg
Payload	2 kg
Autonomy (high capacity battery)	15 min (hovering)

To fulfill our research needs, the T-REX 600 has been heavily customized. In what follows we describe the equipment and the avionics we have put on board. Figure 8 presents the position of the major installations on the helicopter.

2.2.1 Inertial Measurement Unit (IMU)

This unit is the most essential part of the avionics, since it computes the orientation of the vehicle on its body-frame system. 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). These angles provide the orientation and heading of the helicopter which is the most necessary information in autonomous navigation. Figures 6 and 8 present the placement of this sensor on the helicopter. For the communication between IMU and control station a USB-serial data and power cable is used.

2.2.2 Digital Switch

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, which is very useful in case of failure or insufficient control.

The way digital switching works is quite simple (Figure 7). A digital switch with two inputs and one output is placed onboard the helicopter (Figure 8). Each input consists of control signals (lateral cyclic, longitudinal cyclic, throttle) coming from the human operator (pilot) or the control unit. Pilot input involves an extra switch signal dedicated to the selection between manual and autonomous flight. It is quite easy for the operator to change manually between these two modes by sending a signal through the transmitter. Digital switch monitors this signal and forwards the appropriate control actions (manual or autopilot) to the helicopter actuators.

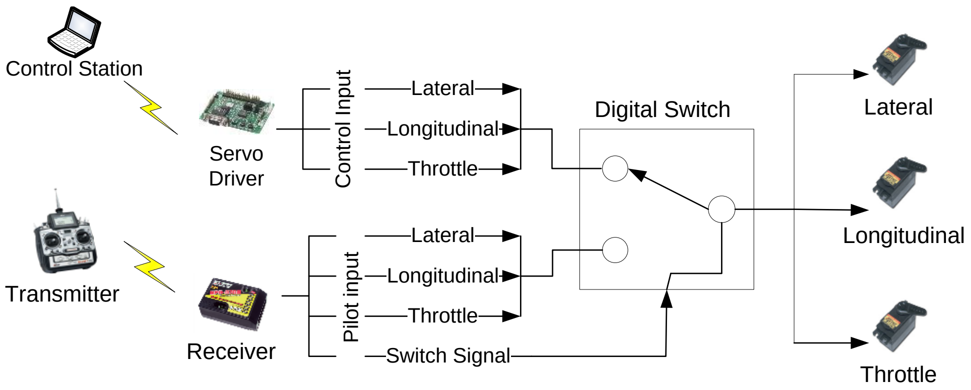


Fig. 7 Digital switch function

2.2.3 Servo Driver/Controller

RC servos are the actuators used to control the motion of the helicopter. In manual operation, the onboard receiver forwards the transmitter commands to servos by sending appropriate PWM (Pulse Width Modulation) signals. In order to send such signals from the control station to the servos, a servo driver is needed. For that reason a PIC microcontroller (Figure 8) is used, which translates control signals from the ground station to RC PWM servo signals and drives the servos. Further, the PIC reads the input from the localization system (x-y position, altitude) and sends it to the control station.

2.2.4 Communication System

A wireless communication system has been established between the control station and the PIC 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 PIC and the serial port of the control station. Through this communication, control signals are transmitted to the helicopter from the control unit, while input from the localization sensors is transmitted to the control unit. In Figure 8, the transmitter/receiver unit attached to the helicopter is presented.

2.2.5 Power System

All electric helicopters have high power consumption. During hovering, the electric motor of the helicopter used needs about 50A current of 24V. Normally in these helicopters, LiPo (Lithium Polymer) batteries are used that have high capacity and the ability to sustain such currents. With this consumption and with a high capacity LiPo battery, the helicopter can perform hovering for only about 15 minutes. To overcome this limitation, the test bed is provided with constant power supply of 24V that gives continuous current to the helicopter (Figure 9). Power is supplied through wires that do not block the movement of the helicopter or the flying stand. This setup assures continuous experiments without the need of recharging the battery or changing it with a charged one.

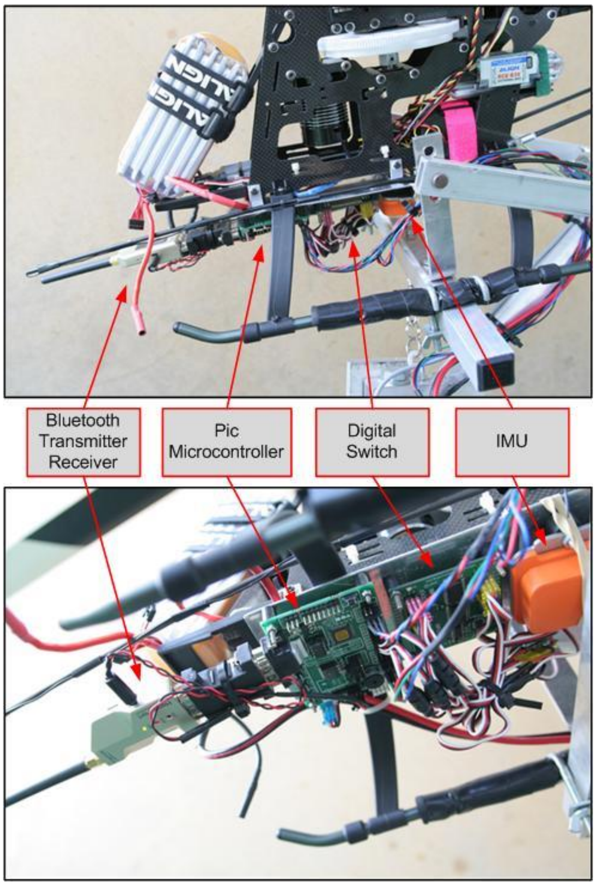


Fig. 8 Helicopter Avionics

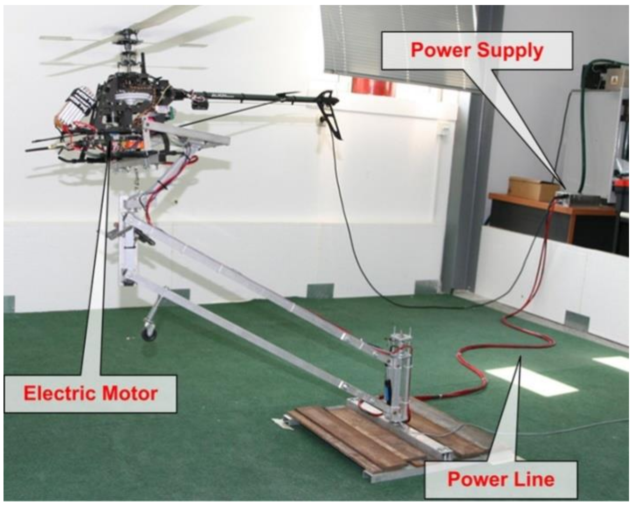


Fig. 9 Test bed power supply

2.3 Ground Control Station

For the autonomous navigation of the helicopter, the use of a computer who serves as the operator is necessary. This computer manages the signals from the sensors and calculates the appropriate control signals in order to efficiently control the helicopter. 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 the helicopter. 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.

2.4 Connection of the subsystems

In Figure 10, a block diagram for system architecture is presented along with the connections of the equipment and the data transmission through these connections. Rotational encoder and infrared sensor are mounted on the stand and connected to the PIC microcontroller through wires, which do not block the movements of the stand. PIC, IMU and Bluetooth modem are mounted on the helicopter's fuselage. The only wired connection between helicopter and control station is the one with the IMU.

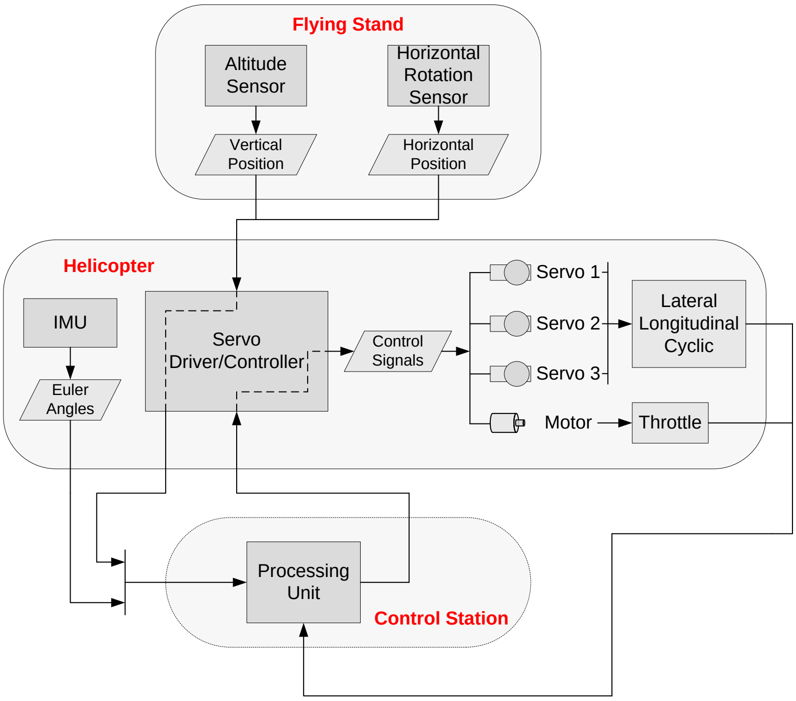


Fig. 10 System Architecture.

2.5 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.

Fig. 11 View of the safety cage that contains 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 (Figure 11). 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.

3 Altitude & Hovering Control

To validate the appropriateness of the developed system as a flight control test bed, we started experimentation with easy-to-implement, yet reliable, controllers. Since the test bed is a complex system and requires analytical study in order to derive an accurate dynamical model, we designed a fuzzy controller which does not require mathematical modeling. It is known that 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 are capable of imitating human operators, as we have observed in the past [19-21].

The objective of the controller developed is to hold the helicopter stable at a predefined horizontal position and altitude, as described in the sequel.

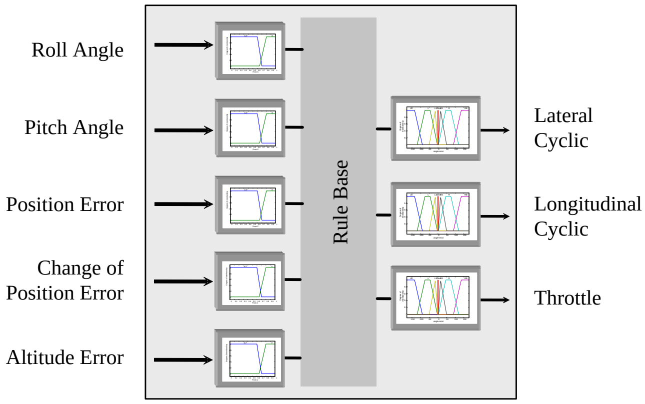


Fig. 12 Hovering and Altitude Fuzzy controller.

3.1 Fuzzy Controller

A fuzzy controller of the Mamdani type has been designed and implemented in the MATLAB environment. As shown in Figure 12, the inputs of the fuzzy controller are the *roll* and *pitch* angles of the helicopter at every time instant, the *position error*, the *change of position error* and the *altitude error*. The outputs of the controller are the change of the roll and pitch angles (*lateral* and *longitudinal* cyclic command variables respectively), and the change in the *throttle* of the helicopter.

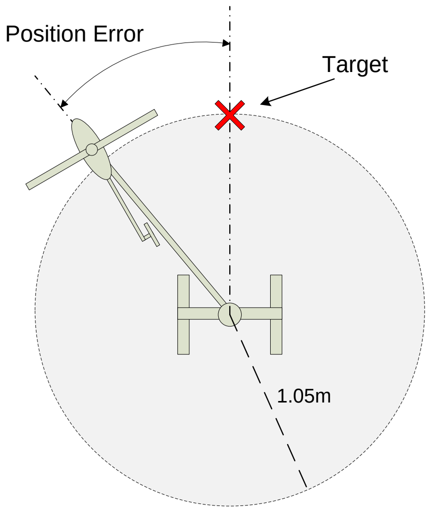


Fig. 13 Position error representation.

3.2 Inputs and outputs

The first input of the fuzzy controller, *roll* angle, is given by the IMU in real time. Although the flying stand permits roll angles from -40º to 40º, the flight control system takes as input degrees from -90º to 90º. The linguistic variables that represent the *roll* angle are: *left big* (*LB*), *left* (*L*), *zero* (*ZERO*), *right* (*R*), *right big* (*RB*), and their membership functions are shown in Figure 14.

The second input variable is the *pitch* angle of the helicopter. The linguistic variables for this input are: *back big* (*BB*), *back* (*B*), *zero* (*ZERO*), *front* (*F*), *front big* (*FB*), with membership functions also presented in Figure 14.

In Figure 13, we show the representation of the *position error* input, which 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. Since for safety reasons we do not want the stand to rotate out of its limits (-180° to 180°), we set the range of the *position error* variable to be between -180° and 180°. The linguistic variables for these inputs are: *negative big* (*NB*)*, negative* (*N*)*, zero* (*ZERO*)*, positive* (*P*)*, positive big* (*PB*) (Figure 14).

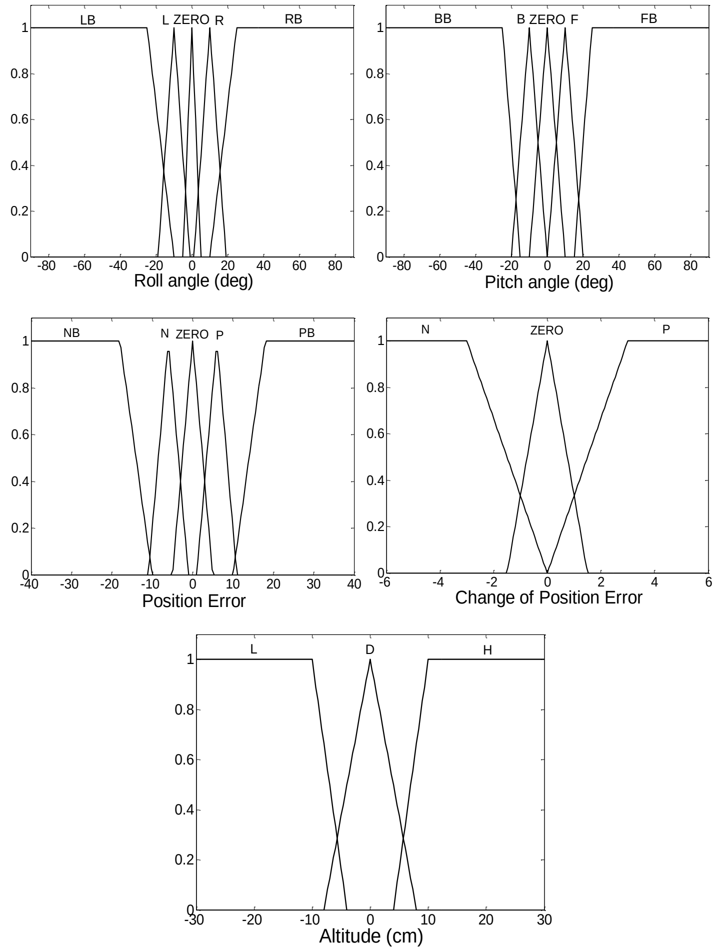


Fig. 14 Membership functions for input variables.

The next input in the fuzzy controller is the *change of position error*. This variable 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 degrees) between the previous position error and the current position error (change of position error = previous position error – current position error), and it is represented by the linguistic variables: *negative* (*N*)*, zero* (*ZERO*)*, positive* (*P*) (Figure 14).

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 linguistic variables for this input are: *lower* (*L*), *desired* (*D*), *higher* (*H*) (Figure 14).

The outputs of the fuzzy controller are the changes of roll and pitch angles (Lateral and Longitudinal cyclic commands respectively) and Throttle change. The membership functions of *lateral*, *longitudinal* and *throttle*, are presented in Figure 15. The linguistic variables for *lateral* are *left big* (*LB*), *left* (*L*), *left small* (*LS*), *zero* (*ZERO*), *right small* (*RS*), *right* (*R*) and *right big* (*RB*). The linguistic variables for *longitudinal* are *back big* (*BB*), *back* (*B*), *zero* (*ZERO*), *front* (*F*) and *front big* (*FB*). Both *lateral* and *longitudinal* output commands are presented in PWM control signal units.

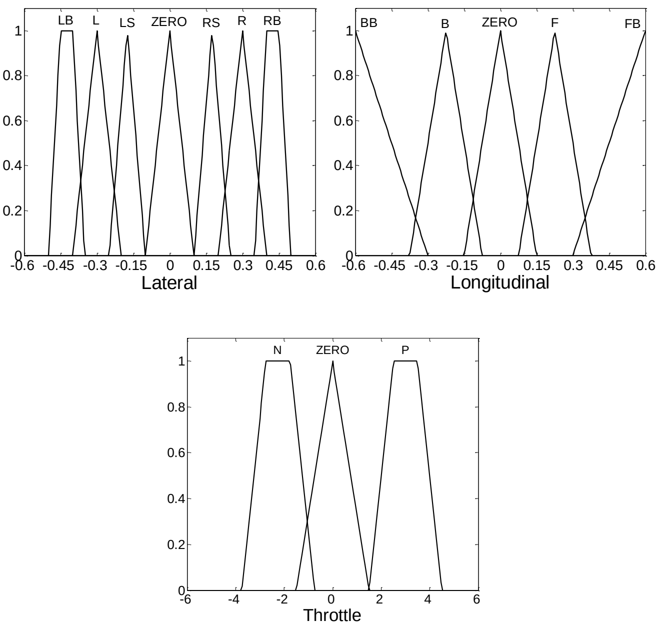


Fig. 15 Membership functions for output variables.

The linguistic variables for *throttle* change are *negative* (*N*), *zero* (*ZERO*) and *positive* (*P*). The values of throttle output are also presented in control signal units. Negative output reduces throttle of the helicopter while positive output increases it.

3.2 Control Rules

The control objective in the experiments performed was the stabilization of the helicopter at a specific point (defined by horizontal and vertical coordinates). The transition between the states of the controller is presented in Figure 16, while Figure 17 shows the pseudo-code that describes the control scheme. 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.

For the implementation of this scheme, three sets (rule bases) of fuzzy IF-THEN rules were used.

One was responsible for the control of the pitch angle. The target was to keep the pitch angle always close to zero as this is what needs to be done when the helicopter hovers. This was achieved with simple rules of the form: <IF *Pitch* is *X* THEN *Longitudinal* is *Y*>, where *X*, *Y* represent the membership function of *pitch* and *longitudinal*, respectively. In Table 3 an example of two rules of this base is presented.

Table 3 Example rules for Rule Base 1

	IF Pitch is	THEN Longitudinal is
Rule Base 1	back	front
	front	back

The second rule base contains rules of the form: <IF *Roll* is A AND *position error* is B AND *change of position error* is C THEN *lateral* is D>. These rules lead the helicopter towards the desired point, as they tend to minimize the distance between the helicopter's horizontal position, at each moment, and the desired one. This is a typical

PD-like fuzzy controller with one extra input: the roll angle. In Table 4, an example of two rules of this base is presented.

Table 4 Example rules for Rule Base 2

	IF Roll is	AND Position Error is	AND Change of Pos Error is	THEN Lateral is
Rule Base 2	left	zero	zero	right small
	zero	right	negative	zero

The third rule base is responsible for handling the throttle of the helicopter. Here the changes in the throttle of the helicopter occur only when the helicopter hovers at the desired horizontal position (roll and pitch angles are close to zero, change of position error is close to zero) or when the altitude becomes higher than a top safety limit. This policy tends to ensure that sudden throttle changes will not cause unwanted behavior, like aggressive maneuvers. The rules of this rule base have the form <IF *Roll* is A AND *position error* is B AND *change of position error* is C AND *Altitude* is D THEN *throttle* is E>. An example of two rules is presented in Table 5.

Table 5 Example rules for Rule Base 3

	IF Roll is	AND Position Error is	AND Change of Pos Error is	AND Altitude is	THEN Throttle is
Rule Base 3	zero	zero	zero	lower	up
	zero	zero	zero	higher	down

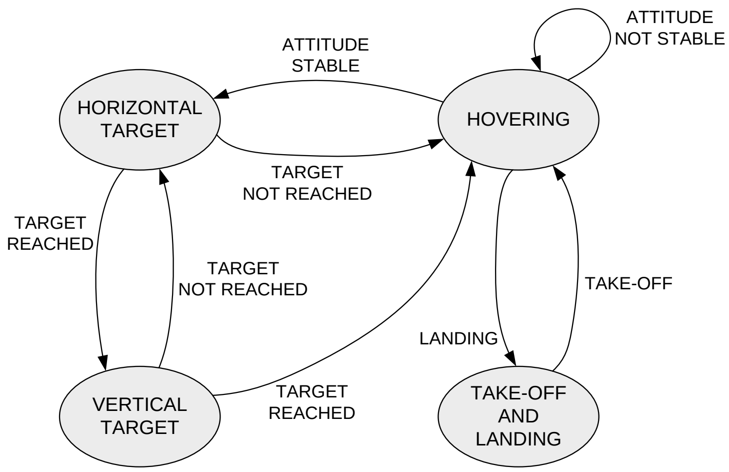


Fig. 16 Controller state transition.

4 Experimental Results

Experimental results for two test cases may be seen in Figures 18 and 19. In these figures *Roll*, *Pitch*, *Position Error* and *Change of Position Error* values are measured in degrees, and *Altitude* is measured in centimeters. *Lateral, Longitudinal* and *Throttle* values are measured in PWM control signals.

```
If attitude is not stable
Stabilize helicopter to hovering
Else
    If current horizontal position is not the desired
        Drive helicopter to the desired horizontal position
Else
        If Current Altitude is not the desired
            Change throttle in order to reach target altitude
          Else
            Hovering
          End IF
End If
End If
```

Fig. 17 Pseudo code of the hovering controller.

In **Test Case 1** (Figure 18) 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.

As it can be seen in Figure 18, the helicopter is placed on the desired horizontal position (area A). The controller keeps roll and pitch angles close to zero and gradually increases throttle (area B), in order to increase the altitude and reach the targeted one (area C). When the target altitude is reached (area D), few oscillations around the horizontal position occur but the controller manages to hold the helicopter hovering in the desired position (area E).

In the beginning of autonomous navigation (area B), it is clear that the position error tends to be a small positive number, which means that the helicopter always drifts to the left of the desired position. This is explained by the position of the test bed area, which is close to the walls of the surrounding building. Air flow from the main rotor of the helicopter, circles through the walls and returns as a disturbance to the helicopter. This air flow gives a small left drift to the helicopter. The developed controller seems to recognize this disturbance and make corrections in order to hold stable the helicopter in the desired position.

Through this test case we observed that the controller manages to successfully accomplish its mission subject to the disturbances that occur due to the indoor position of the test bed.

In Figure 19, 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 (position error in area A in Figure 18) 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 (area B) and then by raising the altitude until the targeted one has been reached (areas C and D). After a few iterations that the target position has been reached, the controller reduces the throttle and lands the helicopter (area E). Small oscillations occur while the autopilot tries to keep the helicopter in stable position. It is also clear, as in test case 1, that we face the air disturbance that causes small drift in the helicopter in this test case too.

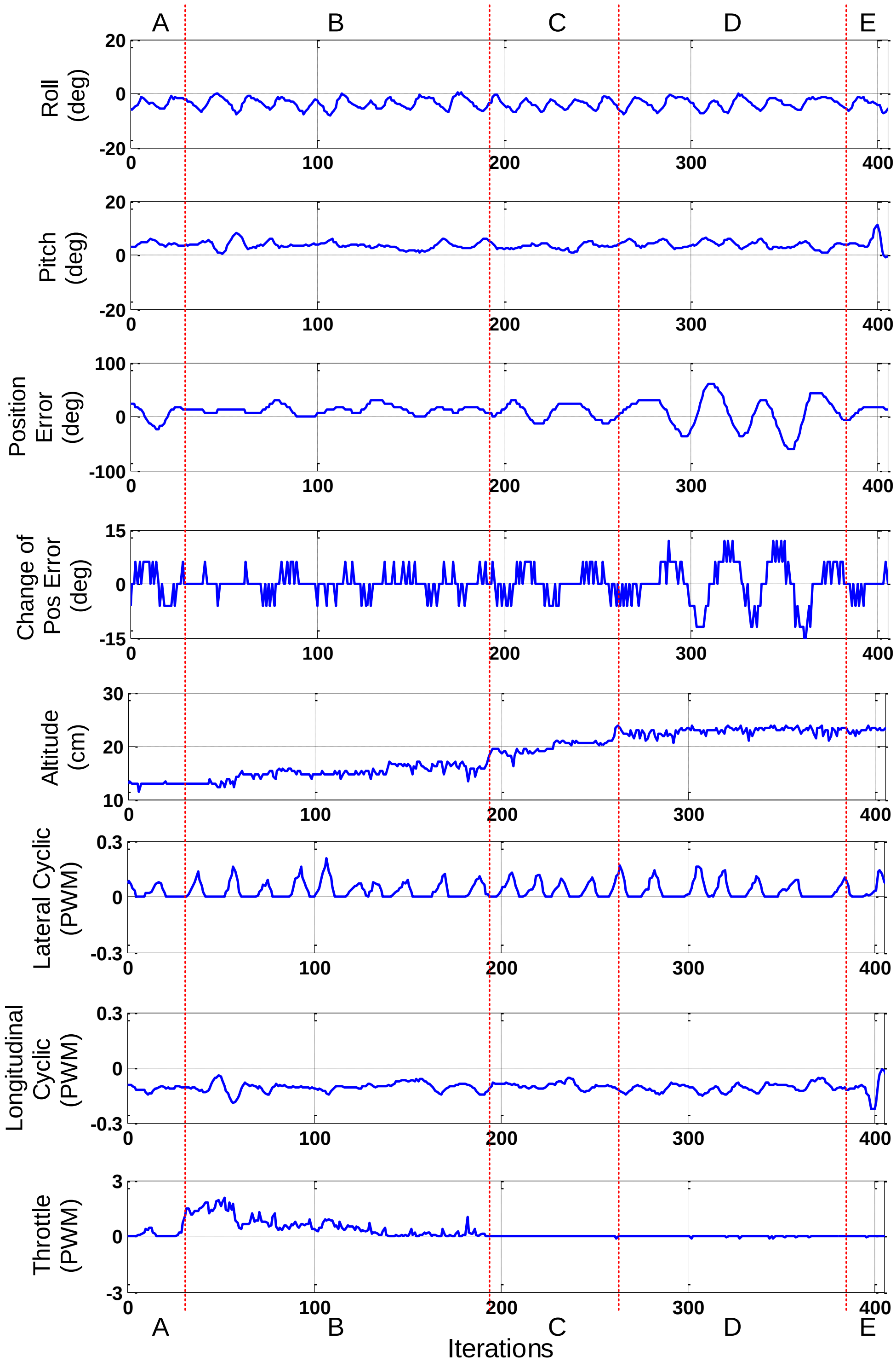


Fig. 18 Experimental results for test case 1: Autonomous take-off and hovering evaluation

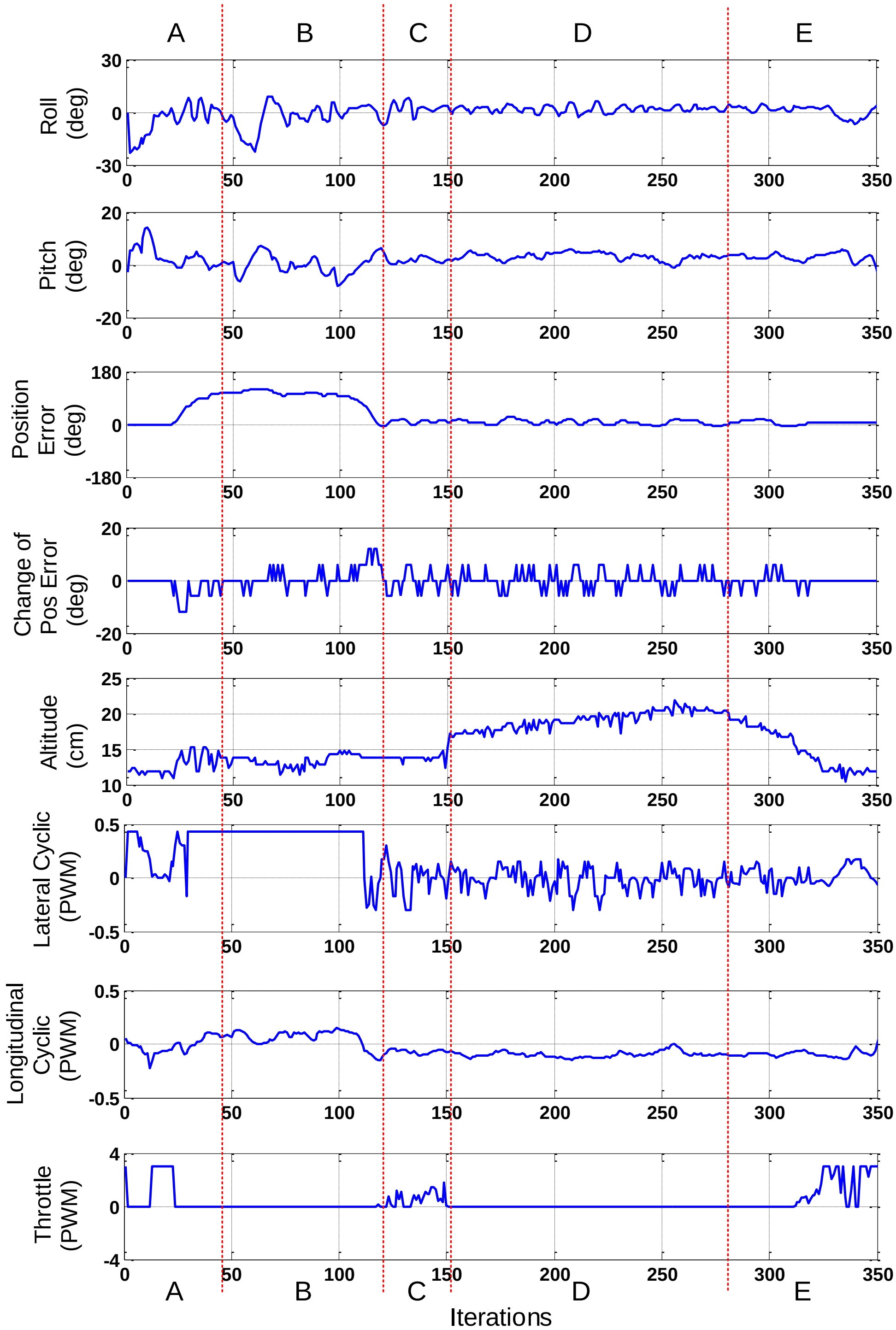


Fig. 19 Experimental results for test case 2:
Horizontal position reach and autonomous landing evaluation

In Figure 20, snapshots during experimentation are presented where one may see that the helicopter performs autonomous navigation guided by the ground control station.

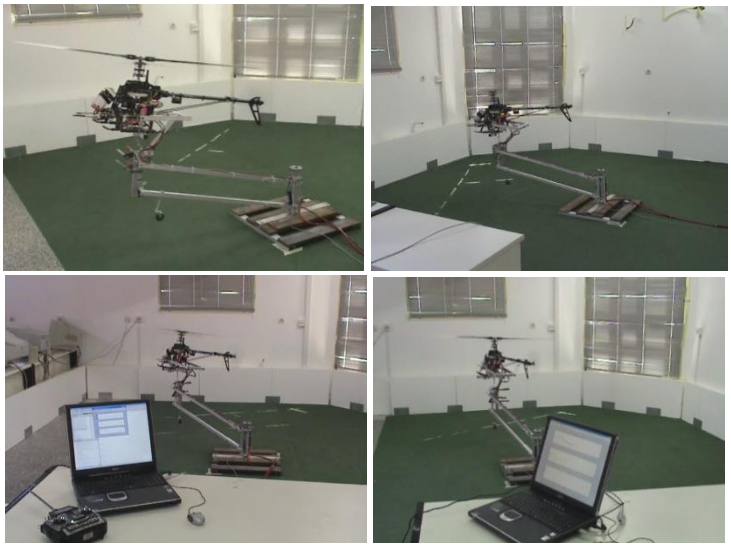


Fig. 20 Snapshots during experimentation.

5 Remarks

The flying stand that is used for the development of the test bed allows free and natural movements of the helicopter. During experimentation, there were no signs that this stand affects the helicopter flight. Although there is no clear evidence for the opposite, one important topic that should be checked is if this stand affects the dynamics of the helicopter.

The test bed seems to work well and is able to be used for controller development purposes. One improvement for better and more accurate experimentation is the replacement of the rotational encoder with a higher accuracy one, in order to have high accuracy in the calculation of the horizontal position. Future work includes this improvement.

Furthermore, the test bed could be even more developed using an onboard camera. This setup would give the ability for experiments in the area of visually guided navigation (the helicopter could follow a pattern on the wall), collision avoidance and target tracking.

6 Conclusion

A prototype experimental test bed for unmanned helicopters has been introduced in this paper. This test bed involves a small electric powered unmanned helicopter mounted on a flying stand that permits free movement in 5 degrees of freedom.

This setup works indoors in secured area, providing safe, crash and noise free testing and continuous experimentation regardless the weather conditions and power consumption of the helicopter. This platform also minimizes the need for experienced pilots since it can also be used for safe training of inexperienced operators.

This test bed can be used for research on various fields of robotic helicopters, like control and navigation design and development, kinematics and dynamics analysis, flight stability, power supply and autonomy control, etc.

For the validation and proper evaluation of this test bed, a fuzzy controller for hovering and altitude control has been developed and presented. Experimental results from the evaluation of the altitude fuzzy controller were presented and commented. These results show that this setup works well and the platform can be used in the research for novel control techniques for unmanned helicopter.

From the literature review comes up that there is not such a similar test bed that utilizes all degrees of freedom and is capable for controller development and evaluation, overcoming the drawbacks of simulation and proving direct and reliable results. This test bed will enhance the field of experimental and field robotics where tests are made on real vehicles and results are directly evaluated. It fills the gap between simulation runs and actual experimentation on real vehicles.

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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References

1. Spanoudakis, P., Doitsidis, L., Tsourveloudis, N.C., Valavanis, K.P.: The Market for VTOL UAVs. Unmanned Systems Magazine **21**(5):14-18 (2003)
2. Kontitsis, M., Valavanis, K.P., Garcia, R.: A simple low cost vision system for small unmanned VTOL vehicles. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3480-3486. Alberta, Canada (2005)
3. Roberts, J.M., Corke, P.I., Buskey, C.: Low-cost flight control system for a small autonomous helicopter. In: Proceedings of the IEEE International Conference on Robotics and Automation, pp. 546-551. Taipei, Taiwan (2003)
4. Tanaka, K., Ohtake, H., Wang, H.O.: A Practical Design Approach to Stabilization of a 3-DOF RC Helicopter. IEEE Transactions on Control Systems Technology. **12**(2), 315-325 (2004)
5. Andrievsky, B., Peaucelle, D., Fradkov, A.L.: Adaptive Control of 3DOF Motion for LAAS Helicopter Benchmark: Design and Experiments. In: Proceedings of the 2007 American Control Conference pp. 6. New York City, USA (2007)
6. Kutay, A.T., Calise, A.J., Idan, M., Hovakimyan, N.: Experimental Results on Adaptive Output Feedback Control Using a Laboratory Model Helicopter. IEEE Transactions on Control Systems Technology. **13**(2), 196-202 (2005)
7. Dzul, A., Lozano, R., Castillo, P.: Adaptive control for a radio-controlled helicopter in a vertical flying stand. International Journal of Adaptive Control and Signal Processing. **18**(5), 473-485 (2004)
8. A. Mancini, F. Caponetti, A. Monteriu, E. Frontoni, P. Zingaretti, Longhi, S.: Safe flying for an UAV Helicopter. In: Proceedings of the15th Mediterranean Conference on Control & Automation, Athens-Greece (2007)
9. Whiteman, R.: Training Apparatus for Remote Control Model Helicopters. United States Patent No. 4917610. (1990)
10. Pallet, T.J., Ahmad, S.: Real-Time Helicopter Flight Control: Modelling and Control by Linearization and Neural Networks. ECE Technical Reports. (1991)
11. Brock, K.: Development of an Autonomous Robotic Aerial Vehicle. IARC Annual Papers. (2002)
12. Hanford, S.D., Long, L.N., Horn, J.F.: A Small Semi-Autonomous Rotary-Wing Unmanned Air Vehicle (UAV). In: AIAA Infotech@Aerospace, Washington DC, USA (2005)
13. Kim, H.J., Shim, D.H.: A flight control system for aerial robots: algorithms and experiments. Control Engineering Practice. **11**(12), 1389-1400 (2003)
14. Shin, J., Nonami, K., Fujiwara, D., Hazawa, K.: Model-based optimal attitude and positioning control of small-scale unmanned helicopter. Robotica. **23**(01), 51-63 (2005)

15. Kim, N., Calise, A., Corban, J., Prasad, J.: Adaptive output feedback for altitude control of an unmanned helicopter using rotor RPM. In: Proceedings of the AIAA Guidance Navigation and Control Conference and Exhibit, pp. 2004-5323. Rhode Island, USA (2004)
16. Merz, T., Duranti, S., Conte, G.: Autonomous Landing of an Unmanned Helicopter based on Vision and Inertial Sensing. Experimental Robotics IX: The 9th International Symposium on Experimental Robotics. 343-352 (2006)
17. Saripalli, S., Sukhatme, G.S., Montgomery, J.F.: An Experimental Study of the Autonomous Helicopter Landing Problem. Experimental Robotics VIII. (2003)
18. Valenti, M., Bethke, B., Fiore, G., How, J.P.: Indoor Multi-Vehicle Flight Testbed for Fault Detection, Isolation, and Recovery. In: AIAA Guidance, Navigation, and Control Conference and Exhibit, Keystone, Colorado (2006)
19. Doitsidis, L., Valavanis, K.P., Tsourveloudis, N.C., Kontitsis, M.: A framework for fuzzy logic based UAV navigation and control. In: Proceedings of the IEEE International Conference on Robotics and Automation, pp. 4041-4046. New Orleans, USA (2004)
20. Tsourveloudis, N.C., Doitsidis, L., Valavanis, K.P.: Autonomous Navigation of Unmanned Vehicles: A Fuzzy Logic Perspective. Cutting Edge Robotics. 291-310 (2005)
21. Tsourveloudis, N.C., Valavanis, K.P., Hebert, T.: Autonomous vehicle navigation utilizing electrostatic potentialfields and fuzzy logic. IEEE Transactions on Robotics and Automation. **17**(4), 490-497 (2001)