Safe Test Flights for Small Rotorcrafts

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Abstract. In this paper we present an experimental test bed for the development and evaluation of unmanned helicopters control. Main component of the suggested test bed is a flying stand which permits all possible movements but, also, prevents helicopters' damage because of crashing. A variety of sensors mounted on the stand, monitor and feedback rotorcraft's attitude and operational states. Based on the sensory information, a fuzzy logic controller has been developed and tested on a real rotorcraft, using the developed test bed. This controller proved able to perform hovering and altitude control. Experimental results are presented for various test cases.

Keywords: Unmanned Helicopters, Experimental Test Bed, Altitude Control, Fuzzy Control, Aerial Robotics.

1 Introduction

Unmanned helicopters are the most flexible flying machines among the variety of UAVs (Unmanned Aerial Vehicles), since they have the ability to take off and 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 development of robotic vehicles' technology have led to the use of unmanned helicopters and rotorcrafts in many applications [1]. During the last years, small scale (about 1500 mm in length) helicopters are preferred for development and experimentation due to their low cost and expendability.

Although small scale unmanned helicopters offer as experimentation platforms the advantages of low cost and easy operation, the development of autonomous navigation systems for such vehicles is a difficult and dangerous procedure that may increase this overall cost, since except from the equipment needed (helicopter, sensors, telemetry systems etc) one should add the cost of crashes and damages that may occur during experimentation. For this reason, the development 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 the real vehicle.

The simulation procedure has drawbacks as well. At first, the simulation environment cannot imitate helicopter's navigation in detail with all possible environmental disturbances. Therefore, a controller that seems to work satisfactorily in the simulation may be insufficient for the navigation of the real vehicle in a 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 vehicle safely. 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.

At first, in the literature we meet constructions that simulate a real helicopter [2-4]. These setups involve custom helicopter-like constructions whose degrees of freedom are reduced, and are used for the design and evaluation of flight stabilization controllers. Further in the literature, we meet systems that use real helicopters for the experiments. In [5] and [6], 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 in only one or two axes and within limits. As a result the helicopter cannot take any dangerous orientation or collide to the ground.

The drawback of the work presented in the above references, is that either a helicopter emulation construction is used, or a real helicopter with reduced degrees of freedom. In both cases, the developed controller partially covers the control of the vehicle in one or two axes and it is not sufficient to fully control a helicopter in real conditions. The motivation of this 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 helicopter's movement. Indoor flying gives the ability for continuous tests regardless of weather conditions. Moreover, the suggested setup minimizes the need for experienced helicopter pilots within the research group. 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 is 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.

In the literature there is previous work on the autonomous altitude control of unmanned helicopters. Usually altitude control is a part of an autonomous navigation controller [7, 8], where a subsystem dedicated to altitude control cooperates with other subsystems in order to navigate the helicopter. In [9] an adaptive approach is proposed for altitude control for an unmanned helicopter which utilizes rotor RPM to track altitude commands. Significant work has been done also in the field of autonomous landing problem for unmanned helicopters [10, 11].

2 Experimental Test Bed

The laboratory test bed consists of three basic elements; a customized flying stand, a customized helicopter and a ground control station (Fig. 1).

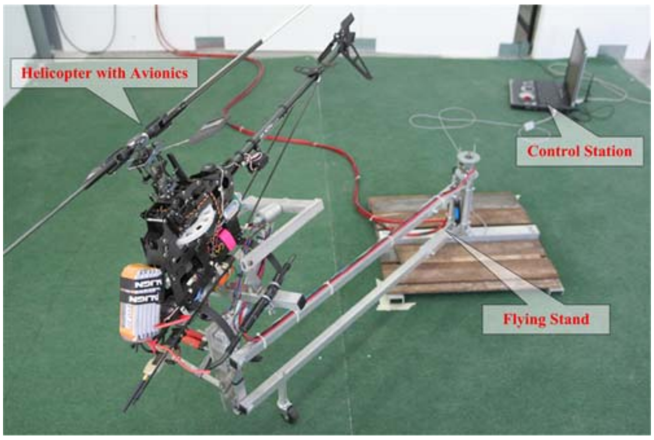

Fig. 1. View of the experimental test bed.

2.1 Helicopter Flying Stand

Helicopter flying stand is a mechanical construction able to hold the helicopter, allowing full movements (6 degrees of freedom) while protecting it from damaging and crashing. It is a customized construction based on the commercially available Whiteman flying stand [12] that it is used by inexperienced pilots for flight training. The stand allows the helicopter move naturally without any constraint around a 2.1m diameter circle (Fig. 7), 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. In Fig. 2, rotations as well as the Euler angles of the helicopter are presented.

Since the test bed will be used for indoor experiments, a positioning system must be developed in order to know helicopter's position during testing. To avoid high cost indoor positioning and localization vision systems [13], 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 Fig. 2, Fig. 7) with a rotation angle which may easily be monitored. For this reason, we put a rotation encoder on the central shaft of the stand (Fig. 3). 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.

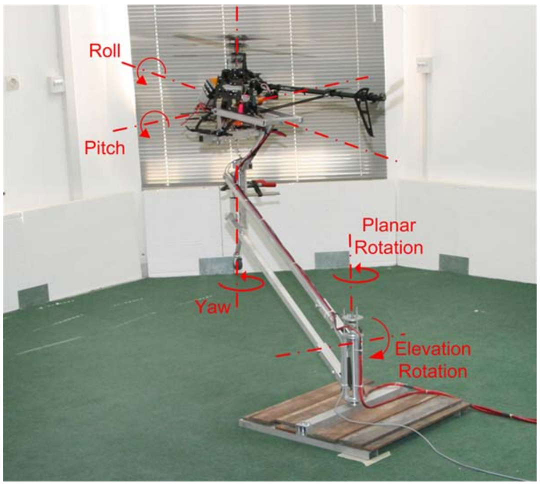

Fig. 2. Euler angles and rotation axes.

Moreover, we need to know the altitude in which the helicopter flies. The flying stand gives the ability to the helicopter to fly at a maximum height of 60cm. 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 Fig. 3. The accuracy of the altitude readings is less than 1cm, which is far better than the accuracy of outdoor altimeters or GPS.

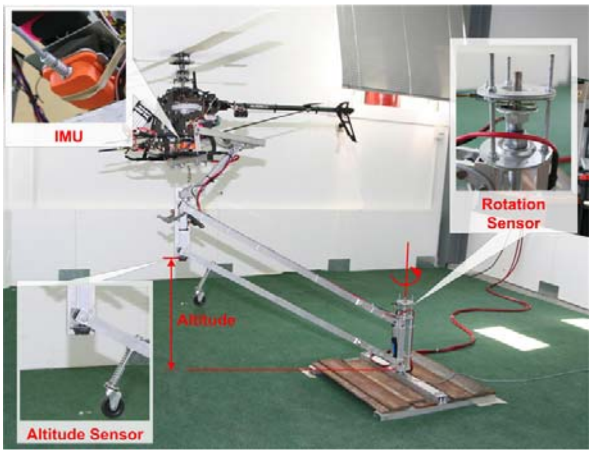

Fig. 3. Positioning sensors.

The final position of the helicopter can be monitored during the experiments using the altitude and the rotation sensors. Orientation (Euler angles) 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, Fig. 3) is used. This sensor is mounted on the helicopter and provides its orientation at each time instant. Further information about this unit is provided in Section 2.2.1.

2.2 Helicopter and Avionics

The VTOL (=Vertical Take-Off and Landing UAV), that we use in our test bed is a customization of a 50-size (1200 mm length, 405 mm height, 1350 mm main rotor diameter) commercially available electric powered RC helicopter. An important characteristic of this helicopter is that it has electric motor 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. 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 have put on board.

2.2.1 Inertial Measurement Unit (IMU)

This unit gives the orientation of the helicopter. The unit consists of 3D gyroscopes, accelerometers and magnetometers and outputs the 3 Euler angles (roll, pitch and yaw). The IMU used is the commercial MTi model of Xsens Motion Technologies. For the communication between IMU and control station a USB-serial data and power cable is used.

2.2.2 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, which is very useful in case of failure or insufficient controller behaviour.

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 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 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 transmits 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.

2.2.5 Power System

The electric helicopter has high power consumption. During hovering, the electric motor needs about 50A current of 25V. Normally in these helicopters, LiPo batteries are used that have high capacity and the ability to sustain big currents. With this consumption and with a high capacity LiPo battery, the helicopter 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 of 24V that gives continuous current to the helicopter.

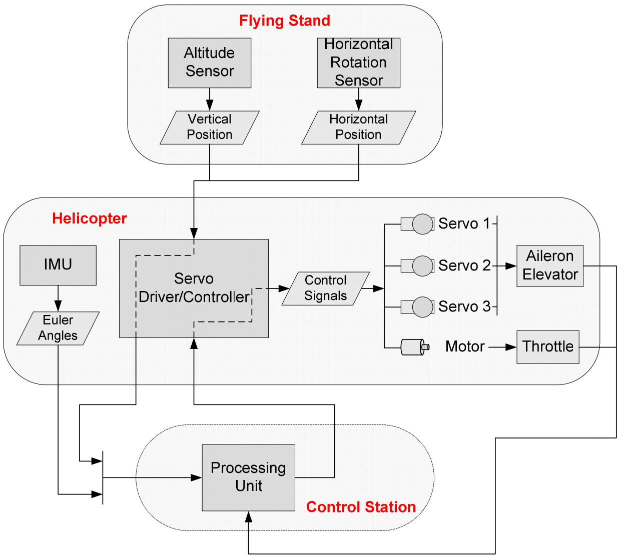

Fig. 4. System Architecture.

2.3 Ground Control Station

Since our test bed works indoor 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.

In Fig. 4, a block diagram presents the connections of the equipment and the data transmission through these connections, for each subsystem (flying stand, helicopter and control station).

2.4 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. 5. 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 (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.

3 Altitude & Hovering Control

The controller developed and tested in the test bed is a fuzzy controller for altitude and hovering control. The objective of the controller is to hold stable the helicopter at a predefined horizontal position and altitude.

3.1 Fuzzy Controller

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 "hovering" at predefined positions subject to wind and other disturbances. As shown in Fig. 6, the inputs of the fuzzy controller are the *roll* and *pitch* angles of the helicopter at every time instant, as well as the *position error*, the *change of position error* and the *altitude error*. In Fig. 7 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.

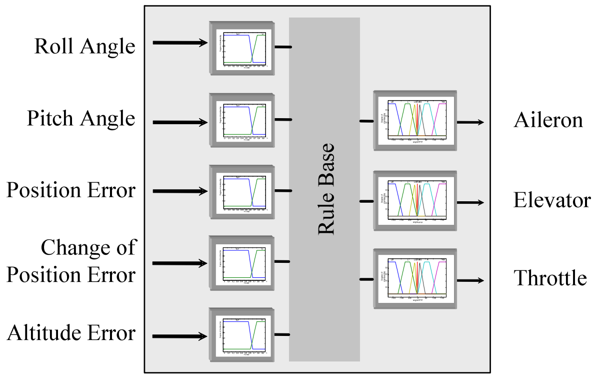

Fig. 6. Hovering and Altitude Fuzzy controller.

As *position error* represents how far the helicopter is from the target point, the *change of position error* represents the way that position error changes and if the helicopter reaches the target point or moves away from it. The *altitude* error is also calculated as the difference between the current and the target altitude. The outputs of the controller are the change of the roll and pitch angles (*aileron* and *elevator* variables respectively), as well as the change in the *throttle* of the helicopter.

In what follows, we present in detail the above input and output variables.

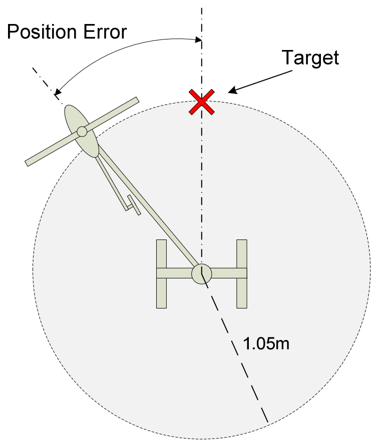

Fig. 7. Position error representation.

Roll angle is given by the IMU in real time. Although the flying stand permits roll angles from -30^o to 30^o, the flight control system takes as input degrees from -90^o to 90^o. 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 Fig. 8.

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 Fig. 8.

The third input variable is the *position error*, which is defined as the difference between the current and the desirable position. Since for safety reasons we do not want the stand to rotate out of its limits (-180^o to 180^o which corresponds to -30 to 30 in odometer units) we set the range of the *position error* variable to be between -30 to 30 (in odometer units). The linguistic variables for these inputs are: *negative big* (*NB*), *negative* (*N*), *zero* (*ZERO*), *positive* (*P*), *positive big* (*PB*) (Fig. 8).

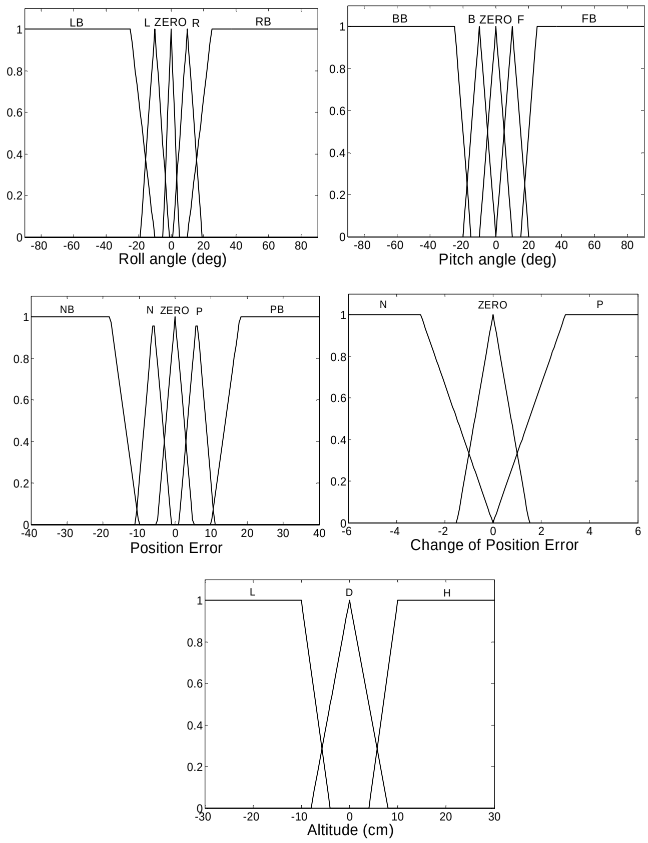

Fig. 8. Membership functions for input variables.

The next input in the fuzzy controller is the *change of position error*. While position error shows how far the helicopter is from the desire position, *change of position error* shows how fast the vehicle is moving towards or away from the desired point. This input is defined as the difference (in odometer units) between the previous position error and the current position error, and it is represented by the linguistic variables: *negative* (*N*), *zero* (*ZERO*), *positive* (*P*) (Fig. 8).

The last input is the *altitude* error input. This input represents the difference in cm between actual and desired altitude by counting if the helicopter is placed lower or higher than the desired position. The linguistic variables for this input are: *lower* (*L*), *desired* (*D*), *higher* (*H*) (Fig. 8).

The outputs of the fuzzy controller are the changes of roll and pitch angles (*Aileron* and *Elevator* movements respectively) and *Throttle* change. The membership functions of *aileron*, *elevator* and *throttle*, are presented in Fig. 8. The linguistic variables for *aileron* are *left big* (*LB*), *left* (*L*), *left small* (*LS*), *zero* (*ZERO*), *right small* (*RS*), *right* (*R*) and *right big* (*RB*). The linguistic variables for *elevator* are *back big* (*BB*), *back* (*B*), *zero* (*ZERO*), *front* (*F*) and *front big* (*FB*). Both *aileron* and *elevator* output values are presented in control signal units.

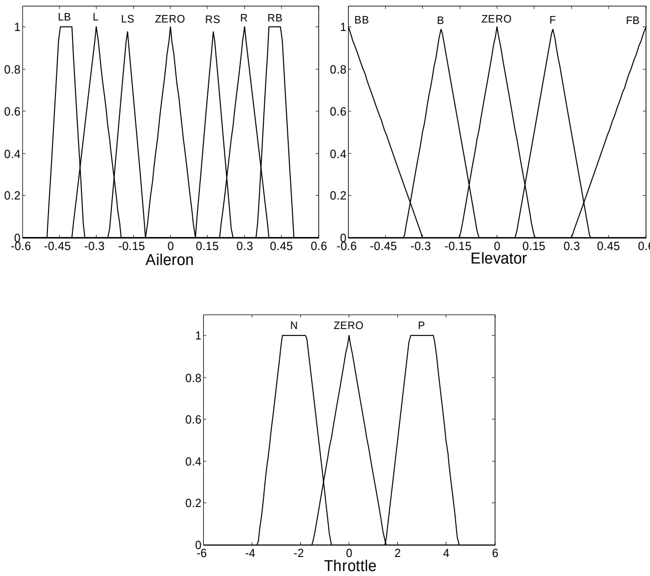

Fig. 9. Membership functions for output variables.

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 helicopter at a certain point (defined by horizontal and vertical target coordinates). The transition between the states of the controller is presented in Fig. 10. After take-off, the controller has as a target to hover the helicopter. Then checks actual horizontal position and drives the helicopter to the desired one. The next step is checking of actual altitude in order to drive the helicopter to the desired one. After some iterations where the helicopter hovers in the target point, the controller lands it.

For the implementation of this scheme, three sets (rule bases) of fuzzy IF-THEN rules were used. The 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. The second rule base contains rules that 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. The third rule base is responsible for handling the throttle of the helicopter. The policy we follow here is that the changes in the throttle of the helicopter occur only when the helicopter is in stable hovering attitude on 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.

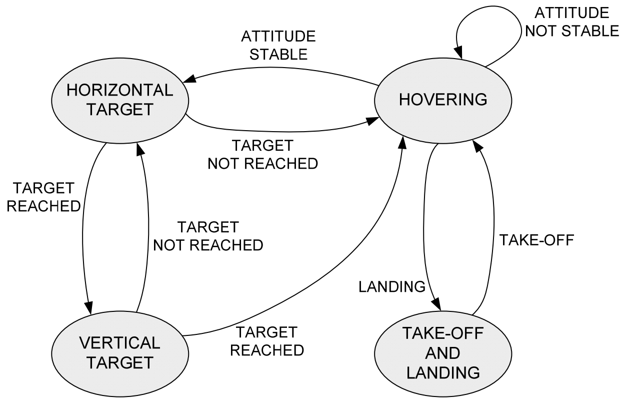

Fig. 10. Controller state transition.

4 Experimental Results

Experimental results for two test cases may be seen in Fig. 11 and Fig. 12. In these figures *Roll* and *Pitch* values are measured in degrees, while *Position Error* and *Change of Position Error* are measured in odometer units (here, 1 odometer unit corresponds to 6 degrees) and *Altitude* is measured in centimetres. *Elevator, Aileron* and *Throttle* values are measured in control signals. The initial altitude of the helicopter (when the flying stand is on the ground) is 10cm.

In **test case 1** (Fig. 11) the ability of the controller to perform autonomous take-off and keep the helicopter in a hovering state, is evaluated. The helicopter is placed on the desired horizontal position and the autopilot takes over with a target altitude of about 22 cm. The controller keeps roll and pitch angles close to zero and gradually increases throttle in order to increase the altitude and reach the target one (Fig. 11). When the target altitude is reached few oscillations around the horizontal position occur but the controller manages to hold the helicopter in hovering. In the beginning, it is clear that position error tends to be a small positive number, which means that the helicopter always drifts to the left. This is explained by the position of the test bed area which is close to the walls of the building. Air flow from the main rotor of the helicopter circles through the walls and return to the helicopter. This air flow gives a small drift to helicopter to the left. The developed controller seems to recognize the disturbance and successfully stabilize the helicopter in the desired position.

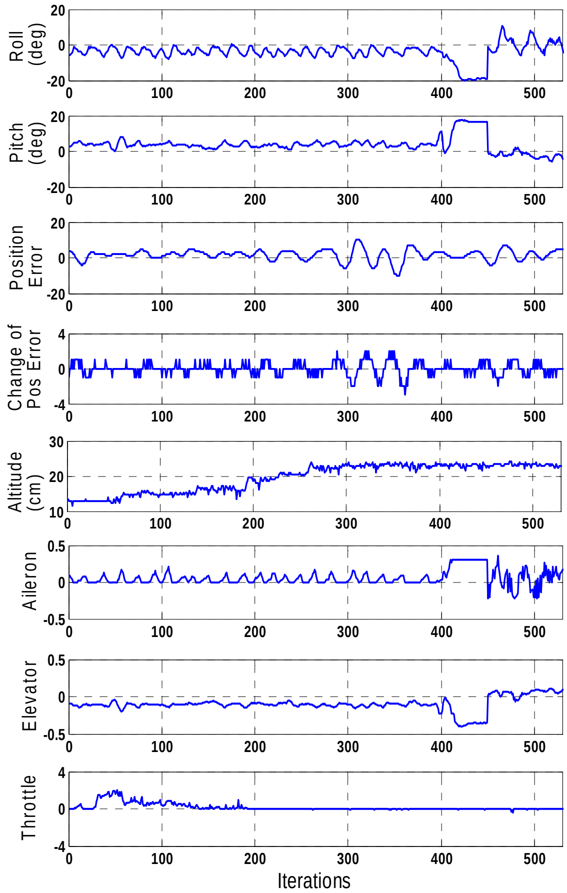

Fig. 11. Experimental results for **test case 1**.

In Fig. 12 we present the results of **test case 2**. In this test, the initial position of the helicopter is different from the desired one and the controller objective is to drive the helicopter to the desired position and then land it autonomously. The helicopter is placed manually to a random position and then the fuzzy autopilot gains control of the helicopter. As one may see in the *Position Error* plot of Fig. 12, the helicopter moves manually from its initial position to a random position. At time instant 50, the autopilot gains control of the vehicle. 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. 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.

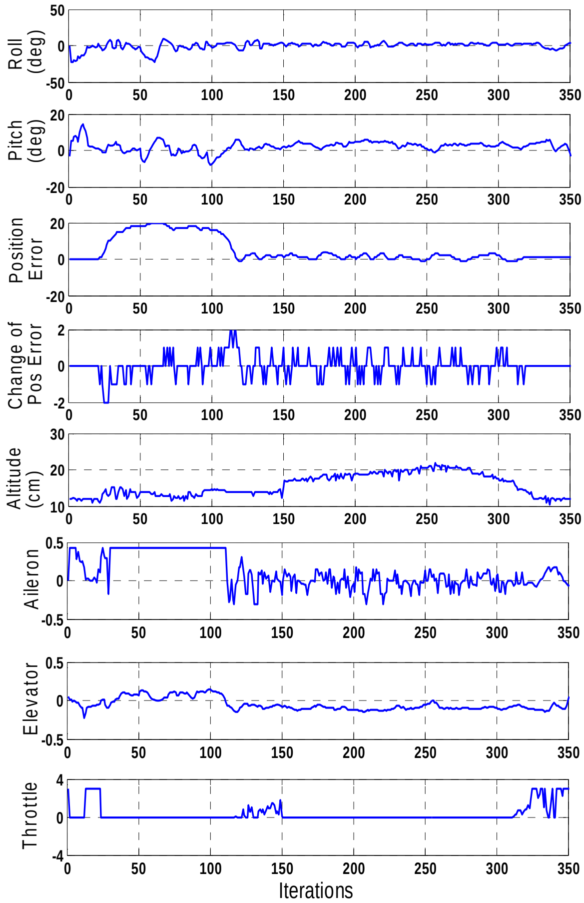

Fig. 12. Experimental results for **test case 2**.

5 Conclusions

In this paper we presented a fuzzy controller for hovering and altitude control of a small-scale helicopter. The controller was developed and tested on a custom made laboratory experimental test bed, where tests on unmanned helicopters can be performed with safety. The test bed works indoors, is independent of power supply and can be used for continuous tests. The development of the controller is done on a real helicopter and not in simulation, so we can have direct and reliable results. Special attention has been paid to the safety of the test bed. The experimental results show that this setup works well. Experimental results from the evaluation of the altitude fuzzy controller were presented.

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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