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# Fuzzy Logic Controller for a Mini Coaxial Indoor Helicopter

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**Abstract** In this paper the design process of a fuzzy logic based controller for a coaxial micro helicopter is presented. The developed controller for altitude, attitude, and position control is tested through simulations on an identified non-linear model of the helicopter. The robustness properties of the controller to parameter variations of the model is assessed, as well as, its ability to accommodate or absorb external disturbances.

**Keywords** Fuzzy logic control · Unmanned Aerial Vehicles · Rotorcrafts

## 1 Introduction

Unmanned Aerial Vehicles (UAVs), and in particular unmanned helicopters, are gaining more and more interest from researchers worldwide because of their ability of hovering and Vertical Taking-Off and Landing (VTOL) capability [12]. Micro Aerial Vehicle (MAV) helicopters are a special category of UAVs with very small sizes, capable of indoor navigation. Their ability to hover and their power to carry payload, makes them particularly suitable for applications in tasks, such as, surveillance and security, search and rescue or inspection and exploration. Many of such vehicles are developed: the Coax [3], the MuFly [10] and the MICOR [2] are the most typical examples.

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A big challenge in the design of an autonomous helicopter in such a size is its feedback control. While the control of a full size and normal size RC helicopter is already very difficult, the micro helicopters additionally suffer from faster dynamics, inaccurate actuators and low output quality of lightweight sensors. Additionally, a very tight and demanding feedback control is required for their mission, as they will be obliged to navigate in dangerous environments, full of obstacles. Various control methods have been proposed for this problem like the traditional PID control [19, 22], a combination of PID and Backstepping (Integral Backstepping) [4], a combination of PID and $H_\infty$ control [21], Sliding mode control [20] and robust $H_\infty$ control [11]. All these techniques need a linearized model of the system in their design process. However, the identification of such a small scale helicopter is a tedious task and few results exist in the literature [7, 11]. The models identified can be linear or a non linear parameter identification method can be used. Linearized models often miss existing effects, like cross couplings between the angular rates, while nonlinear methods suffer from local minima and the curse of dimensionality.

The idea of control unmanned helicopters without the need of a complicated and maybe inaccurate model is very tempting. Reinforcement learning was proposed in [1] and [6] where autonomous aerobatic flight was performed with the help of an "instructor". However, indoor navigation can be a much more complex issue than aerobatic flight where fixed maneuvers are learned by the controller.

Navigation of autonomous robotic vehicles in obstacle filled dynamic environments requires derivation and implementation of efficient real-time sensor based controllers. Effective control algorithms for autonomous navigation, should imitate the way humans are operating manned or similar vehicles. Considering the environment uncertainty that is difficult if not impossible to model, fuzzy logic is one of the most widely used mathematical tools for autonomous vehicle navigation [16]. Fuzzy logic based controllers have been successfully proposed for the control and navigation of small VTOLs [18], fixed wing UAVs [8] and full scale autonomous helicopters [13]. Recently, Tagagi-Sugeno-Kang (TSK) fuzzy systems were used for micro helicopter control [15], but the need for an identified helicopter model is a drawback of these types of controllers. Instead of identifying the system formally beforehand, the fuzzy controller's consequent parameters can be learned using a neuro-fuzzy system (such as the ANFIS: Adaptive Neuro-Fuzzy Inference System) with data collected from an existing, previously implemented proportional controller. This approach was taken in [9] for the heading control of a small indoor helicopter. In [14], a Mandani type fuzzy logic controller was combined with conventional PID controllers. The fuzzy inference system is controlling the translational movement while the PID controllers handle the altitude and attitude of the helicopter. A two-rule Mandani type fuzzy controller was developed for the attitude and altitude stabilization of a coaxial rotor UAV in [17], where the helicopter behavior in a plane is treated as the well-known cart-pole system.

In this paper, Mamdani type fuzzy controllers are used for the full control of a small coaxial indoor helicopter. Attitude, altitude and position of the helicopter are controlled and the ability of the helicopter to follow specific waypoints as well as its robustness to modeling errors is assessed through simulation of an identified model. The main advantage of this scheme, apart from the fast development and the inherent robustness, is that a crisp mathematical model of the helicopter need never be identified.

## 2 The Helicopter

Coaxial helicopters are a particularly suitable design for autonomous indoor flight. The coaxial configuration is able to cancel the gyroscopic effects thanks to contra rotating propellers. It is more compact, avoids the slow dynamics of fixed pitch rotors and exhibits considerable reduced power consumption [5]. The coaxial helicopter is driven by two anti-rotating lightweight brushless DC motors to compensate the resulting torque due to aerodynamic drag. This allows control of the yaw angle by differential speed variation of the two rotors, whereas the altitude can be controlled by varying the rotor speeds simultaneously. A stabilizer bar is attached to the upper rotor to stabilize the helicopter. The helicopter is steered by a conventional swash plate on the lower rotor actuated by two servos and powered by a lithium-ion battery. The configuration is shown in Fig. 1.

The platform is capable of significant payload, allowing the incorporation of several sensors like an Inertial Measurement Unit (IMU) and an ultrasonic distance sensor for the measurement of the distance to the ground. A camera and four distance sensors are installed that can be used for obstacle detection and avoidance. The sensor data is processed by a dsPIC microprocessor and sent to the ground station by a network connection using a Wifi module. The control signals are sent to the helicopter from the ground station through a remote control transmitter (2.4 GHz). The

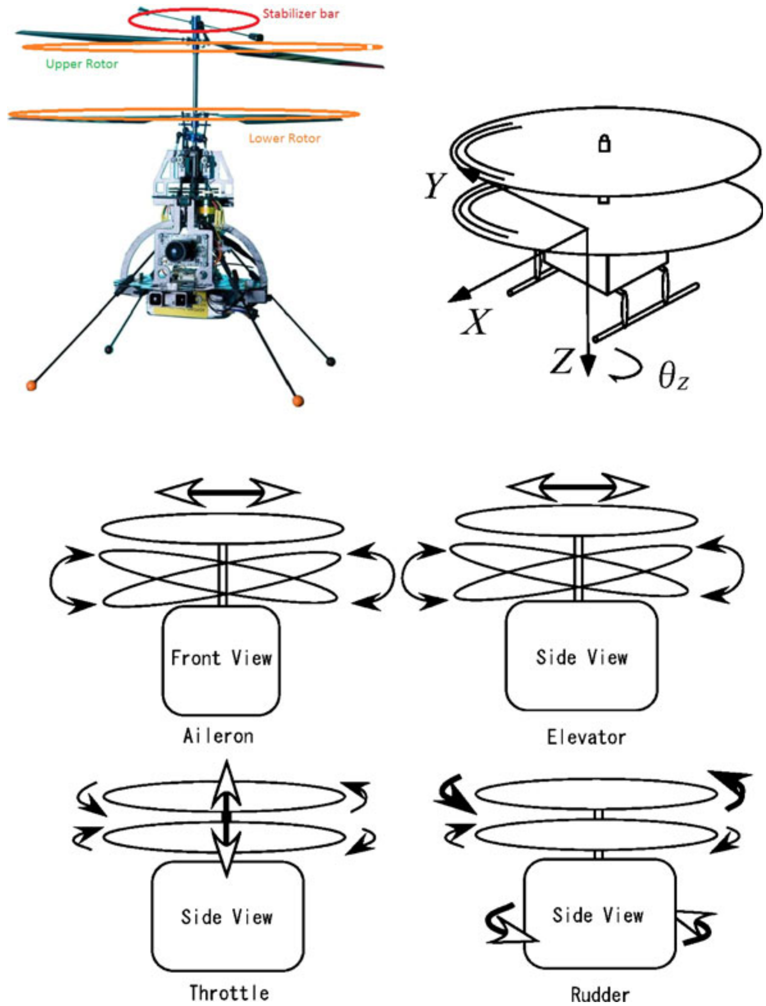


**Fig. 1** Configuration, axes and control of the coaxial helicopter

transmitter is linked to the USB port of a laptop with the use of a commercial interface (PCTx).

### 2.1 Non-Linear Model

The non linear model developed for the helicopter is a physical model based on rigid body motion, similar to the one presented in [11]. As common in aeronautics, an inertial $J$ frame and a body fixed frame $B$ are introduced, resulting in the transformation equation for the position, velocities, angles and angular rates. Using Newtonian mechanics the differential equations for the rigid body motion in the body-fixed frame located at the helicopter's Center of Gravity (CoG) are:

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \frac{1}{m}\mathbb{F} - \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

*and* , (1)

$$\begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = I^{-1}\left( M - \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times I \begin{bmatrix} p \\ q \\ r \end{bmatrix} \right)$$

where $u, v, w$ are the body velocities, $m$ is the system mass, $p, q, r$ are the angular velocities, $I$ is the body inertia tensor and $\mathbb{F}, M$ are the total external force and moment vectors. So far, the equations of motion are independent of the flying platform and can be found in the literature, e.g. [7].

Now the platform dependent total external force $\mathbb{F}$ and moment $M$ vectors have to be defined. The forces and moments acting on the helicopter can be summarized as:

$$\mathbb{F} = T_{up} + T_{dw} + g + W_{hub}$$
$$M = q_{up} + q_{dw} + r_{cup} \times T_{up} + r_{cdw} \times T_{dw} + q_{gyro,dw} + q_{gyro,up}, \quad (2)$$

where $T_{up}$, $T_{dw}$ are the upper and lower rotor thrust vectors, g is the gravity vector, $W_{hub}$ is the aerodynamic fuselage drag, $q_{up}$ and $q_{dw}$ are the rotor drag torques, $q_{gyro,dw}, q_{gyro,up}$ are gyroscopic torques of the rotors and the terms $r_{cup} \times T_{up}$, $r_{cdw} \times T_{dw}$ are the moments due to the cross product of the forces not aligned with the CoG. Aerodynamic forces and moments on the fuselage due to translation of the air are neglected since the helicopter will mainly operate around hover condition.

The next step is to define the single forces and moments. The rotor thrust vector, $T_i$ and the rotor torque vector $Q_i$, can be defined as $Ti = |Ti| n_{T_i}$ and $Q_i = |Q_i| n_{Q_i}$, where the subscript $i \in \{dw, up\}$. In hover, the thrust and torque magnitude of a rotor of radius $R$, can be defined as:

$$|T_i| = c_{T_i} \pi \rho R^4 \Omega_i^2 = c_{T_i} K_T \Omega_i^2$$
$$|Q_i| = c_{Q_i} \pi \rho R^5 \Omega_i^2 = c_{Q_i} K_Q \Omega_i^2, \quad (3)$$

where ρ is the air density, $c_{T_i}$, $c_{Q_i}$ are the thrust and torque coefficients and $\Omega_i^2$ is the rotor speed.

The thrust vectors can be described using two tilt angles $\alpha_i$ and $\beta_i$ around the $x$ and $y$ axis as:

$$n_{T_i} = \begin{bmatrix} \cos\alpha_i \sin\beta_i \\ \sin\alpha_i \\ -\cos\alpha_i \cos\beta_i \end{bmatrix}, \quad (4)$$

while the rotor torque vectors are assumed to act only in the rotor axis (z-axis).

In order to fully define the thrust we thus need to define the angles $\alpha$, $\beta$ for every rotor. For the upper rotor these angles are highly influence by the presence of the stabilizer bar. If we define as $n_{bar}$ and $\zeta_{bar}$, the angles between the rotor axis and the normal of the stabilizer bar frame, the tilt angles of the rotor thrust vector in the body fixed frame are the differences between the two angles $n_{bar}$ and $\zeta_{bar}$ and the roll and pitch angles scaled by the factor $I_{up}$. Thus the equations for the tilting angles of the thrust vector for the upper rotor are:

$$\alpha_{up} = I_{up}(\phi - n_{bar})$$
$$\beta_{up} = I_{up}(\theta - \zeta_{bar}), \quad (5)$$

The angles $n_{bar}$ and $\zeta_{bar}$, are dynamically changing and can be modeled as first order systems with time constant $T_{f,up}$:

$$\dot{n}_{bar} = \frac{1}{T_{f,up}} (\phi - n_{bar})$$
$$\dot{\zeta}_{bar} = \frac{1}{T_{f,up}} (\theta - \zeta_{bar}). \quad (6)$$

The lower rotor on the other hand is controlled by the dynamics of the swash plate. The reaction from the servo input to the change of the tip path plane (TTP) can also be modeled as a first order system. Hereby all the dynamics of the servos and rotors are covered by the time constant $T_{f,dw}$. The tilting angles of the lower rotor are therefore modeled as:

$$\dot{\alpha}_{dw} = \frac{1}{T_{f,dw}} \left(-I_{dw} u_{serv2} \theta_{sp\max} - \alpha_{dw}\right)$$
$$\dot{\beta}_{dw} = \frac{1}{T_{f,dw}} \left(-I_{dw} u_{serv1} \theta_{sp\max} - \beta_{dw}\right), \quad (7)$$

where $I_{dw}$ is the scaling factor, $\theta_{sp\max}$ the maximal swash plate tilting angle and $u_{servi}$ the servo inputs.

Finally, the last torques in Eq. 2, are the gyroscopic torques, that result by the acceleration of the rotors. The gyroscopic torque vectors are assumed to act only in the rotor axis direction with the magnitude:

$$Q_{gyro,i} = J_{drive,i} \dot{\Omega}_i \quad (8)$$

## 3 Controller Design

The control structure for full control of the helicopter is presented in Fig. 2. It consists of six independent controllers. One for the altitude, yaw, pitch and roll, while the position $x$ and $y$

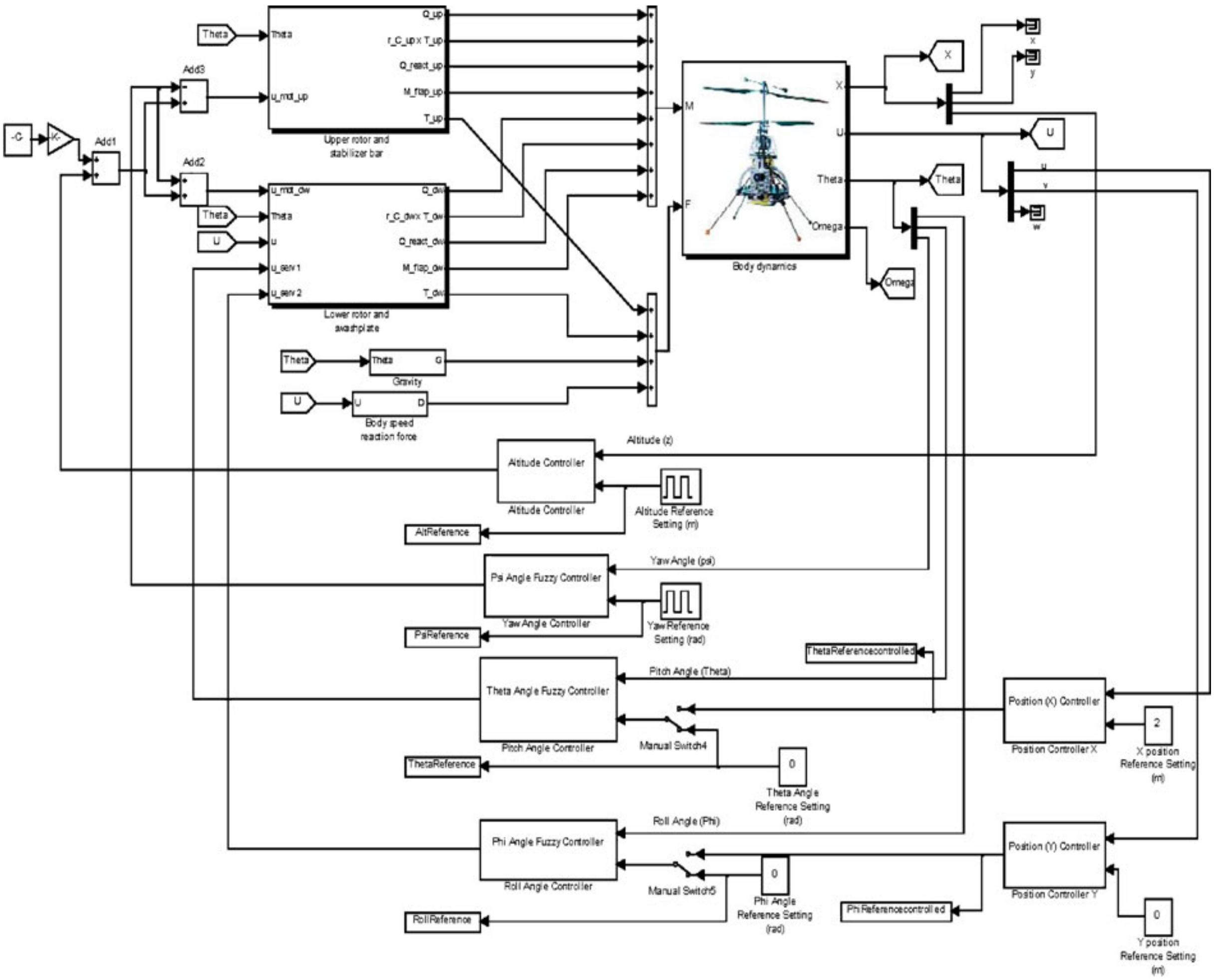


**Fig. 2** The overall Simulink model of the helicopter and the control system

controllers generate reference inputs to be tracked by the pitch and roll controller.

In the following sections, each controller is described and its performance is evaluated through simulations.

## 3.1 Altitude Control

The altitude controller uses the measurement of height provided by the vertical distance ultrasonic sensor to track the reference height by changing simultaneously the speed of rotation of the two rotors and consequently the thrust.

The proposed controller is a PD like fuzzy controller. It uses the reference height and the current height measurement to produce an error signal. This signal as well as its rate of change is calculated and sent to the fuzzy controller as shown in Fig. 3.

The altitude values (both current and reference) are assumed to range from 0 to 2 m as the helicopter is assumed to move in indoor environments. This means that the error signal will range from −2 to 2 m. The linguistic variables that represent the altitude error are: *Verylow*, *Nlow*, *Low*, *Zero*, *High*, *Nhigh*, *Veryhigh*. The membership functions, which have been derived empirically from tests, are shown in Fig. 4a.

The second input to the fuzzy controller is the rate of change of altitude error, which expresses the vertical velocity by which the helicopter approaches the target height. The variable will

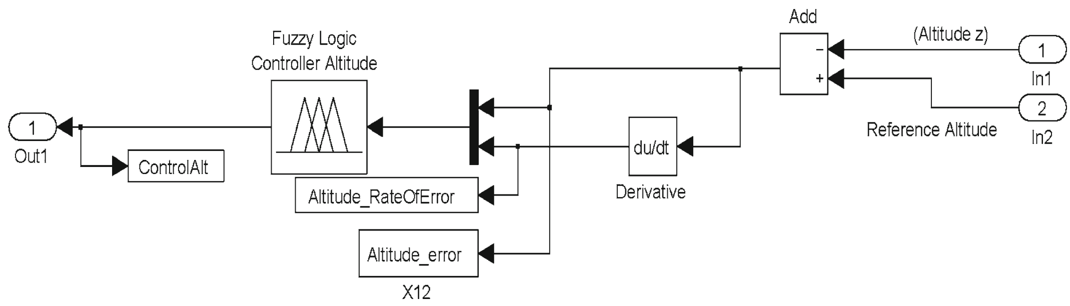


**Fig. 3** The block structure of the Altitude controller

obviously be limited by the vertical velocity capability of the helicopter which is estimated to 0.5 m/s. The linguistic variables that represent the altitude error are: *Low*, *Llow*, *Zero*, *Lhigh* and *High*. The membership functions are shown in Fig. 4b.

The fuzzy controller has one output, the motor speed change which is added to the idle speed of the rotor and supplied to both upper and lower rotor. The linguistic values that represent the altitude tracking command are: *Lowpower*, *Low*, *Llow*, *Idle*, *Lhigh*, *High* and *Highpower*. The membership functions are shown in Fig. 5:

The controller has been developed using 29 IF–THEN rules. An example of rules is demonstrated: IF *AltituteError* is *High* AND *RateAltitudeError* is *Llow* THEN *Motorspeed* is *Idle*. The development of these rules is based on consecutive tests and their control output surface is shown in Fig. 6.

The controller was tested in the Simulink environment using a nonlinear dynamic model of the helicopter. The response of the helicopter (dashed line) to pulse commands (solid line) in heave (altitude) is presented in Fig. 7. During the simulation the helicopter is commanded to descent from 1.5 m height to zero (20 s) and then regain the original height (40 s). It is clear that the helicopter can truck the commands efficiently. The ascent is completed within 5 s from the command while the descent is slower and is completed in 7.5 s.

The identification process of a mini helicopter is particularly difficult and small errors in the identification parameters are expected. This means

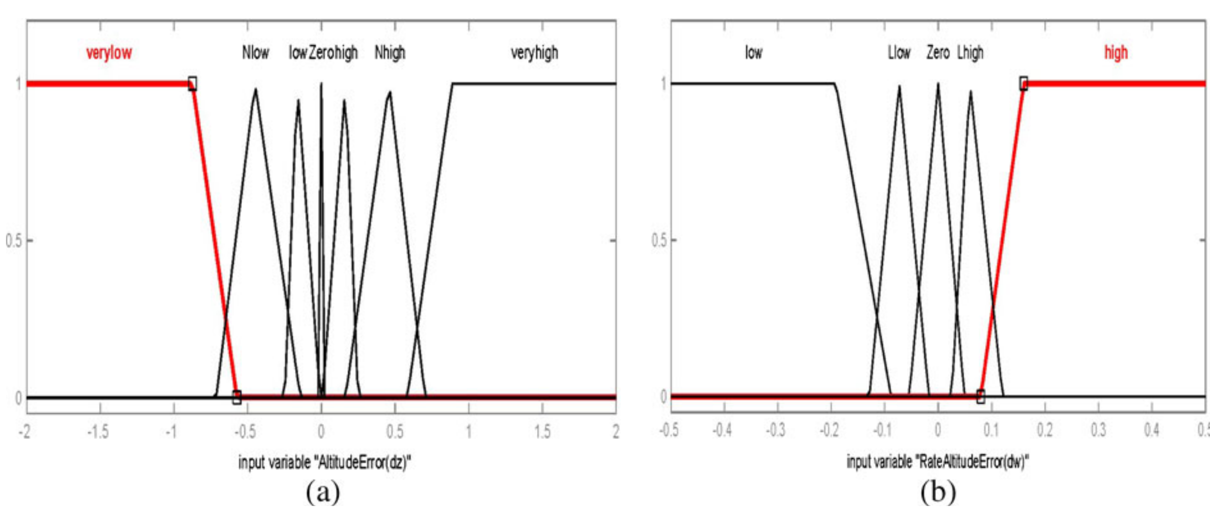


**Fig. 4** Membership function plot of the input variables **a** "Altitude Error", and **b** "RateAltitude Error"

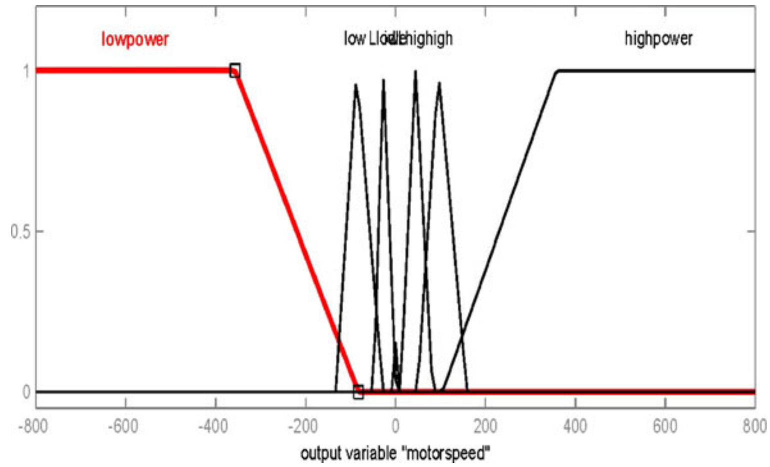


**Fig. 5** Membership function plot of output variable "Motorspeed"

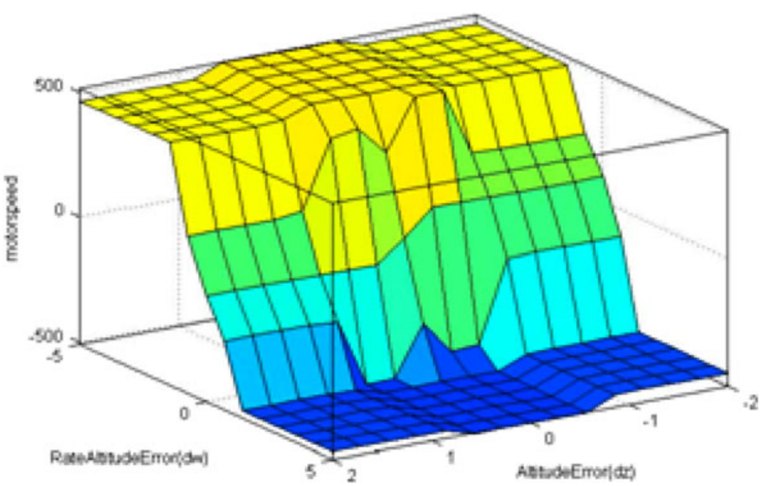


**Fig. 6** The control surface for the Altitude controller

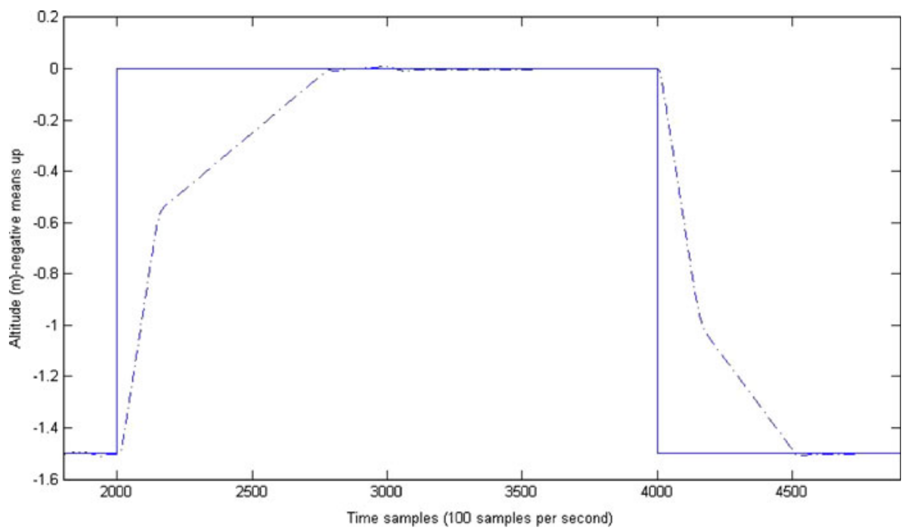


**Fig. 7** The response to Altitude reference commands

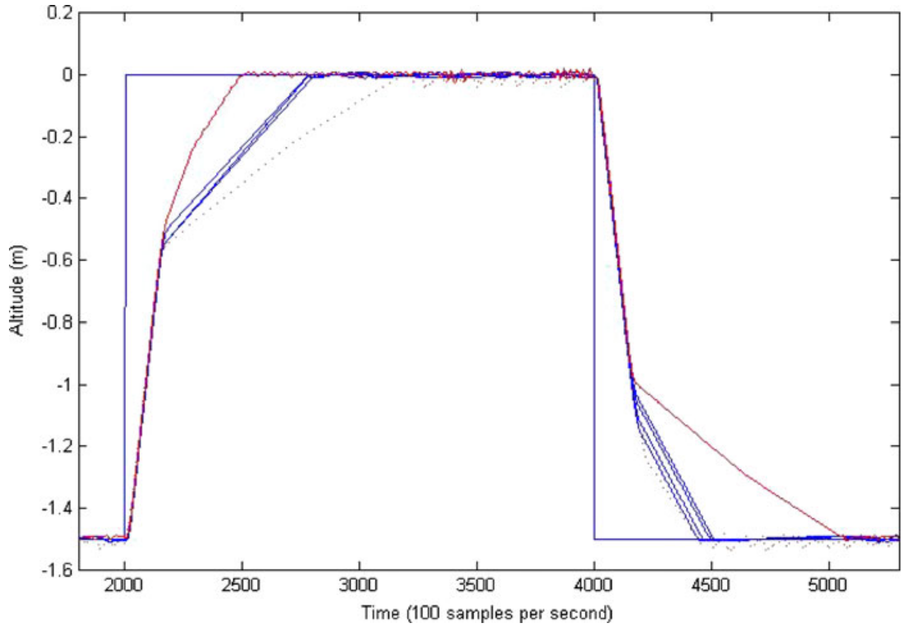


**Fig. 8** Robustness simulation for Altitude reference commands

that any controller has to be robust to parameter variations. The robustness of the altitude controller was tested in simulation by varying three system parameters, namely, the upper thrust and torque coefficients and the upper drive train inertia. In accordance to [11], the parameters are allowed to vary in a deviation range of ±20%. In Fig. 8, the results for pulse commands in heave (solid line) are plotted for the nominal plant and the plant with varying the above mentioned parameters. In the case of the upper rotor torque and upper drive train inertia variation, the performance is very similar to that of the nominal plant (blue lines in the figure). There is a small deviation in the case of varying thrust coefficient (red lines) however the performance can be considered acceptable for such a large deviation. Also, no steady state error is present although small oscillations are observed when the thrust coefficient is varying.

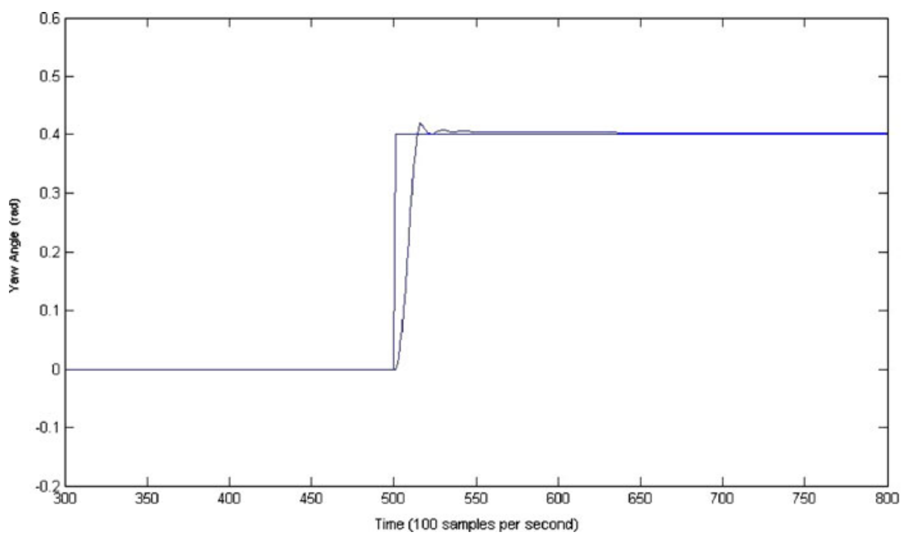


**Fig. 9** The response to a yaw step command (5 s)

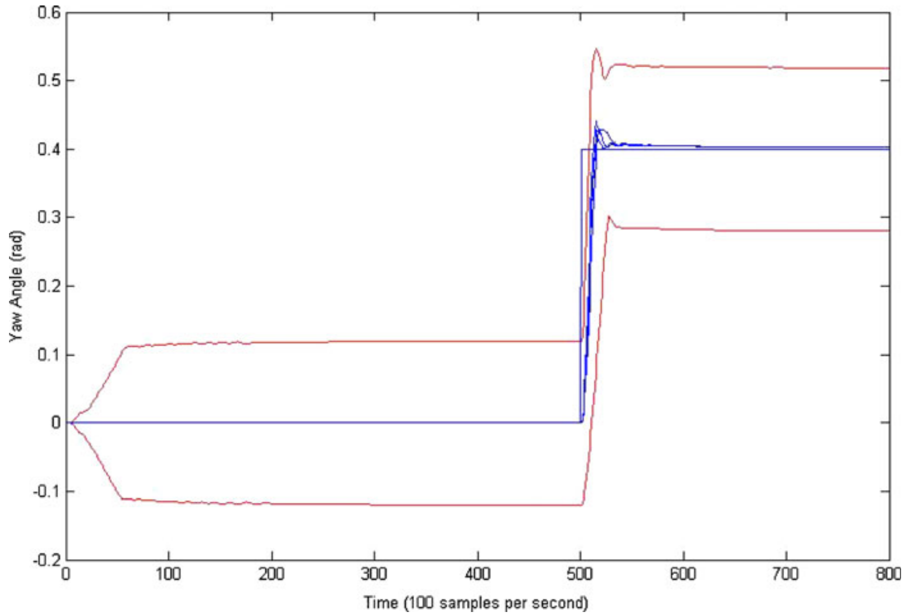


**Fig. 10** Robustness simulation for a step command in yaw (5 s)

### 3.2 Directional (Yaw) Control

The yaw controller is structured in a very similar way as the altitude controller. It is again a PD like fuzzy controller with two inputs and one output. The two inputs is the error between desired and actual yaw (YawError) and its rate of change. The output is the difference in speed between the upper and lower motor. The simulation results for a step command in yaw are presented in Fig. 9. The robustness properties of the yaw controller were tested in a similar manner to the previous paragraph and the results are presented in Fig. 10.

It can be seen that the controller is very fast in following the input command (from zero to a yaw angle of 0.4 rad (23 deg) in 1.5 s, although a small overshoot is present (about 3%). As far as robustness is concerned the controller is relatively insensitive to parameter variations of upper thrust coefficient and upper drive train inertia. However, small deviations of the upper torque coefficient

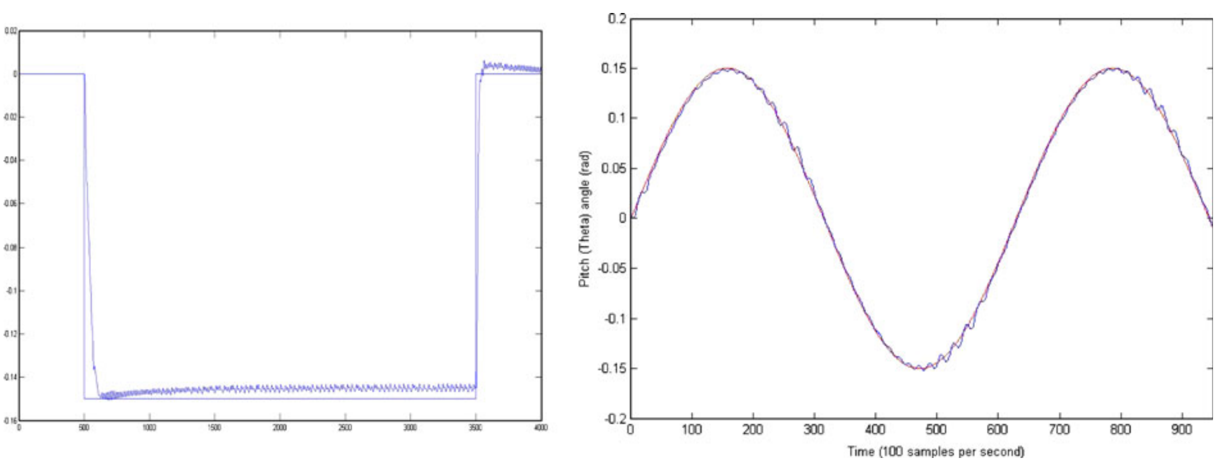


**Fig. 11** The helicopter responses to a pitch pulse command (5 s) of duration 20 s and a sinusoidal reference signal

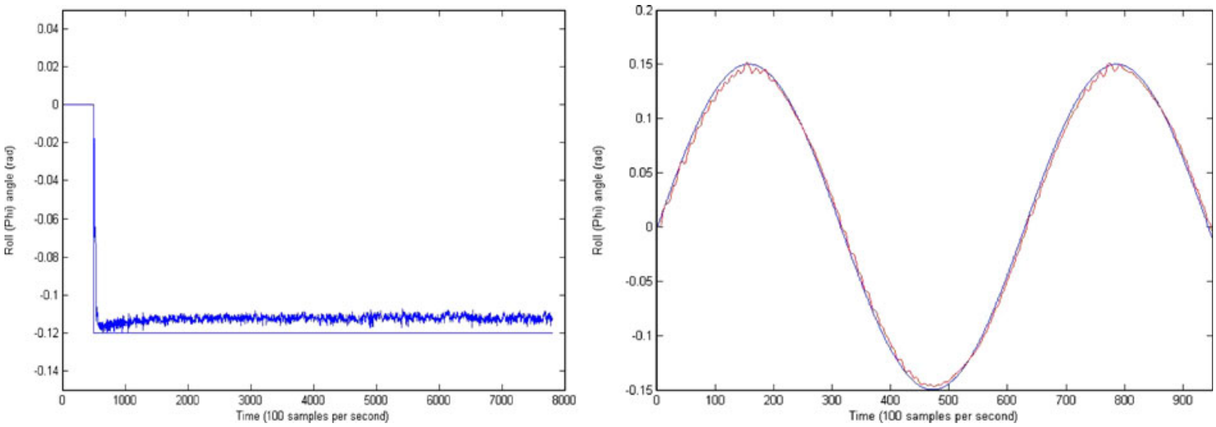


**Fig. 12** The helicopter responses to a roll step command (5 s) and sinusoidal reference signal

(10%) reduce performance significantly and introduce steady state errors (red lines).

### 3.3 Pitch-Roll Controller

Pitch and Roll controllers are designed in a similar way with slightly different membership functions and rules. The simulation results for different reference inputs for pitch and roll are shown in Figs. 11 and 12.

The controllers for pitch and roll are capable of following accurately the reference signals, although a small steady state error is present (2%). Additionally there is a very small oscillation (0.1°). This oscillation has very small amplitude in respect to the reference inputs and can be considered acceptable since the helicopter is going to navigate using small amplitude reference signals and won't be required to sustain large pitch and roll angles. The capability of the controller to track a quickly varying signal (like the sinusoidal input) is much more critical.

The robustness of the controllers to parameter variations were assessed through simulations.

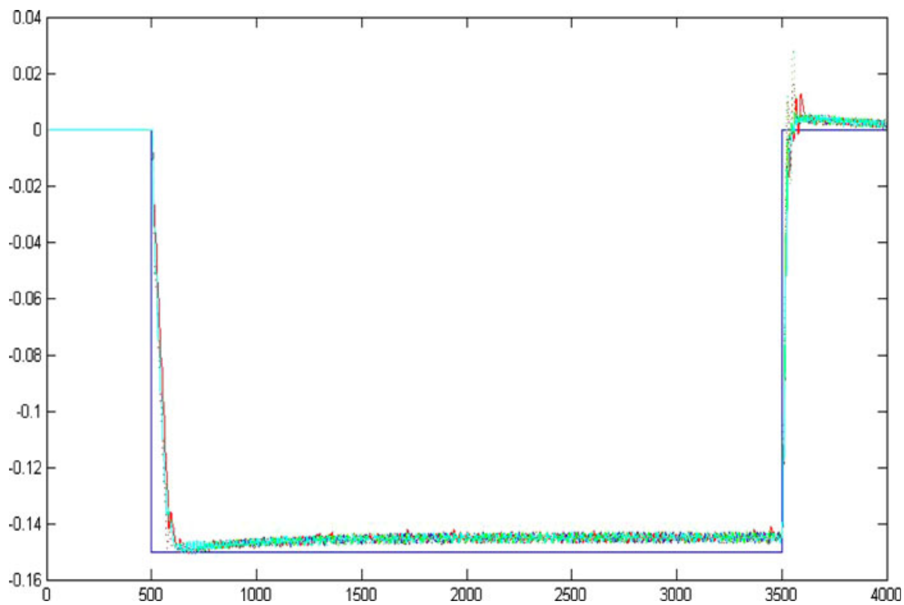


**Fig. 13** Robustness simulation for a pulse command in pitch (5 s)

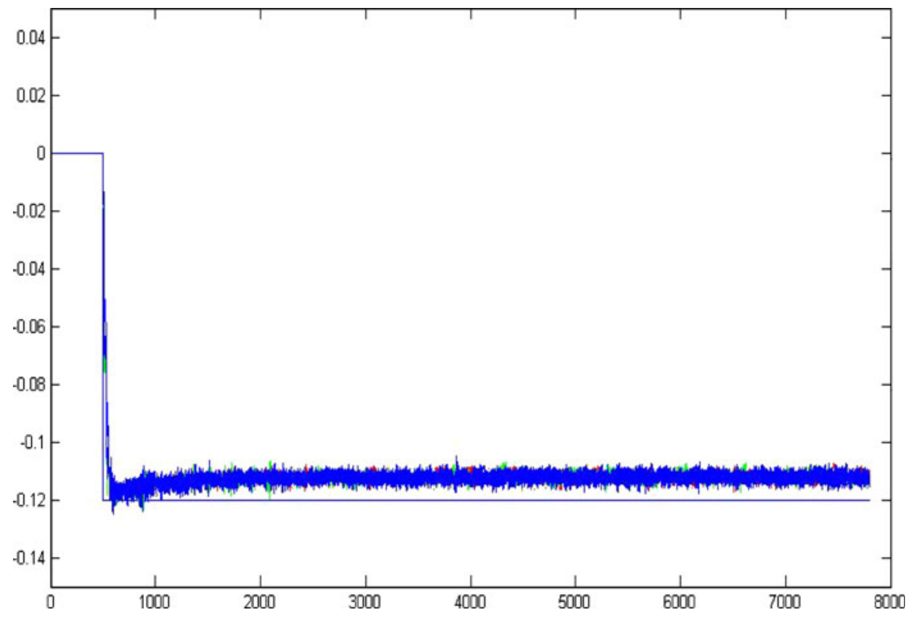


**Fig. 14** Robustness simulation for a step command in roll (5 s)

The results are presented in Figs. 13 and 14. The controllers are relatively insensitive to parameter variation of upper rotor thrust coefficient and upper drive train inertia (±20% range). However, there is reduced robustness in the case of upper rotor torque coefficient (green line), as in the case of the yaw controller, which can be allowed to vary only within ±5%. Larger variations of the specific parameter introduce large overshoot and finally instability.

### 3.4 Position Controller

Position control of the helicopter can be achieved using the IMU measurements. It is certain that MMS inertial sensors have low quality and increased noise, and their accuracy gradually degrades in a flight, however, for the sort flights of the coaxial helicopter their accuracy can be assumed sufficient. Additionally, they provide an independent navigation sensor capable of functioning in

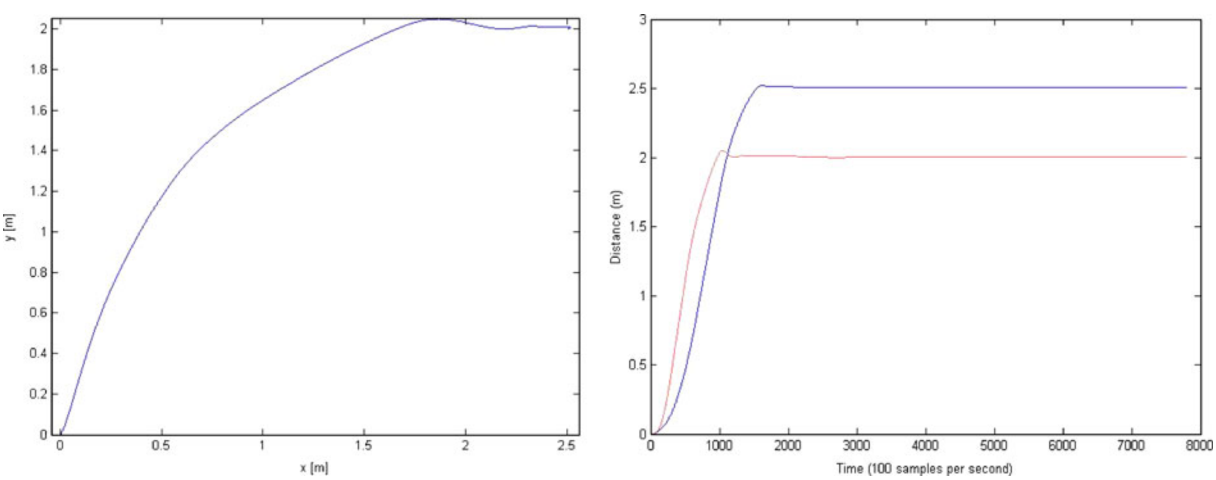


**Fig. 15** Tracking of the waypoint (2.5, 2). The helicopter motion on the x-y plane (*left*) and the state variables x (*blue line*), y (*red line*) as a function of time (*right*)

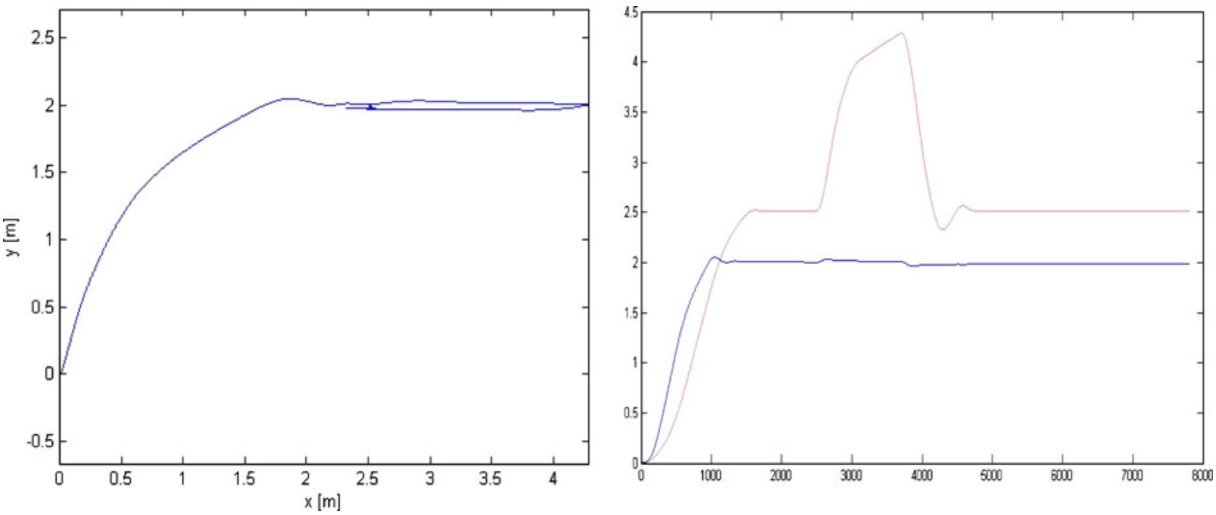


**Fig. 16** Response to Test Scenario 1 (disturbance (force) along the x-axis (25 s to 32.5 s)): The helicopter motion on the x-y plane (*left*) and the state variables x (*blue line*), y (*red line*) as a function of time (*right*)

non structured environments. The IMU position estimate can be enhanced by sensor fusion if additional sensors (i.e. camera) are used for localization. In this paper, the estimated position coordinates ($x$, $y$) are assumed available for control purposes.

The two position controllers for $x$, $y$ coordinates, are assumed decoupled. This assumption is justified by the fact that the helicopter will operate close to hover due to its mission profile. Two PD like fuzzy controllers are designed in a manner similar to the previous sections. Their inputs are waypoint coordinates and their outputs are pitch and roll reference angles to be tracked by the pitch and roll controllers. This structure allows a simple design and 49 IF–THEN rules are used. Simulation results are presented in Fig. 15. It is clear that the helicopter is capable of navigating to the specified waypoint (2.5, 2) and remains there.

A desirable property of a helicopter's control system is its ability to reject external disturbances like air gusts. This robustness is, to an extent,

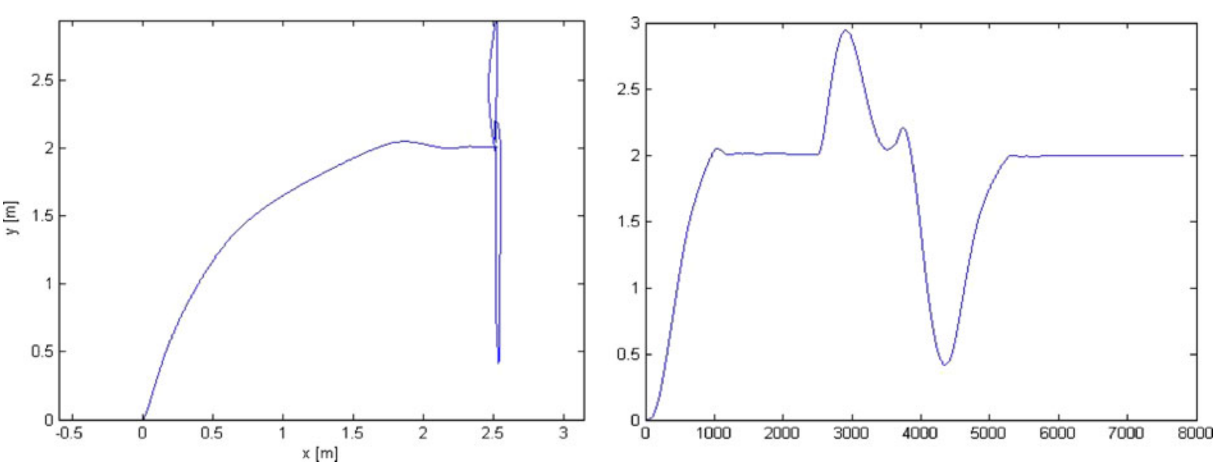


**Fig. 17** Response to Test Scenario 2 (disturbance (force) along the y-axis (25 to 32.5 s)): The helicopter motion on the x-y plane (*left*) and the state variables y (*blue line*) as a function of time (*right*)

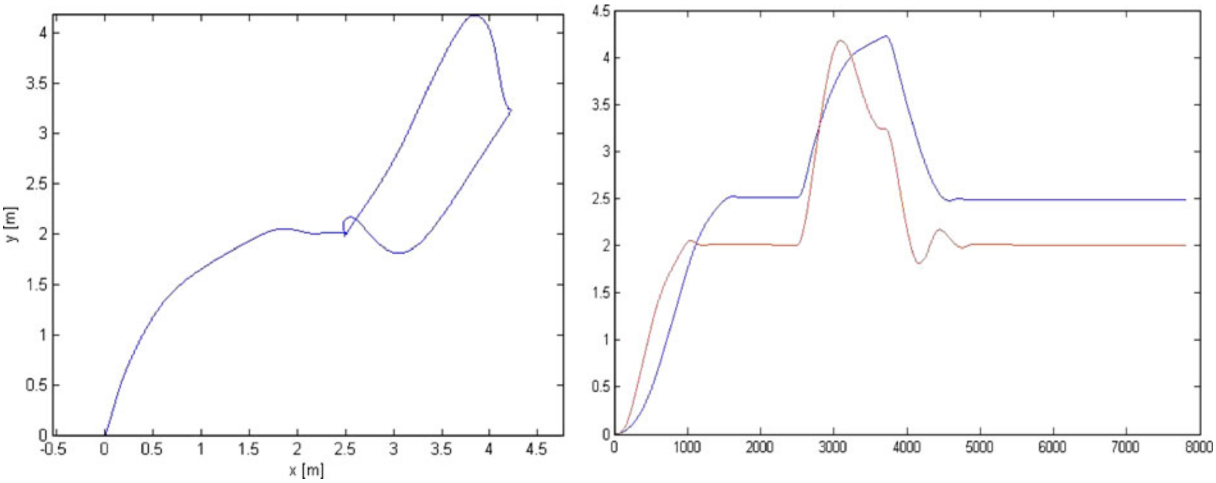


**Fig. 18** Response to Test Scenario 3 (combined disturbance (force) along the x and y-axis (25 s to 32.5 s)): The helicopter motion on the x-y plane (*left*) and the state variables x (*blue line*), y (*red line*) as a function of time (*right*)

inherent to fuzzy controllers. The robustness of the proposed controller to external disturbances was investigated through simulations. The disturbances were injected as pulses added to the several components of the forces and moments acting on the body of the helicopter. The results of the simulations to these disturbances can be seen in the following figures (Figs. 16, 17, 18 and 19). The simulations show that the helicopter responds to sudden forces applied to it by changing its attitude accordingly and can regain its original position and attitude after the disturbance. Several test scenarios where used for the simulations and are summarized in Table 1.

## 3.5 Discussion

Taking under consideration the controller design process, we can argue that it is simple and straight forward. No modeling is required and it can be

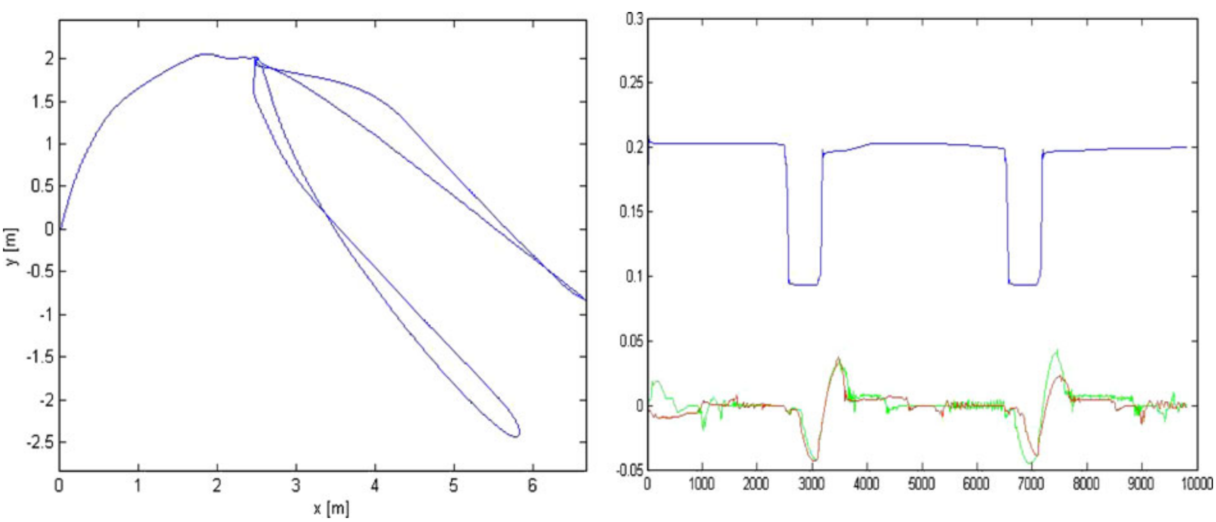


**Fig. 19** Responses to Test Scenario 4 (two combined disturbances (moments) around the x, y and z-axis (25 to 31 s and 65 to 71 s)): The helicopter motion on the x-y plane (*left*) and the state variables yaw (*blue line*), pitch (*red line*) and roll (*green line*) in radians as a function of time (*right*)

**Table 1** Simulated test scenarios for external disturbances acting on the helicopter

| Test scenario number | Disturbance description | Duration of disturbance | Observations |
|---|---|---|---|
| #1 | One pulse added (at time: 25 s) as force component along the x-axis | 7.5 s | The helicopter deviates considerably along the x-axis but is able to regain the original position 15 s after the disturbance. |
| #2 | One pulse added (at time: 25 s) as force component along the y-axis | 7.5 s | The helicopter deviates considerably along the y-axis but is able to regain the original position 20 s after the disturbance. |
| #3 | One pulse added (at time: 25 s) as force component along the x and y-axis | 7.5 s | The helicopter deviates considerably along the x and y-axis but is able to regain the original position 16.5 s after the disturbance. |
| #4 | Two successive pulses (time: 25 and 65 s) added as moment components around the x,y and z axis | 6 s | The helicopter deviates considerably along the x and y-axis. The attitude angles are also disturbed however the disturbance is quickly (within 5 s) suppressed and the control system is able to manipulate the pitch and roll angles to regain the helicopters original position. |

applied directly to the real plant (as long as a reasonable safety mechanism—i.e. a manual/auto switch to disengage the controller and allow control by a human operator—is applied to avoid collisions to the ground). In this way modeling errors due to linearization do not enter in the controller design process.

The controller was also proved to be robust to parameter variations. The simulations showed increased sensitivity to only one parameter (the upper rotor torque coefficient), which can be allowed to vary by as much as 5%. The robustness properties of the controller to the variation of the other parameters are directly comparable to the results obtained in [11] where a robust controller was designed for the same helicopter. In the case of a fuzzy logic controller, robustness properties are not as important as for controllers designed using linear techniques, since modeling errors are avoided and the design is accomplished on the plant itself. However, these properties guarantee acceptable performance and graceful degradation under different flight conditions (when parameters generally vary) or in the presence of faults (i.e. loss of effectiveness of the rotors due to wear).

Finally the simulations showed that disturbances can be rejected by the controller so that the stability of the helicopter is guaranteed. The deviation of the helicopter from its predefined position, is considerable, however it can quickly regain its desirable attitude and position. This deviation can be unacceptable, depending on the mission requirements. It should be pointed out that the disturbance rejection property demonstrated, is inherent to the controller and no special attention was given during the design. Wind gusts are the most usual source of external disturbance and although the helicopter is designed to be operated indoor, flows of air from air-conditioning or air streaming caused by i.e a fire during a search and rescue mission, can make the helicopter deviate from its current position. More sophisticated design to meet wind gust rejection requirements is needed.

## 4 Conclusions

In this paper we have presented a fuzzy logic approach to the design of a full controller for a micro indoor coaxial helicopter. The control system's performance was evaluated through simulations of a realistic non-linear model of the helicopter. The control system was shown to be able to track reference signals in altitude and attitude and to follow desired waypoints. Additionally, the robustness of the system to parameter variations as well as external disturbances was proved. Although the controller does not possess the robustness properties of a robust controller, it is fairly robust to most parameter variations.

The future directions of the research include the implementation of the controller on the real helicopter. The modification of the controller in order to enhance its disturbance rejection capabilities is also possible. Finally, a navigation module capable of creating desired trajectories in an obstacle filled environment and modifying the commanded routes for obstacle avoidance is planned to be incorporated to this design.

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