Fuzzy Logic Assisted Helicopter Flight Control

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Introduction

Flying a helicopter is a task that requires a great amount of experience and skill. This is due to the strong coupling that exists between the six degrees of freedom, resulting in the 12 dimensions needed to describe the dynamics of a helicopter. Therefore, to perform even a simple flight movement, such as “go up” or “go down”, the helicopter pilot has to carefully adjust more than one control simultaneously.

The use of small-sized helicopters as UAV for professional applications is rapidly increasing. Examples of such applications include military reconnaissance and police surveillance, for movie filming, surveying, etc. However the strong nonlinear coupling among the degrees of freedom and the amount of experience and skills required for safe flight control of small-size remote-controlled helicopters, make it attractive to develop a flight assistant that aids inexperienced operators in flying a successful mission. This is even more true for small helicopters, because of their smaller inertia and the associated smaller time scales of the dynamics involved.

This motivated the present research and development of an intermediate intelligent agent that is capable to navigate a small helicopter safely using elementary commands that are given by a non-expert user. This means that anyone can set a flight path via a user interface, by giving elementary commands (e.g. “go up”, “go down”, “hover”, “go forward”). The intelligent agent must take all the necessary actions that the experienced pilot would take to control the helicopter and ensure the implementation of the desired flight path within a safe flight envelope. The architecture of the agent-helicopter system is schematically depicted in Fig. 1.

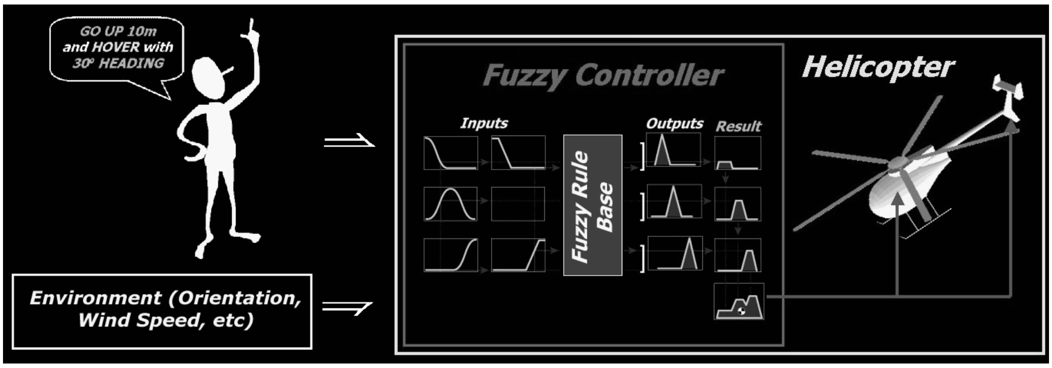

Figure 1. A schematic view of the user-agent-helicopter architecture

Guidance systems have been developed and implemented for model helicopters by different research groups, e.g. Linköping University [1], Swiss Federal Institute of Technology in Zurich [2] and Tokyo Institute of Technology [3]. Within the present paper the fuzzy logic approach will be investigated. The decision to use fuzzy logic for the implementation of the helicopter controller was based on the ability of fuzzy systems to model and absorb human experience and actions, even in the presence of uncertainty.

This research is conducted in order to verify the ability of a fuzzy controller to encapsulate a helicopter pilot's experience and actions. This means that within this work, the capability of fuzzy logic to control systems with strongly coupled degrees of freedom and dynamics will also be investigated. Although M. Sugeno of the Tokyo Institute of Technology has conducted the first work in this field [3] already in 1995 and has developed an autonomous helicopter using fuzzy logic control, it is very difficult to locate any specific publication with details on the implementation of the actual fuzzy logic controllers.

As a first step, we designed the hovering control. This is motivated by the fact that take-off and hovering at relatively high altitude are the first lessons that a real helicopter pilot takes. In order to be able to implement a helicopter movement, first a mathematical helicopter model has been implemented [4-7]. The fuzzy logic controller was designed to encapsulate the experience and knowledge of the pilot in order to take off and make the helicopter hover at a user-specified altitude and heading. Additionally, an interactive Graphical User Interface (GUI) has been developed so that a user can define the desired altitude and heading that the helicopter should reach. Also, within this GUI the user can directly manipulate the helicopter's controls and thus fly the helicopter model manually.

For the development of the mathematical model and the fuzzy logic controller and the implementation of the Graphical User interface, the modelling platforms of Matlab, Simulink and the Matlab fuzzy toolbox were used. This work sets the basis for further development of an ensemble of fuzzy controllers that will be able to perform all of the actions that a helicopter pilot can take. This should ultimately lead to an autonomous flight controller for unmanned helicopters. Therefore the reliability, robustness and safety of such system must be determined.

Fuzzy logic control

The use of soft-computing theory, such as fuzzy logic covers a broad scope, ranging from theoretical work in e.g. the foundations of quantum mechanics [8], to industrial applications in pattern recognition and sensor fusion (for a review see: [9-11]), mission-critical applications [12], and nuclear reactor control [13]. Modelling and simulating human knowledge and intelligence has been an active area of research over the past decades. There are various examples of procedures for which the relation between the inputs and the outputs of a system is only qualitatively known and therefore control cannot be achieved with conventional methods. Still, experienced operators manage to efficiently control such processes without having precise knowledge of the underlying physics or mechanics. In practice, the user consciously or subconsciously uses rules that he has learned and which he constantly updates. These rules are the result of experience acquired from learning in the real world.

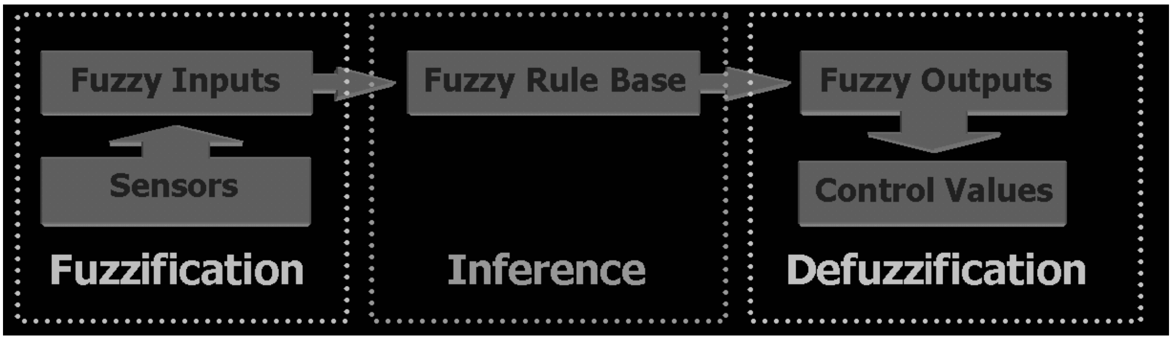

Figure 2. The three main parts of a fuzzy controller: real-world inputs have to be converted to fuzzy numbers, so that the fuzzy rule base (the expert system) can infer with the inputs and generate the fuzzy outputs. The last are defuzzified in the final stage to yield real-world values.

The aggregate of all the rules that describe how a process could be controlled, results in "intuitive skill-based models".

Fuzzy controllers make use of such experience models. The formulation of the control rules is not analytic, instead they are expressed in linguistic form. The basic problem in the design of a fuzzy interface is the representation of such an experience model or expert system in a concise and computationally treatable way. We distinguish different parts of our controller. The basic parts of a generic fuzzy model are displayed in Fig. 2.

In general, there must be a mechanism that is capable of translating numerical (measured) values from the various sensors into fuzzy concepts ("fuzzification"). In addition we must have a mechanism to take fuzzy decisions on the basis of the expert knowledge as stored in linguistic rules ("inference"). Finally we must translate the fuzzy output commands (decisions) into real-world control values ("defuzzification").

Each fuzzy variable, e.g. *InputX,* is characterized by a set of Membership Functions (MFs). Membership Functions may partially overlap with each other. They assign numerical values to linguistic values via weights $\mu_{MF} \in [0,1]$, e.g. $\mu_{MF}(InputX) = 0.85$. In fuzzy set theory MFs are a generalization of the characteristic functions in classical set theory. With the help of MFs it is possible to define operations on sets, such as the complement, union ($\cup$), and intersection ($\cap$).

The inference process translates fuzzy inputs into fuzzy outputs using a rule base that defines the structure of the controller. It makes decisions (i.e. activates output MFs) on the basis of the actual fuzzy input values, i.e. the activated input MFs. Fuzzy rules can be activated simultaneously and are of the following form:

IF *InputX* **is** *MF1* **AND** *InputY* **is** *MF2* **THEN** *OutputZ* **is** *MF3*

The activation σ_j of a rule R^j can be calculated from the fuzzy input values *InputX* and *InputY* (or any other inputs that may exist) in the following way as the (fuzzy) intersection of the relevant input variables:

$$R^j : \sigma_j\left(InputX, InputY\right) = \mu_{MF1 \cap MF2}\left(InputX, InputY\right) \qquad (1)$$

The activation σ_j of a rule R^j can finally be expressed by:

$$R^j : \sigma_j\left(InputX, InputY\right) = \min\left(\mu_{MF1}\left(InputX\right), \mu_{MF2}\left(InputY\right)\right) \tag{2}$$

It should be noted that in contrast to *boolean* logic set operations, *fuzzy* logic set operations, e.g. intersection or union, are not uniquely defined. In Eq. (2) we have chosen to implement the intersection of fuzzy sets as the *minimum* of their MFs. Next the weight for the output membership function(s) for each of the activated rules is calculated (in this example the weight of MF3 of variable *OutputZ*). The final weight ξ_{MF3} applied to the fuzzy controller output MF is determined by aggregating the output weights σ_j from all rules:

$$\xi_{MF3} = \max_{All\ rules}(\sigma) \quad . \tag{3}$$

The final step is to defuzzify the output function to produce a numerical value. There are many methods to implement the inference and defuzzification steps; the most common way is to determine the final value with a simple calculation of the centre of gravity (COG) of the surface below the final output membership function, Eq. (4).

$$\widehat{y}_{COG} = \frac{\sum_{Output\ MFs} \xi^v \mu_v}{\sum_{Output\ MFs} \mu_v} \quad . \tag{4}$$

Overview of helicopter dynamics and flight control

Helicopter flight is a complicated task due to the strong nonlinear coupling of the various degrees of freedom of the helicopter. The work of a helicopter pilot is therefore more difficult than that of a pilot of a fixed-wing airplane. From the military perspective we note that a combat aircraft pilot can only devote a part of his time to controlling the platform, because this is just one aspect of the mission. The extra difficulties associated with flying a combat helicopter are also reflected in its standard crew of two, vs. only one pilot in a jet fighter.

The six degrees of freedom of a helicopter are: up-down and yaw (z-axis), right-left and pitch (y-axis), forth-back and roll (x-axis). The coordinates x, y, and z are fixed to an inertial system in space. As a consequence the state of a helicopter can be represented as a point in the phase space spanned by 6 coordinates (three for position and three for attitude) and 6 velocity components (three each for translation and rotation).

In order to fly and control the helicopter, the pilot has to simultaneously operate three different helicopter controls, which manipulate the angle of attack of the main and tail rotor blades. The prime role of the main rotor is to provide the lift force that allows the helicopter to hover and fly. During flight the main rotor maintains a constant angular velocity and is controlled by two conventional helicopter controls, named the Collective and the Cyclic. The tail rotor produces lateral thrust in the same way as the main rotor of the helicopter does. It changes the amount of thrust that is produced by changing the angle of attack of the tail rotor blades. The tail rotor is connected with the main rotor through a gearbox and therefore also has a constant angular velocity that depends on the gear ratio of the gearbox. The tail rotor is primarily needed to counteract the top axis moment that is exerted on the helicopter body by the movement of the main rotor blades. The secondary effect of the tail rotor is to enable the helicopter to rotate about the main rotor's shaft axis (yaw). The working conditions of the main and tail rotor define the dynamic behaviour of the helicopter. The helicopter controls can thus be divided into two groups, the controls responsible for the manipulation of the main rotor (collective and cyclic), and the ones that are responsible for the tail rotor (tail pedals).

The collective control is responsible for providing the lift of the helicopter. It consists of a hand-operated lever that can be raised or lowered and this position is linearly linked to the angle of attack of the main rotor's blades and the throttle of the engine to keep the angular velocity of the blades constant. The collective control changes the angle of attack of all the blades of the main rotor simultaneously. The higher the lever is lifted, the steeper the angle of attack of the helicopter blades and the more lift force is produced and the more power is delivered by the engine. The cyclic is also a hand-operated control, which is positioned in front of the pilot and can be moved in any horizontal direction (forth-back, left-right and combinations). The cyclic controls the lateral and longitudinal translation of the helicopter and it changes the angle of attack of each rotor blade individually. This allows the helicopter to move in any horizontal direction. The tail pedals allow the pilot to change the angle of attack of the tail rotors blades. In this way, they control the amount and the direction of the tail thrust and therefore the heading of the helicopter body and its yawing movements.

Hovering

First we implemented hovering at a certain altitude with a given heading. Even this elementary action is complicated, since in order to reach a certain height a well-defined thrust of the main rotor is required. The main rotor thrust is strongly coupled with the angular momentum produced about its shaft axis and therefore influences the heading. It is commonly observed at helicopter take-off that the helicopter slightly rotates about the main rotor shaft axis (yaw), before the pilot can stabilise and bring the heading back to the initial heading. Similar phenomena are observed when the pilot tries to change direction while having low forward speed. The difference in the starboard and portside contribution to the lift force due to cyclic control command not only results to a change in direction but also to loss of height, because additional thrust is needed to compensate for the inclination and subsequent reduction of the effective rotor blade surface. When using the tail rotor trying to compensate the yaw torque, the result is an excess of force in the direction, for which the tail rotor is meant to compensate, that will tend to make the helicopter drift sideways. Pilots tend to compensate for this effect by simultaneously applying a little cyclic pitch, but designers also help the situation by setting up the control rigging to compensate ("trimming"). The result is that most helicopters tend to lean to one side when hovering and often touch down consistently on the same wheel first. Hovering in a helicopter requires experience and skill. The pilot adjusts the cyclic to maintain the helicopter's position over a point on the ground. The pilot also adjusts the collective to maintain a fixed altitude (especially important when close to the ground). Finally, the pilot adjusts the foot pedals to maintain the direction that the helicopter is pointing. External disturbances (e.g. wind) further complicate the hovering manoeuvre.

Helicopter modelling and simulation

For the design of the fuzzy controller the use of a competent mathematical helicopter model was required. A mathematical model for a helicopter that was designed by the Aviation Department of M.I.T. [4] was selected for this work. This model was found competent enough for the present study as it describes the dominant behaviour and the coupling among the degrees of freedom of a helicopter, without taking into account secondary flight dynamic effects that only insignificantly contribute to the overall behaviour of the helicopter. The helicopter dynamics can be derived by solving the Newton Euler equations of motion, three for the translational and three for the rotational degrees of freedom:

$$\frac{du}{dt} = (vr - wq) - g\sin\theta + (X_{mr} + X_{fus})/m \tag{5}$$

$$\frac{dv}{dt} = (wp - ur) - g\sin\varphi\cos\theta + (Y_{mr} + Y_{fus} + Y_{tr} + Y_{vf})/m \tag{6}$$

$$\frac{dw}{dt} = (uq - vp) - g\cos\varphi\cos\theta + (Z_{mr} + Z_{ht})/m \tag{7}$$

$$\frac{dp}{dt} = qr(I_{zz} - I_{yy})/I_{xx} + (L_{mr} + L_{tr} + L_{vf})/I_{xx} \tag{8}$$

$$\frac{dq}{dt} = pr(I_{xx} - I_{zz})/I_{yy} + (M_{mr} + M_{ht})/I_{yy} \tag{9}$$

$$\frac{dr}{dt} = pq(I_{yy} - I_{xx})/I_{zz} + (N_{mr} + N_{vf} + N_{tr})/I_{zz} \tag{10}$$

where:

- m is the mass of the helicopter;
- u, v, and w are the translational velocities along x, y and z axis;
- p, q, and r are the angular velocities along x, y and z axis;
- X, Y, and Z are the forces applied along x, y and z axis;
- L, M, and N are the moments along the x, y and z axis respectively;
- φ, θ, and ψ are the angular displacements about the y, x, and z axis, respectively;
- g is the acceleration of gravity;
- I_{jj} are the moments of inertia along the j-th axis (the I-tensor is diagonal in x,y,z).

Fig. 3 shows the position where the forces and moments are applied on the helicopter, as well as the direction of the resulting velocities and rotations.

The inputs of the mathematical helicopter model are the control commands (Collective, Cyclic and Tail Pedals Value) and the outputs are the speeds and displacements (translational and angular) for each of the axis (x, y and z).

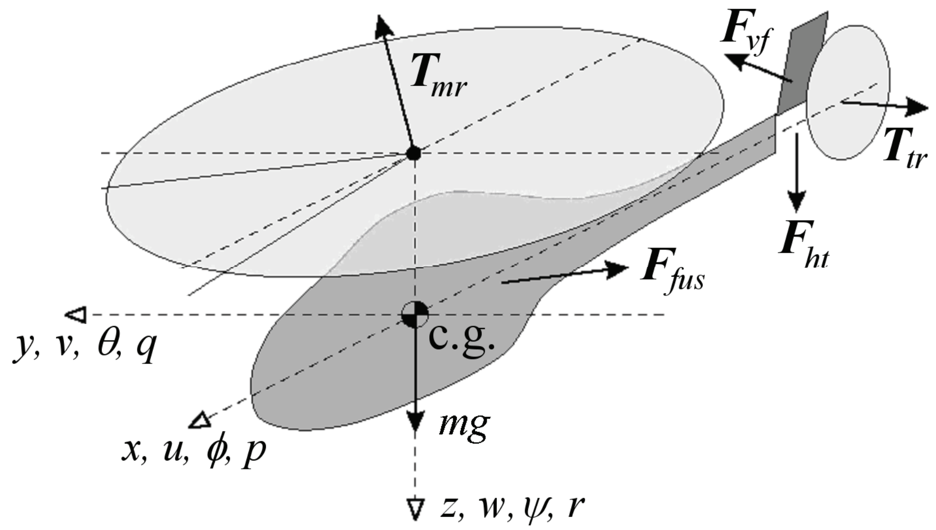

Figure 3. Coordinate system and forces (F) and moments (T) acting on a helicopter. The various subscripts that accompany the forces and moments are: $(\ )_{mr}$ for main rotor, $(\ )_{tr}$ for tail rotor, $(\ )_{fus}$ for fuselage, $(\ )_{vf}$ for vertical fin and $(\ )_{ht}$ for horizontal stabilizer.

Fuzzy Logic Controller

The role of the fuzzy logic controller (FLC) is to carry out the user's commands and translate them into actions of the helicopter. That, in a real life situation could be translated as a helicopter passenger that tells the pilot what actions the helicopter should perform. The "passenger" (user) does not need to know what actions the "pilot" (i.e. the FLC) has to take in order to correctly and safely carry out the required commands. The requirements for the design of the fuzzy controller are to control lift-off, vertical position and hovering with certain heading. Since this movement involves only the vertical position and orientation of the helicopter, cyclic commands will not be investigated in this paper and therefore will be assumed to be "zero". Therefore, the pilot's knowledge and experience to be modelled by means of fuzzy logic is limited to the use of the collective and the tail pedals. Two separate fuzzy controllers have been developed to perform the pilot's actions, one for each of the conventional helicopter controls.

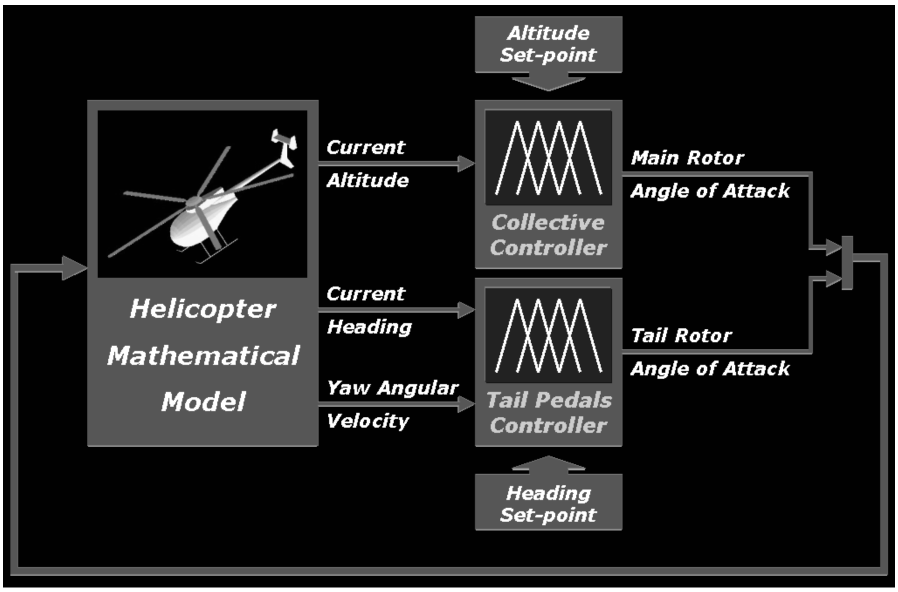

Figure 4. Architecture of the fuzzy controller and its interconnection with the mathematical model of the helicopter

The two controllers together compose the Controller system. As is displayed in the Fig. 4, the inputs of the controller are the actual altitude (vertical displacement along the z-axis), heading and yawing angular velocity of the helicopter model, as well as the set point values specified by the user. The output of the control system directly sets the angles of the main rotor collective and tail rotor pedal controls. The fuzzy logic controller was designed and tested using the fuzzy logic toolbox of Matlab.

Main rotor collective controller: Altitude

The main rotor control system consists of a fuzzy logic controller (Fig. 5) that controls the main rotor collective command according to the required vertical displacement. The output of the "Fuzzy Altitude Controller" is incremental, as schematically indicated by the delay feedback loop, labelled "memory". The limiter placed after the output ensures that the output value will not exceed the actual physical limits of the helicopter model. The memory loop provides the possibility to have different output values for the same input conditions, since different hovering altitudes require different angles of attack on the rotor blades. Therefore integration via the memory loop is required to distinguish between the several altitude hovering positions. The inputs of the controller are the "altitude error", which represents the difference between the current and the required altitude of the helicopter model, and the "altitude rate of error", the rate at which this error changes.

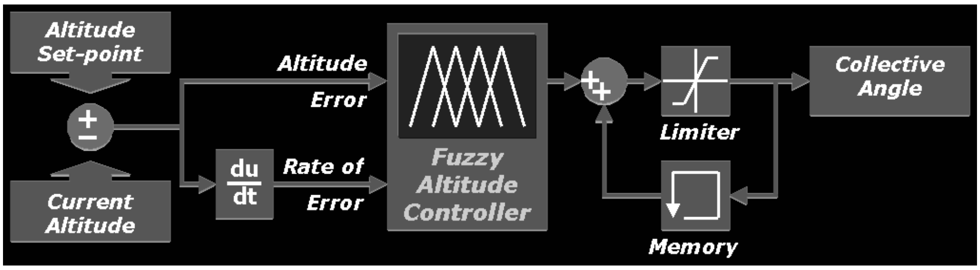

Figure 5. Altitude controller architecture

The controller has the structure of a fuzzy PD (proportional and differential) controller. The input "altitude error" consists of 5 membership functions, labelled {BNE, SNE, NoE, SPE, BPE}. These are displayed in Fig. 6. In determining the range of the fuzzy membership functions, scientific judgement on magnitude of the altitude error has been taken into account. The "altitude rate of error" input, which represents the rate of the error input, also consists of 5 membership functions, labelled {BN, SN, ZA, SP, BP} that have been determined experimentally by manual flying the helicopter model, that the maximum "altitude rate of error" values assumed, are within the range of [-10, 10] m/s. The collective angle output variable of the main rotor collective fuzzy controller consists of 7 membership functions, labelled {BNT, NNT, NT, ZT, PT, NPT, BPT}.

The rules for the altitude control are straightforward. The helicopter pilot increases the collective angle when he wants to gain altitude, and decreases it when he wants to lose altitude. The collective command is kept at a certain angle when the pilot wants to hover. Each altitude has a different hovering angle as air density and temperature greatly influence the lift produced by the main rotor blades at constant speed of rotation. Taking these rules of thumb as a basis for our design, a set of fuzzy rules was determined (Table 1). From the structure of Table 1, the nonlinear relation between the output and the two inputs is apparent.

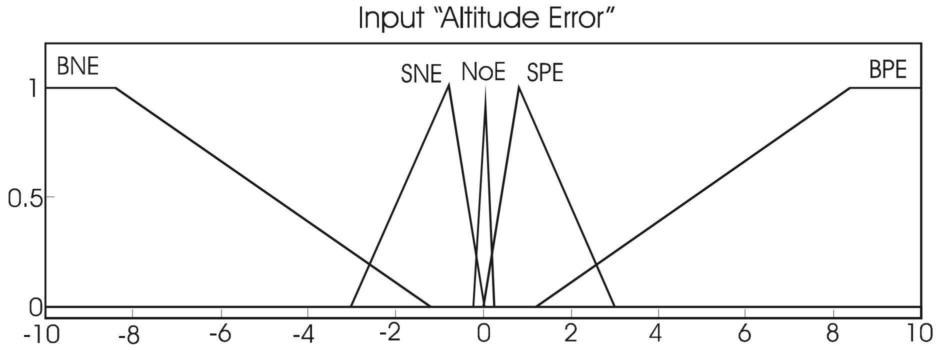

Figure 6. Membership functions for Altitude Error Input [m]: Big Negative Error (BNE), Small Negative Error (SNE), No Error (NoE), Small Positive Error (SPE), Big Positive Error (BPE)

Table 1: Collective fuzzy controller rule base. The table displays the activated output membership function according to possible input membership function combinations. A typical rule (see highlighted cell) is: **IF** (AltError **is** NoE) **AND** (AltRateError **is** ZA) **THEN** CollectiveOutput **is** ZT

	Altitude Rate of Error Input				
Altitude Error Input	**BN**	**SN**	**ZA**	**SP**	**BP**
BNE	BNT	NNT	NT	NT	ZT
SNE	NNT	NT	NT	ZT	ZT
NoE	NNT	NT	ZT	PT	NPT
SPE	ZT	ZT	PT	PT	NPT
BPE	ZT	PT	PT	NPT	BPT

Pedals controller for tail rotor: Heading

The tail rotor control system consists of two fuzzy logic controllers (Fig. 7), one to control the yawing angular velocity of the helicopter and the other to control its heading (angular position). The need for the two controllers arises from the fact that we have two different control objectives, corresponding to two different control regimes. The first control objective has to do with safety and staying within the operational flight envelope. The second control objective is maintaining the desired heading. We note that high angular velocities about the z-axis can produce instability of the helicopter system. Once the velocity of the helicopter is controlled and does not introduce any instability factors into the system, it is possible to implement the positioning control for obtaining the required heading. Helicopter pilots use a similar approach. They also make the helicopter rotate with constant (low) yawing angular velocity until they stabilize the helicopter in a certain heading.

As can be seen in Fig. 7 the fuzzy heading controller has a similar structure as the fuzzy altitude controller. While trying to achieve the desired heading, special care must be taken as to prevent the helicopter from obtaining high yaw velocity since this may yield instability. The fuzzy yaw controller is responsible of keeping the yaw velocity of the helicopter within the required limits for safe and stable aviation. If the yaw velocity of the helicopter is normal (within the flight envelope), the output of the fuzzy yaw controller is very small or zero. In this case the heading controller takes over and is responsible for the value of the angle of attack of the tail rotor's blades.

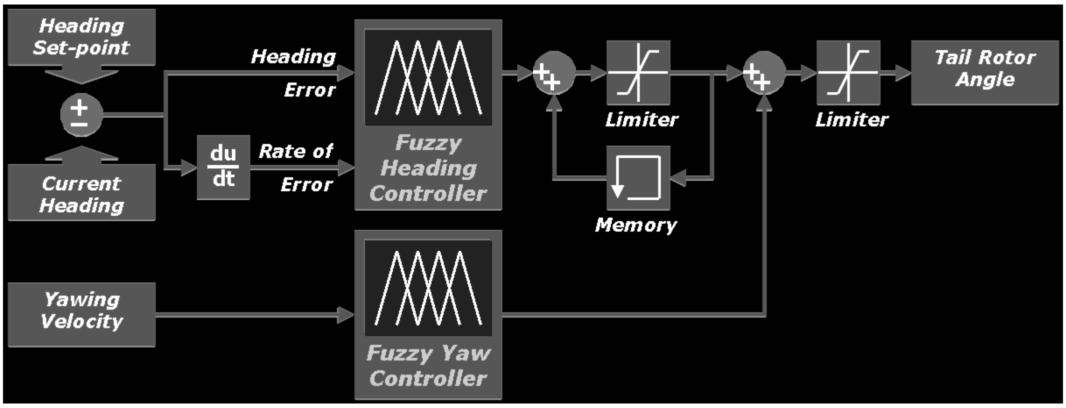

Figure 7. Heading Controller Diagram

The fuzzy yaw controller is responsible for the control of the yawing angular velocity. It consists of one input and one output. If the yawing velocity becomes large, this introduces the risk of instability of the system, the controller takes actions to oppose the current movement and reduce the velocity to within the required margins. The input of the controller is the yawing velocity, which represents the angular velocity of the helicopter model about its z-axis and is represented by 3 MFs, labelled {NegYaw, NormYaw, PosYaw}. It was determined from experiments with the helicopter model, that with a maximum yawing velocity of -1 to 1 rad/sec, it is possible to control the helicopter, whereas outside this flight envelope the control of the tail angular velocity becomes very difficult and this renders the system unstable. Therefore the allowed velocities are the ones that exist within the membership function of "NormYaw". The range of allowed values ("support") of NormYaw is [-1,+1] rad/s and defines the flight envelope. The output of the controller is the "Tail Rotor Angle", which represents the angle command that is passed to the tail rotor blades and consists of the 3 membership functions, labelled {NegOut, NoOut, PosOut}.

The control commands that can be given to the helicopter model's tail rotor angle of attack varies from -28.6^o to 28.6^o. These limits are prescribed by the limitations of the actual helicopter model. These limits also apply for the output values of the fuzzy heading controller and integration scheme of Fig. 7. While trying to obtain the required heading, it is crucial to simultaneously control the yawing speed of the helicopter to avoid instability. Due to the control approach chosen, the parallel fuzzy controller responsible for the yawing speed needs to be able to numerically override the commands of the heading controller. Therefore the numerical output of the yaw rate controller must be at least twice the output of the heading controller after the integration scheme (Fig. 7). The fuzzy rule base for the control of the yawing velocity of the helicopter is quite simple. When the velocity is very negative, the controller applies positive angle to the tail rotor in order to counteract it. On the other hand, when the yawing velocity is very positive, the controller applies negative angle to the tail rotor. When the yawing velocity is between the desired limits, the controller does not apply any force. Taking these empirical rules as a base, the following set of fuzzy rules has been determined:

1. If (YawSpeed is NegYaw) then (TailAngle is PosOut)
2. If (YawSpeed is NormYaw) then (TailAngle is NoOut)
3. If (YawSpeed is PosYaw) then (TailAngle is NegOut)

The fuzzy heading controller is responsible for the control of the yawing angular displacement (i.e. the heading). It consists of two inputs and one output. The inputs of the controller are the "heading error", which represents the difference between the actual and the desired heading of the helicopter model, and the "heading rate of error", which is the rate of change of this error. The input "heading error" consists of the 7 MFs {NegOut, Neg, SmNeg, Zero, SmPos, Pos, PosOut}. For the range of the fuzzy membership functions, human judgement (of both the pilot and the flight engineer) on magnitude of the heading angles and heading was taken into account. The "heading rate of error" input, which represents the rate of the error input, also consists of 5 MFs, labelled {BigNeg, NegError, ZeroRate, PosError, BigPos}. It was determined from experiments with the helicopter model, that by manually flying the helicopter, the maximum heading rate of error values that were developed are within the range of [-300, 300] °/sec.

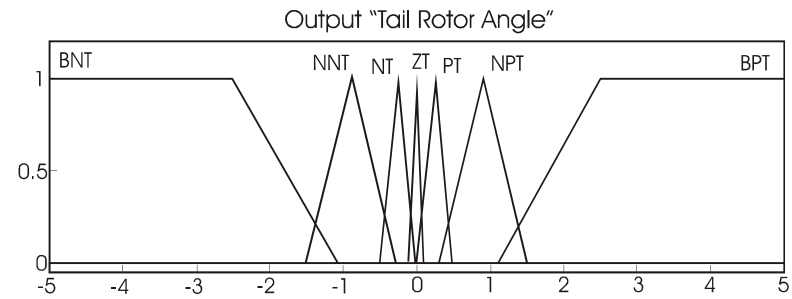

Figure 8. Tail Rotor Angle output from heading position control [°]. With membership functions: Big Negative Tail Angle (BNT), Normal Negative Tail Angle (NNT), Negative Tail Angle (NT), Zero Thrust (ZT), Positive Tail Angle (PT), Normal Positive Tail Angle (NPT), Big Positive Tail Angle (BPT).

The "tail rotor angle" output variable consists of the seven membership functions displayed in Fig. 8. The rules for the heading angle control are straightforward. When the helicopter heading error is very big on the positive side and it is growing even bigger, then the angle of attack of the tail rotor must get a value that will help it counteract and reduce the error. The opposite occurs when the helicopter's tail error is becoming smaller. Then the pilot takes actions to counteract the movement and make the yawing angular velocity equal to zero when the heading angle error is becoming small. Generally, the action of the helicopter pilot is to keep a constant speed while yawing and taking suitable counteracting measures to the movement only when the pilot needs to maintain a heading. Taking these empirical rules as a base, a set of fuzzy rules has been determined (Table 2).

Experiments and results

To estimate the performance and quality of the fuzzy logic approach to the helicopter aviation problem, a number of tests have been conducted. The tests have to prove the ability of the fuzzy controller to perform helicopter take-off and landing as well as to hover at several altitudes with different headings. Therefore the altitude and heading time response characteristics as a function of time are of importance for each of the tests. In this section all three actions (take-off, hovering and landing) are investigated. For each of the tests, two plots are presented. The top plot contains the characteristic of the obtained altitude, whereas the bottom plot contains the characteristic of the heading of the helicopter model.

Take-off and hovering at various altitudes and headings

The first test was to determine the ability of the controller to make the helicopter to take off, and to change altitude and heading according the user commands. The controller should be able to manipulate the pitch angle of the rotor blades in such way that the helicopter body will not start revolving about the main rotor axis and that the helicopter model will be able to reach a certain altitude with a desired heading as quickly as possible without interfering with the safe flight envelope. For this test the initial conditions of the model helicopter are starting from the ground (0 m) with zero heading (0°). The initial set-point for the fuzzy logic controller was to bring the helicopter to an altitude of 4 m with a heading of 10° (Fig. 9 movement to point A).

Table 2: Tail rotor fuzzy heading controller rule base. The table displays the activated output membership function according to possible input membership function combinations.

	Heading Rate of Error				
Heading Error	**BigNeg**	**NegError**	**ZeroRate**	**PosError**	**BigPos**
BigNeg	BNT	NNT	NNT	NT	ZT
Neg	NNT	NT	NT	ZT	PT
SmNeg	NNT	NT	ZT	ZT	PT
Zero	NT	NT	ZT	PT	PT
SmPos	NT	ZT	ZT	PT	NPT
Pos	NT	ZT	PT	PT	NPT
BigPos	ZT	PT	NPT	NPT	BPT

As can be seen from Fig. 9, the helicopter model is gaining altitude and reaches the desired altitude without overshoot. Due to the extra moment that is produced from the increase in thrust on the main rotor, small fluctuations (overshoot at t = 0.1, 2.2, 2.7 s and undershoot at t = 0.7, 1.3, 3.7 s) appear at the required heading until the helicopter stabilises its altitude. Then the tail rotor control takes additional action and stabilizes the heading of the helicopter at the required value. Next the controller was instructed to bring the model helicopter to different altitudes with different headings. The following commands were given to the fuzzy controller for implementation:

- Raise altitude to 6 m and simultaneously change the heading to -3° (Fig. 9, point A to point B).
- Maintain the altitude of 6 m and change the heading to 16° (Fig. 9, point B to point C).
- Change the altitude to 13 m and maintain the heading of 16° (Fig. 9, point C and on).

In Fig. 9 the resulting trajectories are presented. The helicopter model ascends quickly and reaches the desired altitudes without any noticeable overshoots. The heading shows some fluctuations as before, in terms of overshooting and undershooting, due to the changes of the imposed moment from the main rotor.

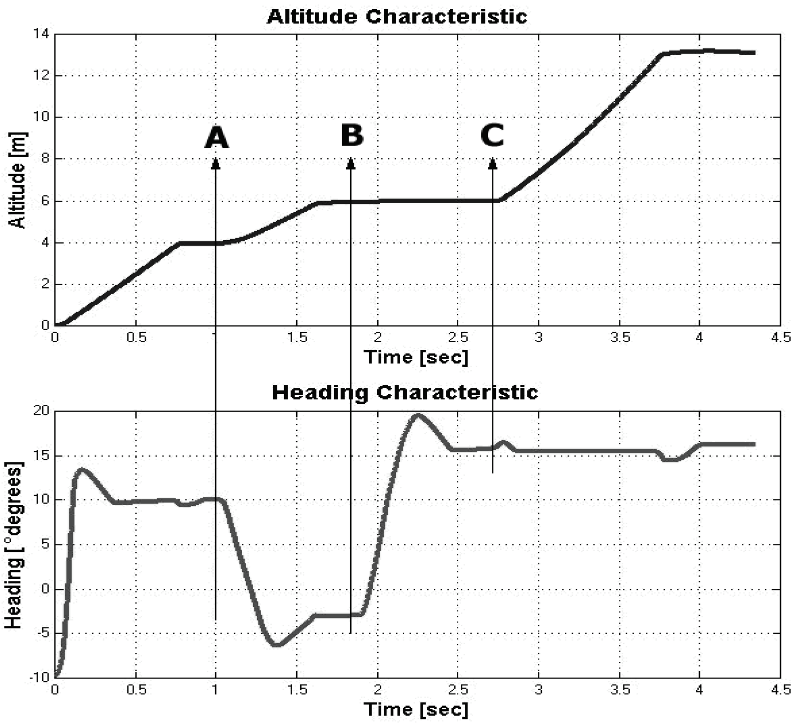

Figure 9. Results of hovering: Changing the altitude and heading of the helicopter. A, B, and C correspond to stable hovering with setpoints (Altitude [m],Heading [°]) of (4,10°), (6, -3°), and (6,16°), respectively.

Landing

In the second test the ability of the controller to safely land an initially hovering helicopter was investigated. For this test the initial conditions of the helicopter model were, starting at an altitude of 10 m with a heading of 16°. The setpoint for the fuzzy logic controller was to bring the helicopter down to an altitude of 0 m with a heading of 10°. The resultant trajectory is presented in Fig. 10. The helicopter model descends with gravitation until a point where the helicopter is increasing its throttle in order to drastically decrease its vertical speed and make a smooth landing. The smoothness of the landing is well observed when zooming in as shown in Fig. 11, starting after 5 seconds of flight time. Approximately at 0.1 m the helicopter changes its descending speed by more than an order of magnitude and the landing follows a smooth trajectory towards a soft touchdown. In the real world several phenomena could take place at that point (wind gusts, sudden change in wind direction, turbulence, etc.) and therefore it could be more advantageous for the controller to initiate a smooth landing earlier in the descend. We also note that in real life helicopter pilots generally prefer to maintain a small forward speed during landing approach in order to avoid the helicopter landing in its own "downwash", i.e. the air that is forced down by the main rotor during the creation of lift.

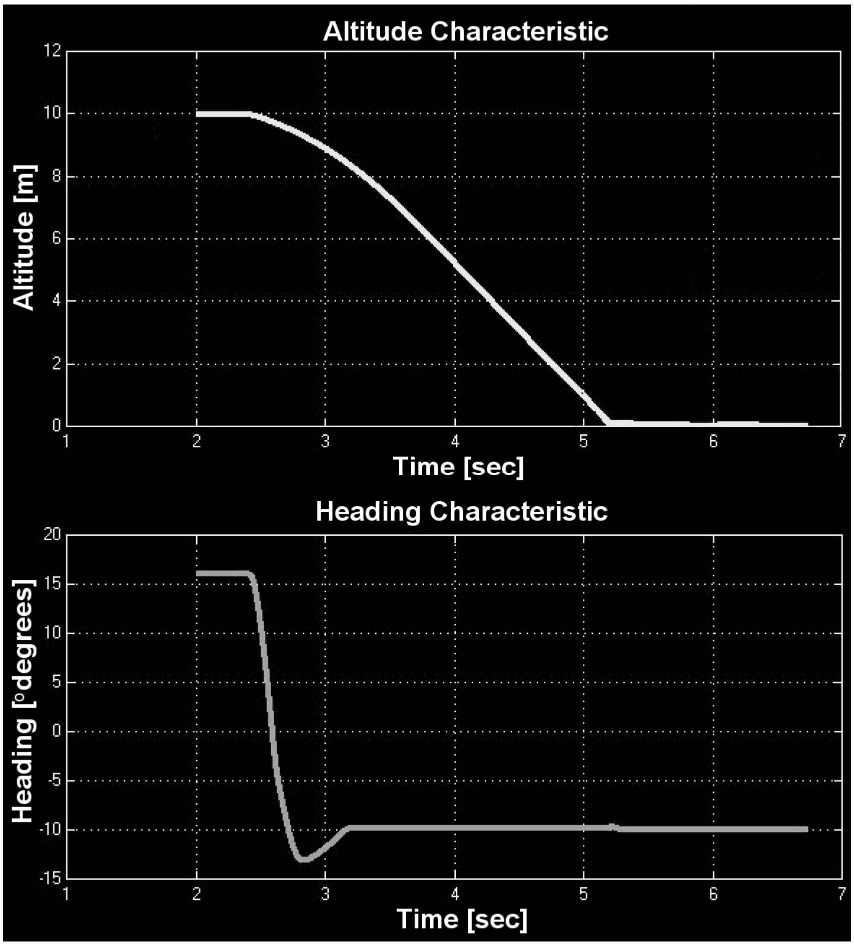

Figure 10. Flight trajectory of a helicopter landing: Altitude and heading as a function of time. Note that the typical timescale of the heading controller is of the order of 0.5 s, whereas the altitude controller changes much slower. This is explained by a combination of two effects: In the first place elementary physics limits the flight dynamics via mass and moment of inertia and in the second place one must follow the requirements set by the flight envelope. The last is implemented in the controller models by inserting limiters in the controller outputs.

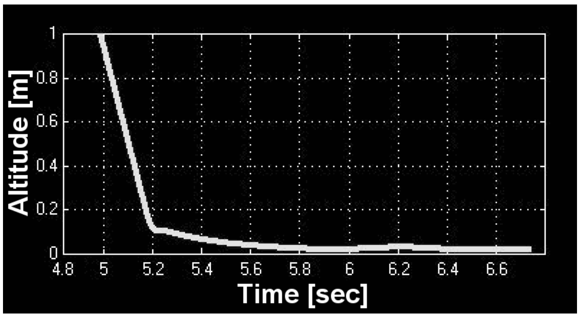

Figure 11. Detail of the altitude vs. time graph (Fig. 10) showing a soft landing by reducing the vertical speed at t=5.2 s with a factor of more than 10

Conclusion

We have demonstrated in the present work that fuzzy logic controllers are capable of controlling two of a model helicopter's coupled degrees of freedom. The incorporation of both scientific knowledge and the helicopter pilot experience into a fuzzy rule base has been experimentally demonstrated by successful take-off, hovering with defined heading and controlled soft landing. The system is open for extensions that could further enhance its performance (supervisory fuzzy controller, learning control, speed control). Developments to also control the other degrees of freedom of the helicopter are necessary in order to fly a fully autonomous aerial vehicle. Finally, it should be understood that this work describes laboratory-scale experiments and that in order to apply these controllers for real-life UAV missions ICAO certification must be obtained for the system.

References

[1] E. Skarman, "A Helicopter Control System", Linköping Electronic Articles in Computer and Information Science, Vol.4, No. 15, 1999.
[2] J. Chapuis, C. Eck, M. Kottman, M. Sanvido, O. Tanner, "Control of Helicopters", ETHZ Swiss Federal Institute of Technology - Measurement and Control Laboratory, Zurich, 1999.
[3] M. Sugeno, H. Winston, I. Hirano, S. Kotsu, "Intelligent control of an unmanned helicopter based on fuzzy logic", American Helicopter Society/51st Annual Forum Proceedings, Houston, 1995, pp. 791-803.
[4] V. Gravilets, B. Mettler, E. Feron, "Nonlinear Model for a Small-Size Acrobatic Helicopter", AIAA 2001-4333, August 2001.
[5] G. Padfield, "Helicopter Flight Dynamics", Blackwell Science Ltd, 1996.
[6] M.R. Spiegel, "Theory and Problems of Theoretical Mechanics", McGraw-Hill Book Company, 1967.
[7] G. Sposito, "An Introduction to Classical Dynamics", John Wiley & Sons, 1976
[8] A.J. van der Wal, "The role of fuzzy set theory in the conceptual foundations of Quantum Mechanics: an early application of fuzzy measures", (invited), Foundations and Applications of Possibility Theory, Vol. 8 of Advances in Fuzzy Systems, World Scientific, Singapore, 234-245 (1995).
[9] A.J. van der Wal, "Applications of fuzzy logic in industry", (invited), Proc. FLINS '94, Mol, 91-95 (1994).

[10] A.J. van der Wal, “The potential of fuzzy logic applications in industry”, (invited), Fuzzy Logic Foundations and Industrial Applications, Kluwer, Boston, 275-312 (1996).
[11] K.M. Passino and S.Yurkovich, “Fuzzy Control” Addison Wesley, Menlo Park, CA (1998).
[12] A.J. van der Wal, “The importance of soft-computing networks for mission systems: a tutorial”, AGARD, NATO RTO-MP-3, Monterey CA (1998).
[13] D. Ruan and A.J. van der Wal, “Controlling the power output of a nuclear reactor with fuzzy logic”, Int’l Journal of Information Science 110, 1/4,151-177 (1998).