Some Aspects Regarding the Adaptive Control of a Flying Wing- Micro Air Vehicle with Flexible Wing Tips

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Abstract: - The problem of automatic development of controllers for high maneuverable flexible flying wing micro air vehicles for the situations in which the exact characteristics are not known, has a strong motivation for research because of the low cost bioinspiration emerging technologies, the integration of micro sensors, neural networks and adaptive control. The aim to obtain an enhanced agility and functionality demands that MAV should perform over an extended flight envelope, an increased range of operating conditions with dramatic variations and highly nonlinear aerodynamic phenomena.

Keywords: - micro air vehicle (MAV), flying wing MAV (FW-MAV), morphing, adaptive control.

1 Introduction

The typical missions for MAVs require a very good adaptability and agility, critical to achieve capabilities in urban and agglomerated environment. In the literature exist a variety of morphing strategies (wing curling, wing twisting, multi point wing shapping, leading edge twisting, variable gull/wing angling, wing- tail folding) adapted for classic configurations. For a low cost FW-MAV it is important to use the combination between bioinspired solution and the intelligent adaptive control.

1.1 The modular design of the FW-MAV with flexible tips

The first FW-MAV rigid concept was interesting in comparison with the similar classic configuration of MAVs, because its simplicity and a better aerodynamic efficiency (due to the lack of different passive components), a better maneuverability and controllability in gusts, which influence the flight endurance. The flexible FW-MAV concept is more stable in gusts, but needs slightly more thrust. Gliding distance is less than of the FW-MAV with rigid wings. The flexible wing FW-MAV is very difficult to control during take-off, but has a better controllability in gusts. The aerodynamic efficiency and flight endurance are comparable with the rigid solution, but the flexible model is more fragile (rigid solution is better crashworthiness and easier packaging).

The compromise between these two concepts is *a mixed solution* which combines the advantages of rigid wing with the advantage of a better agility and a better behavior in gusts, given by the flexible component. The semiflexible FW-MAV is a new low cost concept, very simple, and it has a total flexibility only at the tips of the wing, permitting also different morphing strategies. The wing tips are fabricated with carbon fiber skeleton and extensible latex rubber skin or mylar and this concept permits a better adaptability and an extended flight envelope.

The shape of the wing tips changes as a function of airspeed and the angle of attack. Given the limited payload only a small on-board sensing and computation system can be used. For navigation, the absolute position of the MAV could be estimated by an infrared tracking system. The inertial and positional data, appropriately used onboard using Kalman filter. It will be also integrated a full installation of the infra red tracking system, necessary to obtain the flight data for deriving the dynamic model of FW-MAV.

1.2. The morphing of small flying wings

The semi- flexible flying wing is a new, innovative concept, that combine *central wing twisting/ multi-point wing shaping* with flexible wing tips for passive adaptation. Morphing on the MAVs is accomplished by actuation of control effectors located inside the fuselage. These servos are connected to the wings by either use of a torque rod or Kevlar strand. The wing morphing is actuated by moving the arm which rotates the tube or pulls the strand and changes the shape of the wing

2. An analysis of the possibilities to introduce an adaptive control for micro air vehicles

Adaptive control is a term used to describe a large class of control systems. We intend to introduce this technique in the FW-MAV control.

The miniature flight control system (MFCS) based on morphing solutions should provide a better capability to change the state of flight. Based on the flight trajectory, the micropilot reads signals which are fed back through the control laws and generates control signals to the different type of morphing solutions. The microprocessor supports all radio communications and servo operations but also handles the control functions, navigation, data acquisition and telemetry. The GPS unit sends coordinates, ground speed and MAV altitude to the micropilot board. The infrared sensors onboard, provides the micropilot with the MAV's roll and pitch angles based on the measurement of the temperature difference between the sky and ground. MFCS software consists of different modules (configuration files, fly by wire, flight plan, map, micropilot, GPS tools) and two subsystems, the micropilot software onboard and the ground station software (coupled with the micropilot source code). For this application the micropilot will work on a stability augmentation mode (actual commands for servos are computed by the micropilot control loop code). The efficiency of control laws for FW-MAVs depends on the design process based on the linearized equations of motion developed from an estimation of the stability and aerodynamic control derivatives. Special software is used to evaluate open-loop stability of the MAV and to determine control laws for closed loop stability. The aerodynamic derivatives can be determine by using Advanced Aircraft Analysis (AAA 3.0) software and the aerodynamic parameters from numerical simulations based on vortex-lattice method and Tornado 1.0 software.

Adaptive control algorithms realize an adaptation to unknown parameters in a plant. This does not mean that an adaptive controller is the optimal controller for a system; instead, adaptive controllers are able to control plants with parameters that are unknown or changing.

This idea is simply illustrated by the traditional PID control, a technique that can control a large set of plants, and its intent is to drive the error between a desired reference signal and the output of the plant to zero, by operating on that error and passing the result to the plant's input. The proportional part that amplifies the error, is used to drive the error to zero, the integral part amplifies the integral of the error, is used to eliminate steady-state error and the derivative part amplifies the derivative of the error, is used to reduce oscillations caused by the previous two parts. These signals are added together and passed to the plant's input. PID gain controllers are manually tuned for each system to satisfaction of the operator. As the plant's parameters change, the PID controller may need to be retuned. Parameter variation can be caused by changes in environmental conditions, state changes (for example FW-MAV dynamics changing as a result of airspeed, angle of attach, and sideslip angle), time progression, etc. For FW-MAVs, this means that a PID controller that is tuned in one flight regime may not work as well or become unstable under another flight regime, thus requiring retuning.

Adaptive control typically is not influenced by this problem. The goal of adaptive control is to adjust to unknown or changing parameters and is accomplished by either changing parameters in the controller to minimize error, or using plant parameter estimates to change the control signal. There are many different approaches/ types of adaptive control (least square estimation adaptive control, dynamic inversion using neural networks, and *model reference adaptive control*- MRAC). *Least squares adaptive control* uses least squares estimation to perform online system identification. The parameter estimates for the system are then used in the controller. *Dynamic inversion* is the process of inverting the dynamics of the system to make control design easier. When *neural networks* are used in conjunction with dynamic inversion, the neural network can learn to invert the dynamics and adapting to changing parameters. Finally, *MRAC*s use a reference model to update parameter estimates. These estimates are used to help drive the system error to zero.

3. The concept of morphing FW-MAV

3.1. Modern morphing concepts

The morphing of an aerial vehicle is not a strictly defined concept. In the literature, it refers to the shape changes during flight capable to optimize the flight performances. There is a variety of types of *shape changes* including span, chord, angle of attack, dihedral angle, camber, area, thickness, aspect ratio and planform changes. The morphing can also be applied to different control surfaces. The advantage of eliminating the separate actuator and routing is given by the possibility to use thiner profiles or special configurations for MAVs. In our

FW-MAV we introduce the modular design with central morphing and flexible tips, that permits a very easy geometry change procedure, with simple and quick realization.

The concept of morphing has been proposed first time by DARPA and then, NASA showed the aerodynamic benefits; however, the use of morphing for control design has not been studied extensively. The wing morphing techniques for the FW-MAVs are innovative and are based on micro- servos which are attached to the rigid middle of wings.

In the literature, the simulations demonstrated a better aerodynamic efficiency but also showed that these vehicles have unstable lateral-directional dynamics. The use of new smart materials such as shape memory alloys and piezos have been considered in the design of morphing wings but there is still a limitation regarding the energy necessary to twist the semi-wings using these mechanisms, which deteriorate the endurance. Some smart spars have been built which provide different types of morphing but have not been tested on aerial vehicles [1]. An interesting *mechanism for morphing* considered *the sweep of the wings changing* with actuation realized by using inflatable actuators powered by compressed air. Another innovative solution proposed an *inflatable telescopic spar* which can be morphed span wise [2]. This concept design permitted changes in the aspect ratio while still providing enough support from the spars for the aerodynamic loads which are being applied.

To improved maneuverability and performance, roll maneuvers have been studied by using the *flexible wing concept* [5], [6]. Numerical studies were used to consider the aerodynamic loads on a flexible wing in the entire flight envelope. Wing twist is also considered in order to recover the rolling moment lost but has not been tested in flight. This is due to the challenges involved in implementing a functioning mechanism for wing twist on a full scale aircraft. Research has also been done considering the material aspects of shape changing with a finite element model of a wing [6]. Piezoelectric sensors and actuators are very light, have a small volume and can achieve various shapes. This technique has not been tested because of the large deflections needed from such small actuators. Numerical studies have considered *structural and aerodynamic modeling* for variable shape wings [4].

3.2. Morphing strategies to enhance the control in aggressive maneuvering

We present different *morphing strategies* to enhance the control of FW-MAV in aggressive maneuvering:

a)*Wing curling*- is used to control the lateral directional dynamics by using rotary actuators connected to the structure by tensioned Kevlar cables. The actuator adjust the tension on the cable and result the necessary wing deformation and the lift differential that create the roll rate for flight control.

b)*Wing twisting*- is a very efficient morphing solution with the twist produced by a torque rod actuator. The magnitude of the twist deformation is largest at the actuation point and is tapered toward the wing tip and wing root. The use of torque rods admits a bidirectional wing twisting. The twist improve extremely the roll control and the response is largely linear over the airspeed range.

c) *Multi-point Wing Shaping*- is used to increase the control over the wing in twist. The is to enhance the control of the lift distribution over the wingspan. The wings are actuated by four rotating spars that are attached to a flexible, extensible wing skin. If this four rotating spars can be controlled independently is possible to make different complex shape of wing. In this strategy is possible to use spar tubes alone and to both wingtip, and middle-board spar tubes simultaneously. Concentric tubes parts act as both primary load-bearing members and as control linkages(torque tubes). A large diameter tube is fixed to the central part of the wing and acts as a bearing support for the rotating spars. The root section of the wing surface is also attached to the tube, creating an immobile joint between the inboard wing and fuselage. Two smaller tubes, one within the other, are supported by the fixed tube. Each servo is then able to command the incidence angle of the corresponding wing section independently. The flexible wings surface is attached to each of the three wings spar tubes. This structure permits twist morphing of each controlled wing section. Each of the wings sections are *independently controlled* and it result a *differential or collective configurability* with advantages for FW-MAV configurations. Roll control is a achieved by differently actuating the wing tip parts.

d) *Leading edge twisting*- is based on the differential output to the pushrods connected to the rigid leading edge. The actuation system generate opposite torques at the leading edge, producing the deformation in twist. This solution improves lateral direction controls and has a better roll rate, by using a smaller moment arm to actuate the wing in twist. The morphing permits highly aggressive maneuver and quick changes in flight path.

e)*Variable Gull-Wing Angling*- results from articulated the wingtips, with servos on a rod linked to a fixed spar. The servo push the surface away from the spar, resulting the twist which provide the roll. This strategy is used for precise maneuvering at low speed as well as basic maneuvering during high-speed dashes and long range endurance applications.

Depending on the selected strategy, there are several benefits such as improved performance due to the use of wing morphing. Also, morphing is easily achieved on MAVs because the wings are manufactured of flexible membrane materials like mylar. The flexible wings can be grossly deformed via mechanical actuation yet are capable of withstanding flight loads. The flexible nature of the wing also gives rise to the mechanism of adaptive washout which permits small changes in wing shape in response to gusty wind conditions.

For FW-MAV, morphing is limited to changing the shape of the central part of the wing and passive adaptation corresponds to the tips. There are several *bioinspired morphing techniques* that demonstrate how their flight maneuvers can be changed, such as loitering, diving and take-off. The wing can also be morphed by twisting or rotating parts of the wing in order to affect aerodynamic performance.

Another type of morphing is *bioinspired sweeping the wing* either at an elbow joint on the wing or at the root of the wing. The wing surface can also be changed by extending the length or trailing edge as some birds do. The aspect ratio is also affected by the morphing and can be used to improve the aerodynamic efficiency. One of the simplest form of morphing is a *wing twist* and this solution was proposed for control on the *Active Aeroelastic Wing (AAW)*. The *morphing on the AAW* causes the wings to be twisted in response to the moments induced by the control surfaces. Morphing on the FW- MAV is accomplished by actuation of control effectors located in the central wing. The servos are connected to the wings by either use of a torque rod or Kevlar strand. The wing morphing is actuated by moving the arm which rotates the tube or pulls the strand and changes the shape of the wing.

Certain maneuvers are of interest when considering the effects of wing morphing on a FW-MAV. The flight test maneuver of interest is the control doublet for the trailing edge and is performed by commanding a constant left deflection for a certain time period followed immediately by a right deflection for the same time period and finally returning to the neutral position. FW-MAV response characteristics to the control input are then determined by analysis of the servo position and rate responses.

Wing-shaping control doublets induce a different behavior of the FW-MAV. The response to wing shaping is similar in nature to responses from flaperons. Essentially, the MAV response to the morphing is predominantly roll motion with little yaw or pitch coupling. Thus, the doublets are performed without considerable directional or altitude deviation.

Following the completion of the maneuver, which resembles rocking the wings, the airplane is in a banked attitude. Recovery from the wing shaping doublet is considerably easier than that of the rudder doublet. Such a response indicates the wing shaping excites the roll convergence mode. Clearly, the MAV requires a stability augmentation system to facilitate operation and greatly expand its mission capability. In general, lateral maneuvers are particularly difficult because the MAV is so responsive. The introduction of a neuronal controller would lessen pilot workload for trajectory tracking.

The design of a controller is the next step in the research of facilitating the ability to operate these MAVs with the aid of active wing morphing. Open-loop flight tests were performed using wing morphing as an actuation mechanism and demonstrate the value of morphing for consideration of a stability augmentation system. The flaperons can be used to generate lateral maneuvers but the tight coupling of roll and yaw complicates the control needed for trajectory tracking. Conversely, the morphing produces almost pure roll so an associated controller for tracking roll commands is needed to be implemented.

4.Basic configurations and applications of fuzzy control

Fuzzy control was introduced in the 1970's to design controllers for systems structurally difficult to model, and they can now be found in fields such as: decision making or automatic control.

The main advantages of using fuzzy are:

- Is implemented based on human operator expertise, which means is oriented towards the situation/action rules rather than the parameters of diferential equations;
- Offers ways to implement simple but robust solutions that cover a wide range of system parameters;

There are three major phases in the sequence of operations of a fuzzy system:

1. Fuzzification, that converts input data into suitable linguistic values;
2. Inference, a mechanism that infers fuzzy control actions employing the rules of the interface in the fuzzy logic;

3. Defuzzification, that yields a nonfuzzy control action from an inferred fuzzy control action.

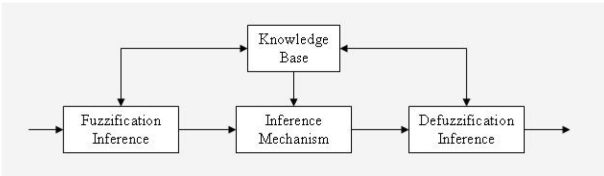

Fig.1

4.1 PID Control

The fuzzy rules are used to determine the control action based on the error signal and its first derivative or difference. Also it is known that conventional fuzzy control has two different types:

- Fuzzy proportional derivative control (PD);generates a control output from the error and change rate of error
- Fuzzy proportional integral control (PI); generates a control output that is incremental from the error and the change rate of the error.

The LOS angle rate and change of LOS angle rate can be used as input linguistic variables, and the lateral acceleration command can be used as the output linguistic variable for the fuzzy guidance scheme. The LOS angle rate and target acceleration can also be used as input linguistic variables to obtain an alternative fuzzy guidance scheme

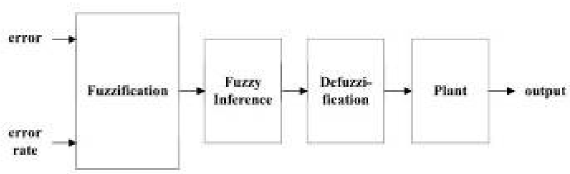

Fig. 2

4.2 Hybrid FL Controller

These types of controllers are robust and need a less complicated rule base because of the fact that the conventional controller filters the signal from the first input, which is the error. Because of the filtered error that is input into the fuzzy system, there are less fuzzy sets that describe the domain of the error signal.

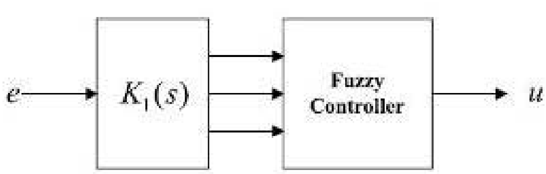

Fig. 3

4.3FL Adaptative Controller

The novalty introduced by the adaptative controller on the similar structure fuzzy to that of the PID controller, is the adaptability to the instantaneous error. Since the membership functions are adaptable, the controller is more robust and more insensitive to plant parameter variations. The figure below shows the typical adaptative fuzzy control scheme.

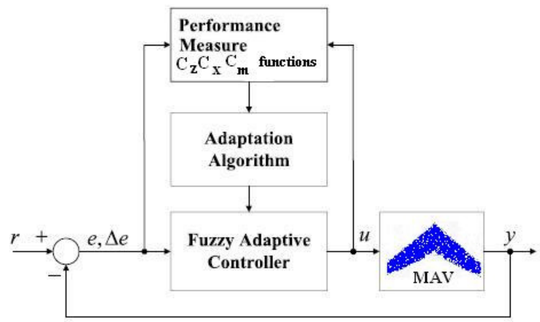

Fig. 4

4.4FL Sliding Mode Controller

The negative aspects of the fuzzy controllers regarding the performance and non-linear stability are not to be neglected. Their similarity with the SMC, good control methods for a specific class of non-linear systems, has provided the fuzzy plants with their succes. The fuzzy SMC can be aplied when there are taken into consideration parameter fluctuations and disturbances, with the condition that the upper bounds of their absolute values are known.

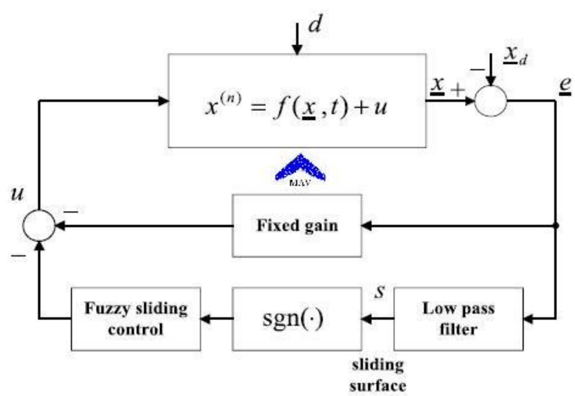

Fig. 5

4.5 FL Model Controller

To achieve the desired level of performance, the fuzzy adaptative sistem can be used with a model controller. As the example in the figure below shows, the error between the plant output and the reference model output is used to adjust the functions of the controller.

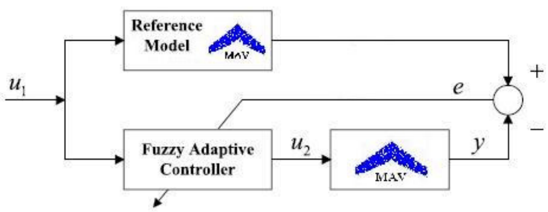

Fig.6

4.6 FL Hierarchical Controller

The main principle guiding this controller is intuitive and consists of dividing the structure into different levels. The controller gives an approximate output at the first level, which is then modified by the next level, and so on.

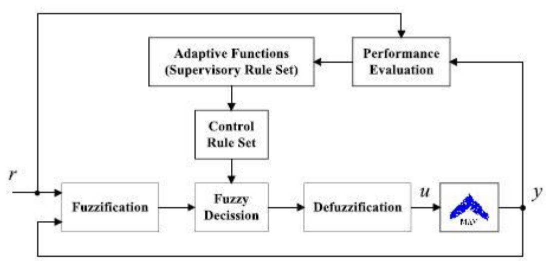

Fig. 7

4.7. FL Technology for Optimal Control

FL technology can be also utilized in optimal guidance law. The exact open-loop optimal control data from the computed optimal hystories of state and control variables could be used to generate FL guidance. The critical parameters of the functions of linguistic variables are equiped with the connecting weights of a NN. The colected data is used to train the NN weights by using numerical optimization/competitive algorithms. After training the MAV trajectories and aggressive maneuver commands for optimal solution and FL guidance solution will be close during actual flight using different scenarios.

The interest is to design a controller capable of following a predetermined some trajectory. The nonlinear continous and continuously differentiable system

$$\dot{\bar{x}}_r = f(\bar{x},\bar{u}) \quad (1)$$

where x_r is a differentiable, slowly varying state trajectory, and u_r is the nominal input necessary to follow the unperturbed state, after linearization, it results:

$$\begin{cases} \dot{\bar{x}}_i = A_i(\bar{x}-\bar{x}_i)+B_i(\bar{u}-\bar{u}_i)+f(\bar{x}_i,\bar{u}_i)=A_i\bar{x}_i+B_i\bar{u}_i+\bar{d}_i \\ \bar{d}_i = f(\bar{x}_i,\bar{u}_i)-A_i\bar{x}_i-B_i\bar{u}_i \end{cases}$$

(2)

$$\begin{cases} A_i = \left.\dfrac{\partial f}{\partial x}\right|(\bar{x}_i,\bar{u}) \\ B_i = \left.\dfrac{\partial f}{\partial u}\right|(\bar{x}_i,\bar{u}) \end{cases} \quad (3)$$

$$\dot{\bar{x}}_i \cong \hat{f}(\bar{x},\bar{u}) = \sum_{i\in I}\mu(\bar{x},\bar{u})\cdot A_i\bar{x}_i + B_i\bar{u}_i + \bar{d}_i$$

(4)

A fuzzy control law for this system is designed as a gain-scheduling controller. The feedback linear control laws can be synthesized, and interpolated through a fuzzy *Takagi-Sugeno* system:

$$\begin{aligned} \bar{u} &= \bar{u}_r + \sum^{i\in I} v_j(\bar{x},\bar{u})\cdot K_j[(\bar{x}-\bar{x}_j)(\bar{x}_r-\bar{x}_j)] = \\ &= \bar{u}_r + \sum^{i\in I} v_j(\bar{x},\bar{u})\cdot K_j[(\bar{x}-\bar{x}_j)] \end{aligned} \quad (5)$$

Substituting (5) in (4), it results the closed loop perturbed system dynamics which gives the dynamics of the perturbation from the desired trajectory

$$\begin{cases} \dot{\bar{x}}-\dot{\bar{x}}_r = \sum_i \mu_i(\bar{x},\bar{u})\cdot[A_i+B_i(\sum_j v_j(\bar{x},\bar{u})k_j)](\bar{x}-\bar{x}_r)+\varepsilon \end{cases}$$

$$\varepsilon = \sum_i \mu_i(\bar{x},\bar{u})\cdot(A_i\bar{x}_r + B_i\bar{u}_r + \bar{d}_i) - \dot{\bar{x}}_r \quad (6), (7)$$

5. A preliminary global modeling of morphing FW-MAV with flexible wing tips

The model can be defined by comparing the relationship between the signals which are observed and can be developed with the use of data from flight experiments. System identification considers the development of the model with the use of observed data. For this purpose the signals typically considered are the output signals, which are measured, as well as the input signals, which consider the effect the observer has on the response of a system. Other signals which can be considered are outside disturbances, which are signals that are produced from outside sources such as noise, wind gusts and sensor drift. The model is a simplified mathematical description but is not an exact one. System identification is performed by first collecting data which emphasizes the parameters considered in the model estimation. Therefore, the input and output signals as well as specific maneuvers are selected prior to the data collection.

It is also useful to describe the models using graphical interpretations. More specifically, they can be described using impulse, step and frequency responses. Certain systems can also be described using mathematical models. These can include continuous-time and discrete-time systems as well as linear and nonlinear systems.

A set of models can then be selected according to the specific application or dynamic system. A model which uses a black box approach considers the input and output signals of the system in order to perform a fit to the data without providing physical meaning to the values. This model is then compared with the values obtained in the experiment in order to determine whether it is a good estimation of the system response.

The simplest model considers input/ output signals that can be expressed in a linear equation:

$$y(t) + a_1 y(t-1) + ... + a_{n_a} y(t-n_a) = b_1 u(t-1) + ... + b_{n_0 u}(t-n_0) + e(t)$$

(8)

which can be expressed in terms of the initial output signal as shown in ARX model:

$$y(t) = -a_1 y(t-1) - ... - a_{n_a} y(t-n_a) + b_1 u(t-1) + + b_{n_b} u(t-n_b) + e(t)$$

(9)

Because the initial output values as well as the input and output terms are collected in matrix form for each time interval, since the initial output and the input values are known it is possible to solve the regression coefficients. The initial output values for each time interval can be also expressed in terms of the input and output values:

$$\begin{bmatrix} y^t \\ y^{t-1} \\ ... \\ y^{t-n} \end{bmatrix} = \begin{bmatrix} -y_1^t & -y_{n_a}^t & u_1^t & u_{n_b}^t \\ -y_1^{t-1} & -y_{n_a}^{t-1} & u_1^{t-1} & u_{n_b}^{t-1} \\ ... & ... & ... & ... \\ -y_1^{t-n} & -y_{n_a}^{t-n} & u_1^{t-n} & u_{n_b}^{t-n} \end{bmatrix} \begin{bmatrix} a_1 \\ a_{n_a} \\ ... \\ b_{n_b} \end{bmatrix} \quad (10)$$

Then the regression coefficients are obtained by solving the matrix equation:

$$A^{-1} B = X \qquad (11)$$

The following transformation:

$$y(t) + a_1 z^{-1} y(t) + ... a_{n_a} z^{-n_a} y(t) = b_1 z^{-1} u(t) + ... + b_{n_b} z^{-n_b} u(t) + e(t)$$

(12)

is then applied to equation (8) and it results the transfer function (13) in which the *B* term contains all the input coefficients from (5) and the *A* terms consists of all the coefficients in the output terms.

$$yu^{-1} = BA^{-1} \qquad (13)$$

Is possible to create a continuous time version of the discrete time system by using a standard bilinear transformation:

$$z = 1 + 2(sT/2) + 2(sT/2)^2 + 2(sT/2)^3 + ...$$

(14)

With a similar structure with ARX, ARMAX is another model for *system identification* and includes a moving average term, but includes in its coefficient calculations the noise.

Another modeling technique considers *recursive identification methods* in which is considered a model calculus simultaneous to obtaining data. However, this is not a requirement for this application. Certain applications include having an up to date model in order to consider these parameters when making decisions about what the system is to do next. This is referred to as an adaptive modeling technique because the input and output signals are calculated in order to be used as they become available.

RARMAX is a recursive model for system identification in Matlab and provides models for single-input, single-output systems. RARX is a similar technique which estimates parameters recursively of a single-output system. The initial linear approximation was done using an ARX technique. The initial step was to design an experiment the roll and yaw rate responses of the system which consisted of specified maneuvers such as doublets to the morphing and flapperon servos. The data processing includes a low pass Butterworth filter on all the parameters. The roll and yaw rate responses are then compared with the simulation responses for all types of morphing. The orders and delays are selected for the parameter estimation.

The orders of the approximation are the orders of the polynomials A and B in (13). Therefore, they are the orders of the polynomials in (15) and (16).

$$A(z) = 1 + a_1 z^{-1} + ... + a_{n_a} z^{-n_a} \qquad (15)$$

$$B(z) = b_1 + b_2 z^{-1} + ... + b_{n_b} z^{-n_b+1} \qquad (16)$$

The factor *nk* represents the number of delays from input to output:

$$A(z) y(t) = B(z) u(t - nk) + e(t) \qquad (17)$$

In multi-output systems, the orders of the polynomials have as many rows as outputs. After conversion to a continuous time system from a discrete time one, the roll and yaw rate responses are compared. The following step is the model validation by evaluating the quality of approximation.

The FW- MAV models were obtained by considering the inputs and outputs of the system and then reproducing significant data for control design, including approximations of certain aerodynamic parameters and time constants. These parameters are useful to design a controller as well as considering the modes. Once the system is represented in physical parameters, controllers such as roll and yaw dampers can be designed by feeding back the appropriate angles, by using a simple proportional gain in the closed loop system.

6. An innovative guidance scheme based on fuzzy systems.

The guidance system (through a set of waypoints generated by a mission planning algorithm) requirements are: the capability to pass a set of prescribed waypoints, the specification of the desired crossing velocity and heading, the adaptability by quickly reconfiguring the waypoint set without delay as an efficient response to some change in the mission scenario, to reach fixed waypoints as well as to track and reach waypoints that are moving with relatively low speed and acceleration.

The 5D MAV guidance assumes that the vehicle knows its position and targets/waypoints *position* (3 dimensions) and the *velocity vector* (2 dimensions). The choice of the fuzzy logic arises from the need to specify desired waypoint's crossing direction, since traditional proportional guidance do not allow specifying it. The MAV is autopiloted and fuzzy controllers can generate separately velocity, heading and flight path angle.

$$\dot{\gamma} = \frac{g}{V}(n\cos\phi - \cos\gamma) \quad (18).$$

The MAV guidance problem is addressed, by designing an inner nonlinear control loop first, which allows tracking of commanded velocity, flight path and heading. An outer loop (fuzzy guidance), generates a reference path command in terms of desired velocity, flight path and heading for the inner loop, in order to reach the desired waypoint.

The mathematical model is based on the following assumptions: no wind effects,no side-slip forces (β is always zero), MAV movements around its center of mass (attitude) can be neglected:

$$\dot{V} = \frac{(T-D)}{m} - g\sin\gamma \qquad (19)$$

$$\dot{\gamma} = \frac{g}{V}(n\cos\phi - \cos\gamma) \qquad (20)$$

$$\dot{X} = \frac{gn\sin\phi}{V\cos\gamma} \qquad (21)$$

and can be summarized as

$$\dot{x} = \frac{gn\sin\phi}{V\cos\gamma} \qquad (22)$$

The MAV dynamics can be feedback linearized with the following control laws:

$$T = k_v(V_d - V)m + mg\sin\gamma + d \qquad (23)$$

$$n\sin\phi = \frac{V}{}k_x(X_d - X)\cos\gamma = c_2 \qquad (24)$$

The resulting linear system is:

$$\begin{cases} \dot{V} = K_V(V_d - V) \\ \dot{\gamma} = K_\lambda(\gamma_d - \gamma) \\ \dot{X} = K_x(X_d - X) \end{cases} \qquad (25)$$

6.1 A simple Fuzzy Guidance (SFG) for MAV

The desired trajectory is specified in terms of a list of waypoints without any requirement on the path between two successive waypoints. The waypoint generator (WG) holds a 5D list of waypoints (LW), checks MAV position, and updates the mission.

Between the WG and SFG, a coordinate rotation system transforms earth-fixed-frame position errors into waypoint-frame relative errors. Each waypoint defines a coordinate frame centered in the waypoint position (X_W,Y_W,H_W) and rotated around the *H*-axis. This coordinate transformation allows to synthesize a fuzzy rule-set valid in the waypoint-fixed coordinated frame. When a waypoint is reached, the next one is selected, the actual reference value *W* is changed and the rotation matrix is updated to transform position and orientation errors into the new waypoint coordinate frame.

The autopilots are designed to track desired airspeed, heading and flight path angle.

The most simple way to generate the desired flight path angle (γ_d) is based on altitude error

$$e_H = (H_w - H) \qquad (26)$$

$$\gamma_d = f_\gamma(e_H) \qquad (27)$$

The second fuzzy controller computes desired MAV velocity:

$$V_d = V_W + f_V(V_W - V) = V_W + f_V(e_V) \quad (28)$$

The most complete form should generate

the desired heading angle (χ_d) using the position errors and the heading error. Because Fuzzy rule-set is designed at a fixed airspeed value, this can produce a lack of tracking performances when the desired way-point crossing-speed differs significantly from tune-up value. The solution is achieved by introducing a speed-correlated scale coefficient to position errors. Let:

$$\begin{pmatrix} e_X^w \\ e_Y^w \end{pmatrix} = Rot(\chi_W) \cdot \begin{pmatrix} e_X \\ e_Y \end{pmatrix} = Rot(\chi_W) \cdot \begin{pmatrix} X_W - X \\ Y_W - Y \end{pmatrix}$$

(29)

the position errors in the fixed waypoint coordinates frame, and

$$\begin{pmatrix} e_{X_C}^w \\ e_{Y_C}^w \end{pmatrix} = S(V_W, V^*) \cdot \begin{pmatrix} e_X^w \\ e_Y^w \end{pmatrix} \quad (30), (31)$$

$$S(V_W, V^*) = \frac{V^*}{V_W}$$

the velocity-compensated position errors. The desired heading angle is:

$$\chi_d = \chi_W + f_\chi(e_{X_C}^w, e_{Y_C}^w, e_\chi^w) \quad (32)$$

Takagi- Sugeno fuzzy controller is based on a blending of fuzzy IF-THEN rules

$$IF\ x_1\ IS\ F_1^1\ AND\ x_2\ IS\ F_2^1\ AND \ldots$$
$$\ldots AND\ x_n\ IS\ F_n^1\ THEN\ y\ IS\ G_y^1$$
$$IF\ x_1\ IS\ F_1^2\ AND\ x_2\ IS\ F_2^{21}\ AND \ldots$$
$$\ldots AND\ x_n\ IS\ F_n^2\ THEN\ y\ IS\ G_y^2$$
$$\vdots$$
$$\vdots$$
$$IF\ x_1\ IS\ F_1^m\ AND\ x_2\ IS\ F_2^m\ AND \ldots$$
$$\ldots AND\ x_n\ IS\ F_n^m\ THEN\ y\ IS\ G_y^m$$

(33)

where x_i are the inputs, y the output and F_j^i the fuzzy sets. Using a weighted average defuzzifier, the output is defined by:

$$y = \frac{\sum_{i=1}^{m} \mu_i(x) u_i}{\sum_{k=1}^{m} \mu_k(x)} \quad (34)$$

where $\mu_i(x)$ is the i^{th} membership function of input.

It is possible to describe each fuzzy controller separately from the others, by using the uncouplet MAV model. The Altitude controller (AC) and the Velocity controller (VC) are less complex than Heading controller (HC). For AC the only input is the altitude error $e_H = (H_w - H)$ and four fuzzy set are designed to map this input and four for the γ_d output:

- $If\ e_H\ Is\ N_\infty\ Then\ \gamma_d\ Is\ P_{20}$: *for big negative errors*
- $If\ e_H\ Is\ N_S\ Then\ \gamma_d\ Is\ P_2$: *for small negative errors*
- $If\ e_H\ Is\ P_S\ Then\ \gamma_d\ Is\ N_2$: *for small positive errors*
- $If\ e_H\ Is\ P_\infty\ Then\ \gamma_d\ Is\ N_{20}$: *for big positive errors*

The VC has 3 input fuzzy sets for e_V and 3 for the resulting output :

- $If\ e_V\ Is\ N_\infty\ Then\ \Delta V_d\ Is\ P_{10}$: *for negative errors*
- $If\ e_V\ Is\ ZE\ Then\ \Delta V_d\ Is\ ZE$: *for near to zero errors*
- $If\ e_V\ Is\ P_\infty\ Then\ \Delta V_d\ Is\ N_{10}$: *for positive errors*

In this case, the MAV is autopiloted in velocity, and the controller acts as gain varying with error itself. Guidance in the horizontal plane is more complex than guidance in the vertical one. The corresponding fuzzy controller takes his input from scaled position errors and heading error:

- N_∞ : *for big negative errors*
- N_S : *for small negative errors*
- ZE: *for near to zero errors*
- P_S : *for small positive errors*
- P_∞ : *for big positive errors*

The output for this fuzzy controller is:

$$y = \frac{\sum_{i=1}^{m} \mu_i(x) u_i}{\sum_{k=1}^{m} \mu_k(x)} = \frac{1}{c(x)} \sum_{i=1}^{S} \sum_{j=1}^{K} \mu_i^{xy}(e_{X_c}^w, e_{Y_c}^w) \cdot \mu_{ij}^{\chi}(e_\chi) u_{ij} =$$

$$= \frac{1}{c(x)} \sum_{i=1}^{S} \mu_i^{xy}(e_{X_c}^w, e_{Y_c}^w) \cdot \delta_{ij}^{\chi}(e_\chi)$$

$$c(x) = \sum_{k=1}^{m} \mu_k(x)$$

$$\mu_i^{xy}(e_{X_c}^w, e_{Y_c}^w) = \mu_i^x(e_{X_c}^w) \cdot \mu_i^y(e_{Y_c}^w)$$

(35), (36)

This relation can be simplified:

$$\sum_{i=1}^{S} \frac{\mu_i^{xy}(e_{X_C}^w, e_{Y_C}^w)}{c(x)} \cdot \delta_{ij}^{\chi}(e_\chi) = \sum_{i=1}^{S} \bar{\mu}_i^{xy}(e_{X_C}^w, e_{Y_C}^w) \cdot \delta_{ij}^{\chi}(e_\chi)$$

(37)

Fixing $(e_{X_c}^w, e_{Y_c}^w)$ in the middle of the P^{th} zone it results

$$y \left| e^{w}_{X^P_C} = \overline{\mu}_P(e^{w}_{X^P_C}, e^{w}_{Y^P_C}) \cdot \delta^{\chi}_P(e_\chi) + \right. \\ \left| e^{w}_{Y^P_C} \right. \\ + \sum_{\substack{i=1 \\ i \notin P}}^{S} \overline{\mu}_P(e^{w}_{X_C}, e^{w}_{Y_C}) \cdot \delta^{\chi}_{ij}(e_\chi) \cong \qquad (38) \\ \cong \overline{\mu}^{xy}_P(e^{w}_{X^P_C}, e^{w}_{Y^P_C}) \cdot \delta^{\chi}_P(e_\chi)$$

This equation shows that the definition of fuzzy sets for e_χ error should be computed looking at each single set partitioning the flight space and then looking the global result. Under this assumption, 7 fuzzy sets are defined

V_A=modulus of aircraft velocity

V= modulus of desired crossing velocity of current waypoint

H_A=aircraft altitude

H_W=waypoint altitude

X_A,Y_A=aircraft position in the XY-plane

X_W,Y_W =waypoint position in the XY-plane

χ_A =aircraft heading

χ_W =desired crossing heading of current waypoint

Simulation results for the SFG shows the following limitations: loss of accuracy under some conditions; presence of some singularities that raise incorrect control signals; high number of fuzzy rules that make behavior analysis difficult.

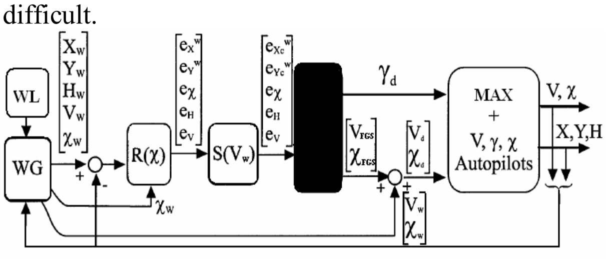

Fig. 8

6.2 An improved Fuzzy Guidance (IFG)

The aim is to analyze how the new solution changed the heading controller. In the remaining of this document, the variables that refer to the waypoint will have a *W* suffix, those for the vehicle/aircraft will have the *A* suffix; later the moving waypoint or target variables will have the *T* suffix.

The first FGS logic can be summarized as follows:

$$\begin{cases} V_d = V_W + f_V(e_V) \\ \gamma_d = f_\gamma(e_H) \\ \chi_d = \chi_W + f_\chi(e^{w}_{X_c}, e^{w}_{Y_c}, e_\chi) \end{cases}$$

$$\begin{cases} e_V = V_A - V_W \\ e_H = H_A - H_W \\ [e^{w}_{X_c}, e^{w}_{Y_c}]^T = S(V_W, V^*) \cdot R^T(\chi_W) \cdot [X_A - X_W, Y_A - Y_W]^T \\ e_\chi = \chi_A - \chi_W \end{cases}$$

(39), (40)

The new structure for heading controller varies significantly. The new control logic is the following

$$\begin{cases} V_d = V_W + f_V(e_V) \\ \gamma_d = f_\gamma(e_H) \\ \chi_d = \hat{\chi}_W + FLC_\chi(\hat{e}_\chi, V_A) \end{cases} \quad (41), (42)$$

$$\begin{cases} \hat{\chi}_W = \chi_W + \chi_{\chi w}(e^{w}_{X_c}, e^{w}_{Y_c}) \\ \hat{e}_\chi = \chi_A - \overline{\chi}_W \end{cases}$$

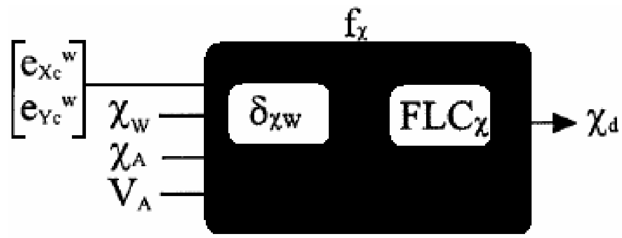

Fig. 9

7. Conclusions

In the present paper, we highlight the recent research in establishing a low cost adaptive FW-MAV with flexible wing tips, with better operational capabilities. Various strategies for morphing (wing curling, wing twisting, multi point wing shapping, leading edge twisting, variable gull/wing angling, wing- tail folding), with rapid fabrication and simple technologies could be used on this FW-MAV configuration. The novelty of this FW-MAV is given by the combination between semiflexible tips and the wing twisting morphing, on a low cost concept. The semiflexible concept offers the advantage of a more stable flight under variable or difficult flight conditions. Because of their very small inertia, wing loading of the MAVs can affect the flight path. Current MAVs are designed with the common features of carbon/ glass fiber airframes (unidirectional fiber prepreg, woven fiber prepreg, Kevlar thread) and flexible membrane wings. The philosophy was to fabricate many modular designs and to perform many flight-tests permitted for a better observation of flight characteristics, stability of flight, payload sensibility, maneuverability. The typical control surfaces which can be implemented on FW-MAVs consist of flapperons. This solution can not be integrated in the design of a MAV with full span flexibility. A different form of actuation based on morphing should improve maneuverability and performance. A particularly demanding mission is one which takes place in an urban environment which requires these vehicles to have advanced maneuvering capabilities. The simple approach to increasing maneuverability is based on an additional control effector with wing morphing. This paper has demonstrated that morphing can be an effective means to achieve roll control for a semiflexible FW-MAV. The flexible nature of the wing tips enables their shapes to be easily altered. Simple mechanisms (torque rod, Kevlar threads) are used on the FW-MAV permits roll maneuvers morphing with significant roll rates and a very good controllability.

For a better maneuverability, first tests were made in an R/C configuration together with a simple data acquisition system (DAS) with gyros and accelerometers for all the three axes. Data regarding the accelerations and rates of the three axes can also be used for a simple linear modeling technique.

Regarding the MAV adaptive control, Lyapunov stability based MRACs look similar to other types of MRAC controllers except they use this idea of stability to define a parameter update law. Parameter estimates of the plant are updated in a manner that guarantees asymptotic convergence of the error between the model and plant. This type of MRAC suffers from high frequency oscillations on the control effort. This can cause unmodeled dynamics to be excited, leading to instability. Also, like gradient based MRACs, the performance of Lyapunov MRACs is dependent upon the magnitude of the reference signal.

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