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2 authors:

Nazim Kemal Ure
Istanbul Technical University

Gokhan Inalhan
Istanbul Technical University

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Nazim Kemal Ure, Gokhan Inalhan
Istanbul Technical University, Controls and Avionics Laboratory,
34469 Maslak Istanbul, +90 212 285 3148,
ure@itu.edu.tr, inalhan@itu.edu.tr

Abstract—This paper discusses the structure of a multi modal control framework for generation and control of aggressive maneuver profiles for agile unmanned vehicles. It is shown that any arbitrary flight maneuver can be decomposed into simpler flight modes and modal parameters, which are derived from combat maneuvers and aerobatics. Feasible maneuver generation problem is complicated by both sequence of the maneuver modes and envelope constraints on control inputs. These problems are solved by developing mode transition rules and a set of agility metrics that bounds the domain. Overall system with flight modes, transition conditions and domains is shown to be a finite state machine which spans full flight envelope of maneuvers of UCAV, where local control of each mode results in control of full flight maneuver. Thus, maneuver controlling problem is reduced into lower dimensional maneuver mode and parameter search.[1][2]

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1. INTRODUCTION

Today, increase of complexity in unmanned vehicle operations, results in need for agile maneuvering for unmanned combat air vehicles (UCAVs). This is due to fact that, UCAVs have to operate in dense and adversary environments, where the aircraft will be operating at the edge of the flight envelope (high angle of attack) while performing sharp turns (high g). These kinds of aggressive maneuvers need specialized control frameworks, where feasible maneuver profile generation and control processes are combined together. In this work, we develop a multi modal control framework for UCAVs to generate and control agile maneuvers.

The methodology is inspired from the fact that, a single control law is in efficient to handle arbitrary reference aggressive maneuver tracking. Due to need for specific control laws for specific maneuvers, a classification must be made for reference maneuver profiles. Such a classification could be made by inspecting well known aerobatics and combat maneuvers, with breaking maneuver profiles into sequence smaller small maneuvers (named maneuver modes) and associated maneuver parameters (named modal inputs). This paper explains derivation of necessary maneuver modes and modal inputs, along with a maneuver generation methodology for generating feasible maneuver profiles over full flight envelope. Multi modal control framework is founded on this maneuver decomposition-generation process, where every maneuver mode can be controlled be a specific controller, which results in a multi modal switched control system. Such a system can be described by the language of hybrid systems, which is also provided in this work.

Motion planning problem for aerospace vehicles are complicated by the fact that, planners based on optimal performance begins to fail in means of computation, when one takes into account of constraints related with dynamic equations of aircraft. Due to fact that, aircrafts state space is at least 12 dimensional, input-state search becomes too complicated; therefore such planners are only successful for vehicles with small state space dimensions [12]. To reduce the complexity of this problem, motion description languages and quantized control concept have been adopted into motion planning [5]. Motion description languages, makes use of classified combination of simplified control laws to track generalized outputs. Most of these languages are strongly connected with the concept of hybrid systems, which in general, classifies the motion by using discrete states which switches in between according to input and state information and each discrete state having its own continuous dynamics. A subclass of such languages which is based on classification of behavior (or reaction) of the dynamic systems, has been successfully adapted for non-holonomic robotic systems [6]. More recently, closed loop hybrid control systems were developed based on linear temporal logic for the same purpose by [7]. For aerospace vehicles, a hybrid model for aircraft traffic management was developed in [8]. Study showed that, hybrid system representation gives opportunity to calculate reachable sets of the system and design hybrid control laws to drive the system to safe states [9]. Frazzoli [12]suggested a maneuver automaton, which uses a number of feasible system trajectories to represent the building blocks of the motion plan of the aircraft, and a trajectory based (based on maneuver regulation principle) control system which

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[1] 978-1-4244-2622-5/09/$25.00 ©2009 IEEE.
[2] IEEEAC paper #1244, Version 4, Updated December 17, 2008

asymptotically regulates the actual trajectory to the trajectory generated by maneuver automaton. However, motion plans and controllable trajectories are restricted to the library of the maneuver automaton. Such libraries can be built by using interpolation between feasible trajectories [10]. [11] Extended this system for online planning of feasible trajectories in partially unknown environments by using receding horizon iterations.

Description of aircraft dynamics from hybrid system point of view has been studied previously in [3], [4], [13] .These works have been successful in using the advantages of hybrid system methodology in control of both single and multiple aircrafts. However, these approaches did not include the full flight envelope dynamics of the aircraft. Specifically, both mode selection and controller design is strictly based on selected maneuvers; therefore controllability is limited [3], [4], [13] to these predefined trajectories. In our work, we make use of parameterized sub maneuvers which builds up complex maneuver sequences. We show that it is possible to cover almost any arbitrary maneuver and the entire flight envelope by this approach.

Organization of the paper is as follows; in section two, derivations of the flight modes is discussed along with examples from aerial combat and aerobatics. In the next section maneuver generation constraints are defined and categorized into two classes; sequential and envelope constraints. In third section concept of multi modal control is defined and switched output tracking controllers are derived. In the final section multi modal control framework is converted to finite state automaton and inspected from hybrid system point of view.

2. Maneuver Modes And Modal Inputs

Multi modal controls basic idea is to quantize the arbitrary flight maneuvers into simpler sub-maneuvers. Inspection of aerobatic and combat maneuvers [20] reveals that these modes can be used as building blocks to generate complex maneuvers in agile flight. In this section, derivation of the flight modes and their parameters are discussed. Section ends with two examples taken from aerial combat and aerobatics, which are decomposed into maneuver modes and parameters.

Derivation of Flight Modes

In order to gain insight to dynamics of agile flight, well known aerobatics and combat-maneuvers were inspected. Two of the common maneuvers, 'Immelmann Turn' and 'High Yo-Yo' are shown in fig.1. Immelmann Turn, which is used to reverse the direction (heading) of the aircraft, consists of a straight level flight at the entry, followed by a pitch up maneuver (which draws a loop in the longitudinal plane) in which the aircraft becomes inverted and corrected by a roll around stability axis. Maneuver results in reversion of heading and altitude gain (Split-S maneuver is basically reverse of the Immelmann, which causes a drop in the altitude). This maneuver is a good example of smooth aerobatic maneuvers, where rolls and loops are connected to each other smoothly. On the other hand, common combat maneuvers are not easy to break up into sequences of simpler submaneuvers as aerobatic maneuvers; High yo-yo maneuver consists of a coordinated turning and diving maneuver, which later switches to diving with constant flight path angle.

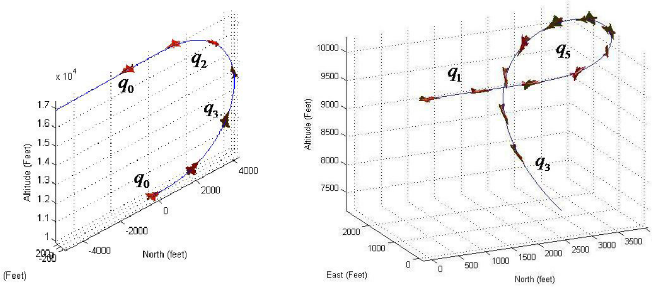

Figure 1 - Common Aerobatics and Combat Maneuvers

Detailed explanations on above examples shows that; no matter how complex it is, every maneuver can be decomposed into smaller sub-maneuver segments. Main aim of this section is to derive all the necessary flight modes to build arbitrary maneuvers, and investigate the necessary conditions to sequence maneuver modes and control them.
Inspection shows that, every flight segment can be characterized by a number of simple observations. Three basic properties that define a submaneuver are:

- Constant (A1) or time varying altitude (A2)
- Constant (B1) or time varying roll angle (B2)
- Drawing a loop in longitudinal (C2) or lateral plane (C3) Drawing a loop in longitudinal (C2) or lateral plane (C3)

Combining results of these three properties gives the total number of flight modes which can be characterized by the combination of these properties. In this case it is twelve distinct modes as it is shown on table 1. First three columns show the combinations of above listed properties and the rightmost column shows the resulting submaneuver. Name of the submaneuvers are taken from either aeronautics literature or aerobatics books.

Table 1.List of all possible flight modes

A1	B1	C1	Level Flight
A1	B1	C2	Pitch Regulation
A1	B1	C3	Coordinated Turn
A1	B2	C1	Rolling Level Flight
A1	B2	C2	Spin Roll
A1	B2	C3	Rolling Circle
A2	B1	C1	Climbing/Diving Flight
A2	B1	C2	Pitch Up/Down
A2	B1	C3	Climbing/Diving Turn
A2	B2	C1	Rolling Climbing/Diving
A2	B2	C2	Barrel Roll
A2	B2	C3	Rolling Scissors

It must be noted that table 1 is not exactly complete; it can expanded by adding coordinated / uncoordinated option (zero or non-zero sideslip angle). Since zero sideslip angle is desired most of the time, this option is omitted from now on. Submaneuvers such as “rolling circle” or “rolling climbing/diving” (which indicated continuous rolling motion while flying) are also rarely seen in combat maneuvers, so we combine such modes into a single “roll mode” which is independent of aircrafts trajectory. This mode acts as a transition mode between other modes, as it will be more evident in maneuver generation constraints.

Another inspection of table shows that submaneuvers such as “Climbing/Diving Turn “ or “Barrel Roll” draws a 3D trajectory on Cartesian space opposed to other modes which draws either 2D or 1D trajectories. Therefore these modes are grouped into a single “3D mode” for the sake of simplicity.

Although these flight modes are sufficient to explain large number of flight maneuvers, giving sequence of these modes alone is not enough. One must also give associated maneuver parameters with each mode (such as radius of the loop, or total speed in level flight). These parameters are named as modal inputs. Modal inputs associated with each mode along with state constraints which describe them, can be found on table 2. Modal inputs associated with each mode are derived from inspection of state constraints on each mode. They also give clue about which outputs must be controlled during local control of each mode (later on this in section four).

Table 2 also contains an extra mode called safety mode. This mode is created artificially for control reasons. Main aim of this mode is to regulate the aircraft back into level flight whenever, the aircraft goes out of domain of a flight mode, due to external disturbances. Its modal input is the set 0-1, which means that mode is either on or off.

State vector of a 6 degrees-of-freedom aircraft is usually chosen as; [19]

$$X = \begin{bmatrix} V_T & \alpha & \beta & \phi & \theta & \psi & P & Q & R & n_p & e_p & h \end{bmatrix}^T \quad (1)$$

Where, V_T is the total speed, α and β are aerodynamic angles, angle of attack and sideslip angle respectively. $\Phi = [\phi \quad \theta \quad \phi]^T$ is 3-2-1 Euler angle set (due singularity of Euler angles at 90 degrees of pitch angle they may seem not convenient for agile flight, however they are still used to represent the maneuvers due to their straightforward nature, singularities can be avoided by switching them with Quaternions during integration of the differential equations or controller design). $\omega = [P \quad Q \quad R]^T$ is the angular velocity vector in the body axes, and $\rho = [n_p \quad e_p \quad h]^T$ is the set of Cartesian coordinates. Flight path Euler angles (or wind axis angles) are denoted with Φ_w.

Table 2. Flight Modes and Modal Inputs

	Mode	State Constraints	Modal Inputs
q_0	Level Flight	$\dot{h}=0,(\dot{\phi},\dot{\theta},\dot{\psi})=0$	V_T,α
q_1	Climb/Descent	$(\dot{\phi},\dot{\theta},\dot{\psi})=0$	$V_T,(\dot{h},\theta_w)$
q_2	Roll	$(\dot{\theta},\dot{\psi})=0,\beta=0$	$V_T,\int P_w dt$
q_3	Longitudinal Loop	$(\dot{\phi},\dot{\psi})=0,$	$(V_T,r_{loop}),\dot{\theta}$
q_4	Lateral Loop	$\dot{h}=0,(\dot{\phi},\dot{\theta})=0$	$(V_T,r_{loop}),\dot{\psi}$
q_5	3D Mode	$\{\ \}$	V_T,P,Q,R $V_T,\phi_w,\theta_w,\psi_w$
q_6	Safety	$\{\ \}$	$\{0,1\}$

It can be concluded that a multi modal maneuver description is an alternative to state space trajectory time history of aircraft as a dynamical system. It gets rid of the redundancy of states while describing certain motions, by benefiting from the fact that some states are constant or zero during propagation of certain maneuver. So instead of giving the total state space time history $X(t)$, maneuver is described by the trio; flight mode q_i, modal input σ_i, and time interval Δt_i; the string $(q_i \quad \sigma_i \quad \Delta t_i), i=1,2,\ldots n$ is referred as maneuver string, and it is of lower dimension compared to $X(t)$. This is illustrated in next subsection with two examples.

Example 1 - Cuban Eight

Cuban eight is a popular aerobatics maneuver, which consists of connected loops and rolls in order to draw an “eight” figure in the 2D plane. Maneuver can be broken down into maneuver mode and modal input sequence as shown by figure 2 and table 3.

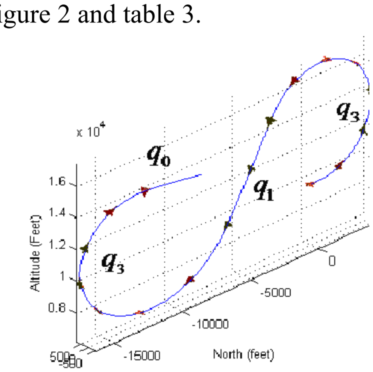

Figure 2 - Cuban Eight

Table 3. Modal Decomposition of Cuban Eight

Maneuver Mode	Modal Inputs	Time Intervals (sec)
q_3	$r_{loop}=3000ft, \dot{\theta}=225/5 \deg.s^{-1}$	$[0,5]$
q_1	$V_T=400ft/s, \theta_W=45\deg$	$[5,7]$
q_3	$r_{loop}=3000ft, \dot{\theta}=225/5 \deg.s^{-1}$	$[7,12]$
q_0	$V_T=400ft/s, \alpha=2\deg$	$[12,14]$

Advantage of multimodal state framework is easily seen; instead of giving 12 time-state curve for these 14 seconds lasting maneuver, all the information is contained in table 3 with only 4 maneuver modes and modal inputs.

Example 2 - Agile Combat Maneuver

This example shows that multi modal decomposition is not applicable only to smooth aerobatic maneuver but also to arbitrary agile maneuvers. This example is inspired from common fighter combat maneuvers [20].

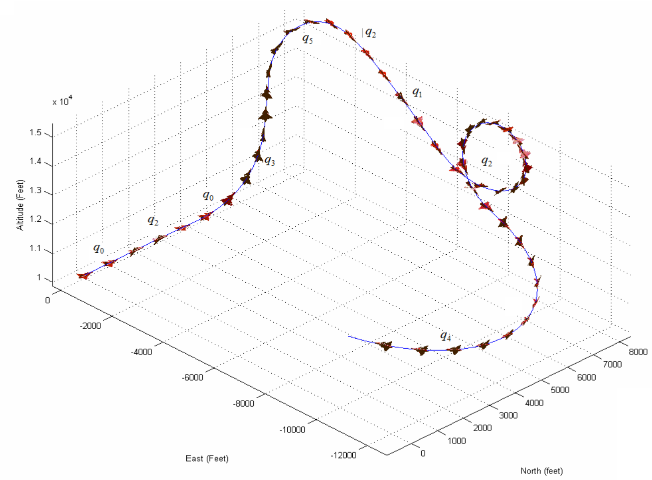

Figure 3 - Agile Combat Maneuver

Table 4. Modal Decomposition of Agile Flight Maneuver

Maneuver Mode	Modal Inputs	Time Intervals (sec)
q_0	$V_T = 500\,ft/s, \alpha = 2\deg$	$[0,1]$
q_2	$\int P_w dt = 90\deg$	$[1,3]$
q_0	$V_T = 500\,ft/s, \alpha = 2\deg$	$[4,5]$
q_3	$V_T = 600\,ft/s, \dot{\theta} = 22.5\deg.s^{-1}$	$[5,10]$
q_2	$\int P_w dt = 180\deg$	$[10,12]$
q_5	$V_T = 600\,ft/s, P = 22.5\deg s^{-1}$, $Q = 45\deg.s^{-1}, R = \psi^*$	$[13,23]$
q_2	$\int P_w dt = 180\deg$	$[23,25]$
q_1	$V_T = 600\,ft/s, \theta_w = 50\deg$	$[25,26]$
q_5	$V_T = 600\,ft/s, P = 25\deg s^{-1}$, $Q = -20\deg.s^{-1}, R = \psi^*$	$[26,45]$
q_4	$V_T = 900\,ft/s, \dot{\psi} = 22.5\deg.s^{-1}$	$[45,60]$

These examples outline the maneuver decomposition methodology; however it is often the case that instead of identifying or decomposing, we want to generate maneuver profiles. Next section deals with the maneuver generation process and feasibility constraints.

3. Feasible Maneuver Generation Constraints

While the methodology described in previous section, replaces the common continuous state history description with a sequence of flight modes and modal inputs, it assumes that given maneuver profile is feasible. However when one wants to generate a feasible maneuver profile based on this methodology to, two important constraints raises.

First type of constraints arises from maneuver sequencing. Due to physical considerations, maneuver execution cannot necessarily be arbitrary. For this, we provide a set of rules reflected on a mode transition chart that describes which maneuver mode can be executed after another. Second type of constrainta is associated with modal inputs. Due to aerodynamic, structural and actuator limitations, modal inputs must lie inside the flight envelope during the execution. Unfortunately there is no direct link between, flight performance of the aircraft and envelope limitations other than simplified cases, but these two quantities can be put together in terms of agility metrics which is explained further in this section.

Methodology developed in this section can be integrated with a path planner to form a hierarchical control system. Example of such a system can be found in [23].

Sequential Constraints

From the example maneuvers given in the previous section, it is evident that, execution of one mode after another is strongly dependent on initial and final conditions of preceding and succeeding modes. For example, in coordinated turn aircraft is naturally banked with a constant roll angle, however in level flight aircrafts wings are level. So in order to translate from level flight q_0 to coordinated turn q_4 aircraft must change its roll angle (i.e. go through a roll mode q_2). Analogous examples can be given for translating from climbing flight to level flight, longitudinal loop to lateral loop… etc. If all of these sequential constraints are collected on a table, we got so called mode transition table which is shown in table 5.

Table 5. Mode Transition Table

δ_{ij}	q_0	q_1	q_2	q_3	q_4	q_5	q_6
q_0	1	θ^*	1	1	ϕ^*	1	1
q_1	θ^*	θ^*	1	1	θ^*,ϕ^*	ϕ^*	1
q_2	1	θ^*	1	θ^*	1	θ^*	1
q_3	1	1	1	1	θ^*,ϕ^*	ϕ^*	1
q_4	ϕ^*	θ^*,ϕ^*	1	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	1
q_5	θ^*,ϕ^*	θ^*,ϕ^*	1	θ^*,ϕ^*	θ^*,ϕ^*	θ^*,ϕ^*	1
q_6	1	0	0	0	0	0	0

In the table δ_{ij} symbol denotes transition relation between each mode. 1 means that transition between two modes is always possible and no transition mode is needed, 0 means that transition between these modes is blocked. Roll and pitch Euler angles means that change in the associate angle is needed for transition.

Inspection of the table shows that roll mode and longitudinal loop mode acts as a transition mode between the others because they can create the desired shift in roll and pitch angles. Thus one can construct maneuvers by using level and climbing flights along with loops and connect them using rolling and pitching. It is also noted that safety mode is accessible all the time, once it is activated it automatically regulates back to level flight, so all other transitions from this mode is blocked.

As a side note, formal analysis of mode switching conditions could be found on [21].

Envelope Constraints and Agility Metrics

Second type of constraints is related with domains of each mode. Maneuver parameters (or modal inputs) are limited by the performance envelope of the aircraft. For example, there is a limit on maximum total speed in level flight which depends on engine power, altitude and aerodynamic characteristics of the aircraft. So in execution of each individual mode these parameters must lie within their envelope, if not maneuver is not feasible.

If the performance and saturation envelopes (such as V-n diagram) could be converted to modal input envelopes, then this problem could be solved by choosing modal inputs that satisfy the envelope constraints all the time. Unfortunately this is not possible except for simplified aerodynamic and propulsion models.

In this work we use agility metrics as a measure of feasibility for each mode. Agility metrics were investigated during 1990s, to develop a set of meaningful metrics for fighter aircraft comparison [15]. These metrics portray the performance characteristics of fighter aircraft and their limits reflect the combined effect of both flight envelope limits and actuator saturation limits.

Methodology in this section is consists of selecting an agility metric for each mode, then it is concluded that if the modal inputs chosen so that they satisfy the limits of the metric (limits of the metric can always be gathered from nonlinear 6 DOF simulations) then maneuver mode is feasible. Selected agility metrics are chosen from [15], [16]. For use of agility metrics in fighter aircraft performance comparison, interested reader may refer to these documents.

Level and Climbing Flight:

For level flight total speed is the most important parameter. Maximum and minimum achievable speed depends heavily on available power and thrust. Selected agility metric is power onset/loss parameter which can be written as:

$$\dot{P}_s = \frac{d}{dt}\left(\frac{V_T\left(T-D\right)}{W}\right) \tag{2}$$

Where T is thrust, D is drag and W is weight. This agility metric quantifies maximum thrust and drag of the aircraft, which determines the total speed. If this metric is plotted against velocity and angle of attack, regions where engine becomes incapable could be determined and feasible region could be estimated.

Roll Mode:

For rolling motion either average roll rate or time to go through certain roll displacement can be used. Second one is more convenient as it gives transient performance more clearly. For specific angle 90 degrees can be used, because most of the rolling maneuvers consists of rolling aircraft to side (knife edge), or inverting it (180 degrees). Therefore selected agility metric is

$$TR_{90} = \text{Time To Go Through 90 degrees roll angle} \tag{3}$$

This agility metric can be plotted against various angles of attacks to determine the feasible region and feasible modal input for the mode can be selected form this region.

Longitudinal Loop:

For pitch up/down motion, very simple and convenient metric is average pitch rate which can be written as

$$Q_{avg} = \frac{\int_{t_1}^{t_2} Q dt}{t_2 - t_1} \tag{4}$$

Similar to roll mode this metric can be plotted against various angles of attack to determine feasible region.

Lateral Loop:

For turning performance load factor and turning radius is chosen as a predominant factor, by using the simple kinematic equation (Hale, 1984):

$$r_{loop} = \frac{V_T^{\,2}}{g(n^2-1)} \tag{5}$$

Where g is the gravitational acceleration and n is the load factor. This metric can be plotted in a 3D region where 2D plane consists of V-n diagram of the aircraft (which could be evaluated by numerical simulations). Feasible loop radius interval could be determined from this plot.

3D Mode:

Angular velocities play an important role in this mode so agility metric is chosen as weighted average of angular velocities;

$$3D_{avg} = K_1 P_{avg} + K_2 Q_{avg} + K_3 R_{avg} \qquad (6)$$

Where average rates are calculated as in eq. (4). K_i Corresponds to weights on each average rate and can be chosen according to maneuver, for example more weight could be put on rolling rate when it is a barrel roll. This metric can be evaluated with multiple plots on 3D space, with keeping one rate constant at each plot.

Example

By using six degrees of freedom high fidelity F-16 simulation [18], agility metric associated with roll mode is potted at fig. 4.

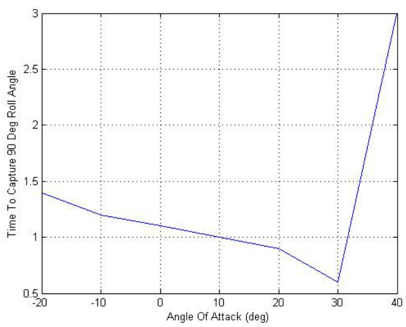

Figure 4 – Plot of Roll Mode Agility Metric

The plot of the metric shows that as the angle of attack increases less time is required to capture the roll angle, but at some critical point around 30 degrees, plot has a jump related with the stall characteristics (i.e. loss of aerodynamic lift and moment). So it can be concluded that roll modes modal input can be selected to have 90deg/s in -20, 30 degrees angle of attack region, but roll rate must be lowered at higher angles of attack for efficiency.

After generation of e feasible maneuver profile which satisfies the constraints on this section, next step is to control the maneuver profiles. This can be done via multi modal control framework which is explained in next section.

4. Multi Modal Control Framework

After creating a maneuver profile which is decomposed into flight modes and modal inputs as shown on section two, and tweaked to satisfy the constraints in section three, next step is to execute maneuver using a low level controller system. Main idea of multi modal control framework is to assign a different output controller to each mode (so that every mode has its own modal inputs, agility metric and controller).

Although these low level output tracking controllers can be designed by any methodology, linear controllers would not be able to handle inherent nonlinearities of agile maneuvering, so application of nonlinear control design techniques is required. Performance of a linear controller based on robust PID synthesis, is shown on fig. 5.

Fig. 5 shows that, as the reference signals amplitude increases, linear controller's performance degrades and eventually system becomes unstable. In figure 6, also performance of a linear and nonlinear controller is compared in terms of maneuver tracking, it is seen that nonlinear controller could track agile maneuver profiles which are not trackable by classic designs.

In this section, selection of appropriate output profiles is discussed for each mode. Because that stability of internal dynamics of the system (minimum and non-minimum phase outputs) is also a major concern in nonlinear control design, [1], [2] NMP and MP controllers are also pointed out during this section. Derivations of such controllers are out of the scope of this paper. Design of low level, higher order sliding mode controllers for multi modal control framework is covered in [17].

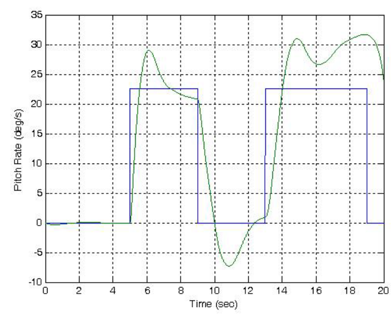

Figure 5 – Incompetent Performance of Linear Controller

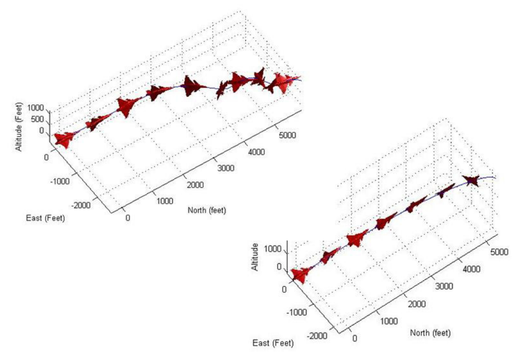

Figure 6 – Agile Maneuver Tracking with linear (left) and nonlinear (right) controllers

For switched controller design, we review the associated part appeared on [17]:

Switching Controllers

Although it is theoretically possible to design one controller which tracks the inertial trajectory of the aircraft, it is much more structured and performance wise feasible to design specific control laws to each mode (or a set of similar modes). After designing such a set of controllers, control of a complete agile trajectory can be achieved by switching between these controllers following the mode transitions. Due to fact that mode transition sequence is already given by decomposed maneuver profile, transition logic of these controllers is automatically set (it is the same as mode sequence). This idea is illustrated in fig. 6, in which three different output tracking controllers are switched between to track the Immelmann Turn.

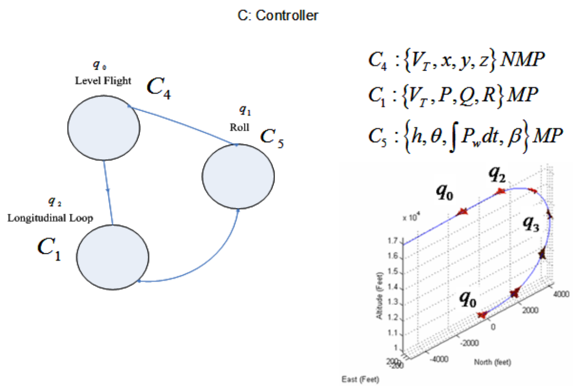

Figure 6 - Controller Switching Diagram for Immelmann turn

Following the maneuver descriptions and their modal inputs (maneuver parameters) in table 2, table 6 summarizes the output tracking controllers assigned to each mode.

Table 6 - Tracked Output Sets for each controller

	Controlled Variables	Type
C_1	V_T, P, Q, R	MP
C_2	$V_T, \phi_w, \theta_w, \psi_w$	NMP
C_3	V_T, ϕ, θ, ψ	MP
C_4	V_T, x, y, z	NMP
C_5	$h, \theta, \int P_w dt, \beta$	MP
C_6	$V_T, \{Quaternions\}$	MP

Choice of the control set as defined in Table 7 is based on both the modal inputs and the mode constraints of each mode. For example, the roll mode controller combines both modal input integration of wind axis roll rate, and mode constraint of zero sideslip angle. In Table 6, although C_4 can be observed as an ultimate controller which controls any maneuver given by a flight path, the effectiveness of this controller is limited. This is based on the fact that C_4 is an NMP attitude controller which requires restrictions on Cartesian coordinates of the aircraft. This is in comparison to the MP controllers which stabilize both rotational and translational elements. Note that if every mode is locally controllable by the set of output controllers defined as above, then we can globally control any maneuver, by decomposing it into sub modes and switch between controllers at each transition step.

After selection of tracking output profiles, high level portion of multi modal control framework is completed, summary of framework is displayed on table 7.

5. Conversion Into Hybrid System Form

Up to this point nothing had been said about hybrid system presentation of the framework, but all of the results indicate that multi modal control framework is naturally a hybrid system, where discrete and continuous dynamics are found together. Each flight mode represents an element of discrete dynamics and each flight modes has continuous dynamics (represented by state vector). Each mode has its domain defined by agility metrics. Execution of the flight modes is constrained by mode transition table and execution of continuous states is constrained by 6 degrees-of-freedom differential equations. Also, discrete modes and continuous dynamics have different input set (mode transition commands and modal inputs).

In the light of above discussion, we put the multi modal framework into an automaton in this section, and then we briefly discuss advantages of such a representation.

Multi Modal Control Framework as an Automaton

Multi modal control framework is converted into an automaton called Mode Based Maneuvering Automaton (MBMA), elements of MBMA are,

$$MBMA = \{Q, X, U, \Sigma, f, \delta, Dom, Init, \Omega\}$$

Q is the set of discrete flight modes,

$$Q = \{q_0, q_1, q_2, q_3, q_4, q_5, q_6\} =$$

{Level,Climb,Roll,Long. Loop,Lat. Loop,3D, Safety}

X is the set of continuous states (flight dynamics)

$$X = \begin{bmatrix} V_T & \alpha & \beta & \varphi & \theta & \psi & P & Q & R & n_p & e_p & h \end{bmatrix}^T$$

U is the set of continuous inputs (parameters that generate modal inputs);

$$U = \left\{V_T, \dot{h}, \int P_w dt, r_{loop}, \dot{\theta}, \dot{\psi}, P, Q, R, \phi_w, \theta_w, \psi_w\right\}$$

Σ is the set of discrete inputs (transition commands between modes) $\Sigma = \bigcup_{i=1,j=1}^{i=1,j=7} \sigma_{ij}$ $\dot{X} = f_i(X, U, Q)$, is the continuous differential equations (state propagation in each flight mode), Discrete transitions are governed with transition relation $q_j = \delta_{ij}(q_i, \sigma_{ij})$, where δ_{ij} symbolizes the elements of mode transition table. Dom is the domain of continuous states and inputs, which is defined by agility metrics in table 7. $Init$ is the set of initial states and flight modes. Mode transitions has to obey trajectory acceptance condition,

$$\Omega = (q_1 \in Init) \wedge (q_{i+1} = \delta_{i,i+1}(q_i, \sigma_{i,i+1})) \wedge (q_i, x_i \in Dom) \quad (12)$$

Once the system is converted to hybrid form, algorithms and methods developed for the system can be applied to automaton; this has two powerful advantages. First one is

Table 7. Summary of Multi Modal Control Framework

	Mode	State Constraints	Modal Inputs	Agility Metric	Controller
q_0	Level Flight	$\dot{h}=0,\left(\dot{\phi},\dot{\theta},\dot{\psi}\right)=0$	V_T, α	$\dot{P}_s=\frac{d}{dt}\left(\frac{V_T\left(T-D\right)}{W}\right)$	C_2, C_4
q_1	Climb/Descent	$\left(\dot{\phi},\dot{\theta},\dot{\psi}\right)=0$	$V_T, \left(\dot{h},\theta_w\right)$	$\dot{P}_s=\frac{d}{dt}\left(\frac{V_T\left(T-D\right)}{W}\right)$	C_2, C_4
q_2	Roll	$\left(\dot{\theta},\dot{\psi}\right)=0, \beta=0$	$V_T, \int P_w dt$	TR_{90} = Time To Go Through 90 degrees roll angle	C_5
q_3	Longitudinal Loop	$\left(\dot{\phi},\dot{\psi}\right)=0,$	$\left(V_T, r_{loop}\right), \dot{\theta}$	$Q_{avg}=\frac{\int_{t_1}^{t_2} Q dt}{t_2-t_1}$	C_1, C_3
q_4	Lateral Loop	$\dot{h}=0,\left(\dot{\phi},\dot{\theta}\right)=0$	$\left(V_T, r_{loop}\right), \dot{\psi}$	$r_{loop}=\frac{V_T^{\,2}}{g(n^2-1)}$	C_2
q_5	3D Mode	{ }	V_T, P, Q, R $V_T, \phi_w, \theta_w, \psi_w$	$3D_{avg}=K_1 P_{avg}+K_2 Q_{avg}+K_3 R_{avg}$	C_1, C_3, C_4
q_6	Safety	{ }	{0,1}	{ }	C_6

the reachability concept [22]. By using the system verification tools one can prove that every mode is reachable from given initial conditions which imply that there always exists a hybrid system trajectory as in eq. (12), that will connect an initial and final mode. Second advantage is for proving switched system stability; by constructing Lyapunov functions and using hybrid system stability one can show that stability in each discrete mode also implies switched system is stable [14]. These subjects are left to future research.

6. Conclusion And Future Work

In this work we have laid out a multi modal control framework suited for UCAVS, which quantizes the flight maneuver into discrete flight modes and parameters. Decomposition methodology has been shown by examples. Maneuver generation constraints are also discussed in terms of sequential and envelope constraints, which have been overcome by use of a set of transition rules and agility metrics respectively. Lastly, local tracking output of each mode is discussed and system is converted into a hybrid system for future research. Overall system, which is named as Mode Based Maneuvering Automaton has the capability of decomposing and generating complex feasible agile maneuver profiles which are tracked by nonlinear controllers assigned to each mode. System has ability to track every maneuver which has been generated by this system (full flight envelope control) as opposed to control limited set of pre-defined flight trajectories in previous researches.

Future research consists of studying the hybrid system tools outlined in the fifth section, and expanding the automatons coverage by adding non-coordinated flight (i.e. non-zero sideslip angle).

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BIOGRAPHY

Nazim Kemal Ure *is Ms.c student in Istanbul Technical University, in the department of Defense Technologies. He had graduated from Aeronautical and Astronautical engineering departments in 2008 with honors. He had been working as a research assistant in Controls and Avionics Laboratory since 2006. His primary research area is hybrid systems and nonlinear control with special emphasis on agile maneuvering and sliding-mode-control.*

Gokhan Inalhan *is an assistant professor at Istanbul Technical University in the department of Aeronautical Engineering and serves as the director of the Controls and Avionics Laboratory. He received his Ph.D. degree in Aeronautics and Astronautics from Stanford University with Ph.D. minor in Engineering Economic Systems and Operations Research in 2003. Between 2004 and 2006 he had worked as a Post-doctoral associate at Massachusetts Institute of Technology. During this period he had led the Communication and Navigation group in the NASA CER project. He is a member of IEEE Technical Committee on Aerospace Control.*