A Mode-Based Hybrid Controller Design for Agile Maneuvering Unmanned F-16 Aircraft

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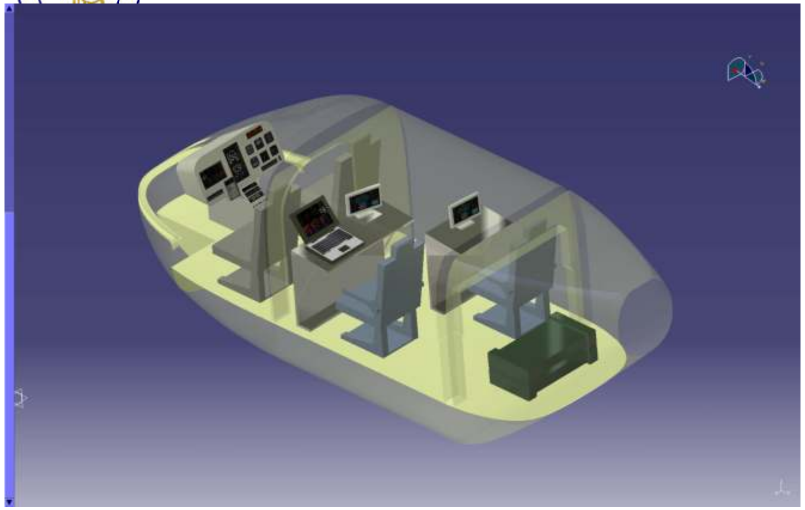
Controls and Avionics Laboratory

CAL INDUSTRIAL PROJECTS



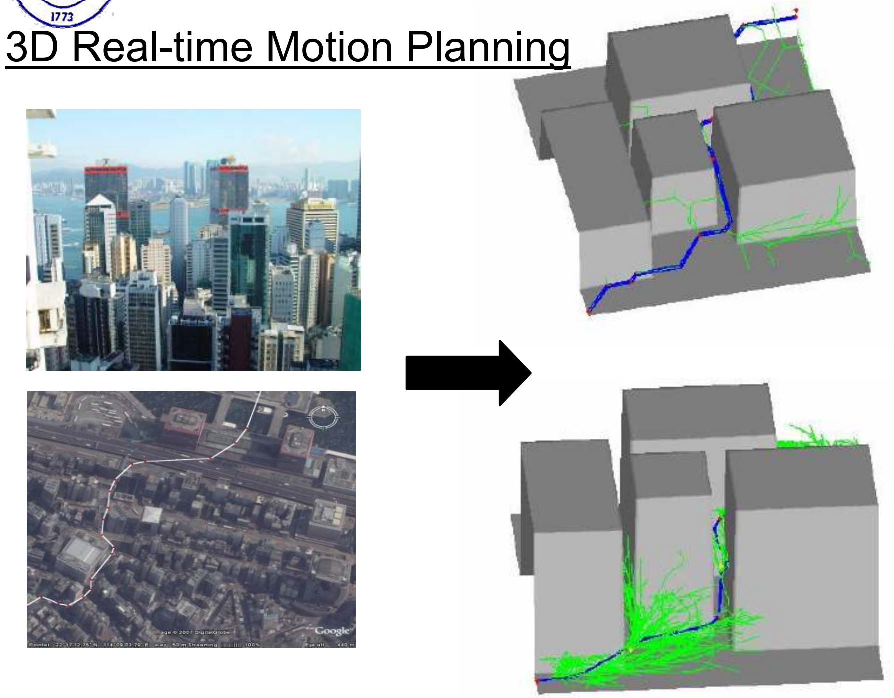
İTÜ LCH AVIONICS SYSTEMS

- Primary Funding Sources
  - DPT
  - ASELSAN

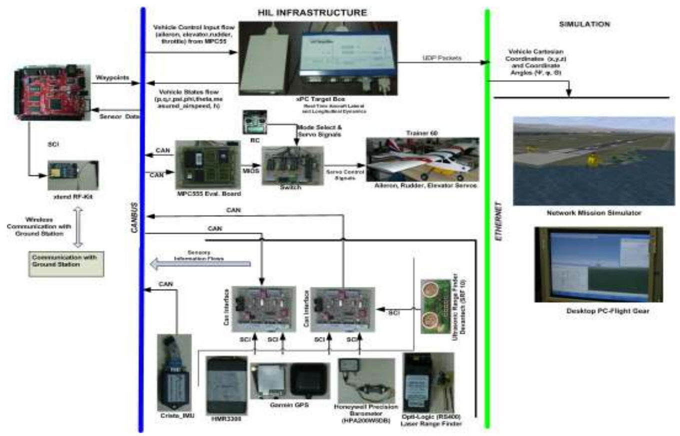
İTÜ ASELSAN Research Flight Simulator

CAL RESEARCH PROJECTS

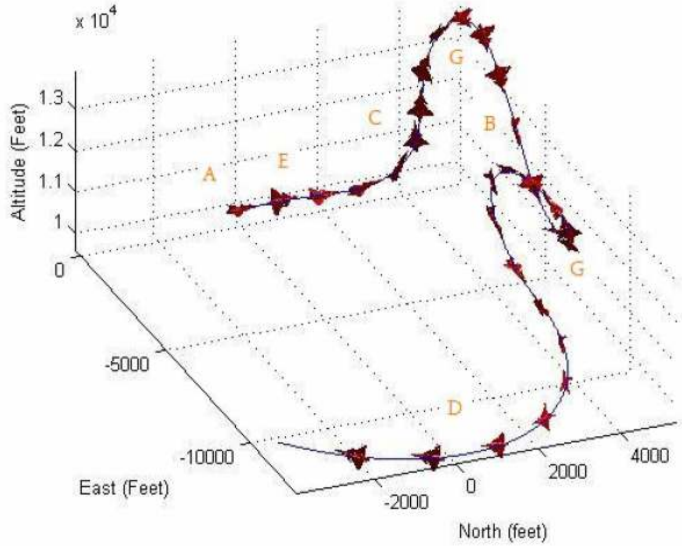
3D Real-time Motion Planning



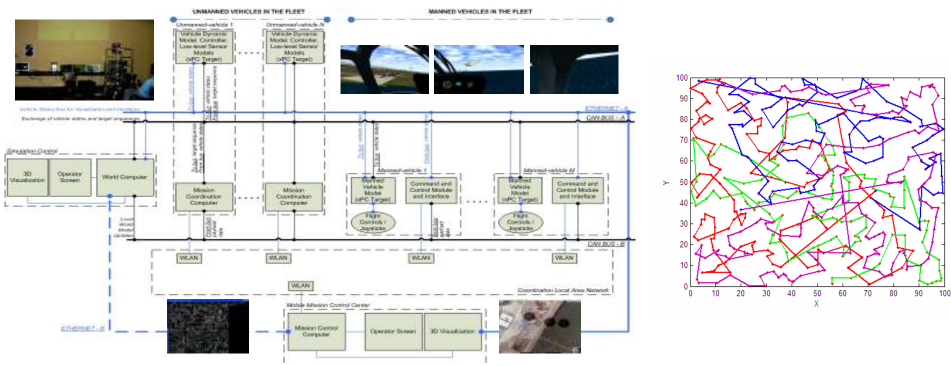
Bus backboned Microavionics



Agile Nonlinear Flight Controls



Mission Planning for Manned and Unmanned Fleets

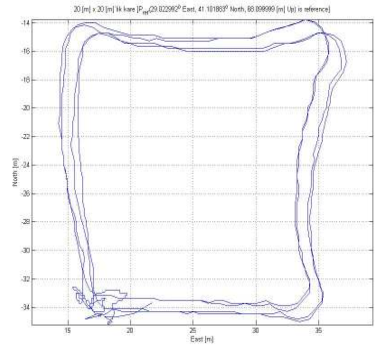


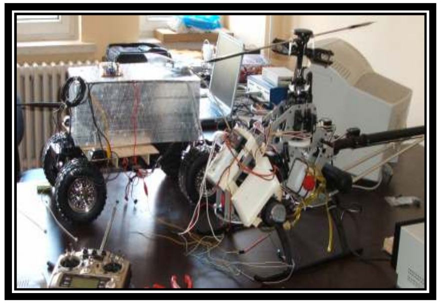
CAL STUDENT PROJECTS

MicroBee

• Micro-avionics test platforms : Flight controls and image processing

Autonomous control





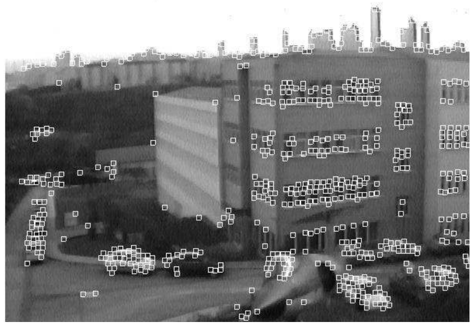
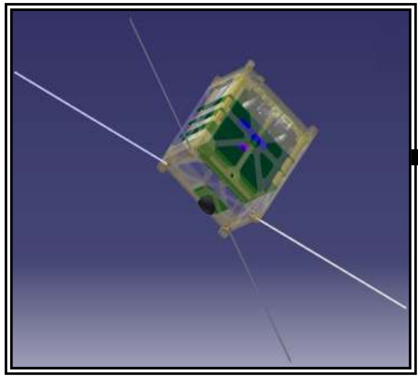
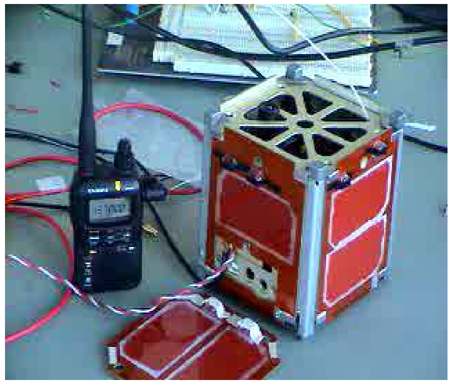


Image Processing

ITU-pSAT I



• Scheduled for launch
In late 2008- early 2009



ITU pSAT I Engineering Model

Outline

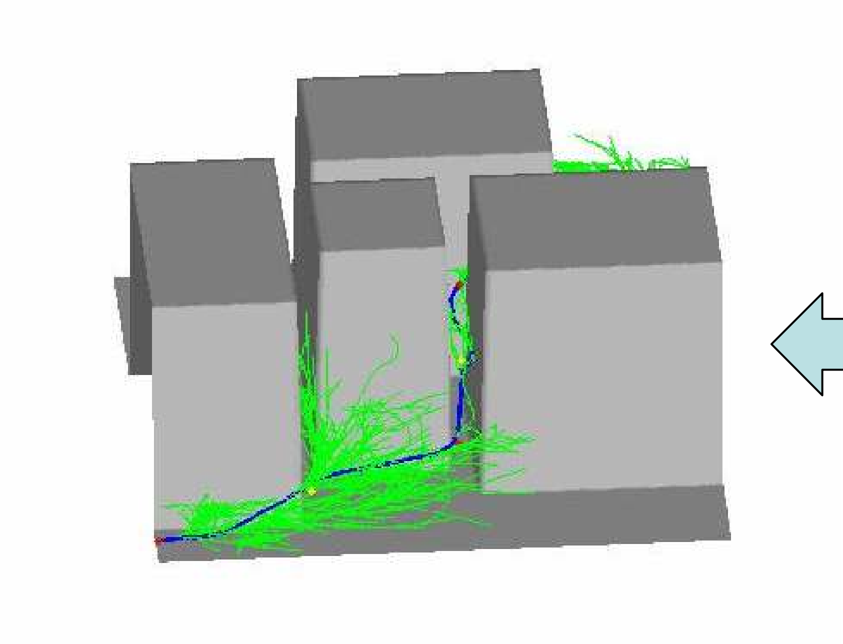
- Problem Statement and Previous Work
- F-16 Aircraft Model
- Motion Language for Agile Maneuvering
- Hybrid System Representation of Agile Maneuvers
- Properties and advantages of Hybrid System Description
- Nonlinear Sliding Control of full flight envelope Dynamics
- Simulations

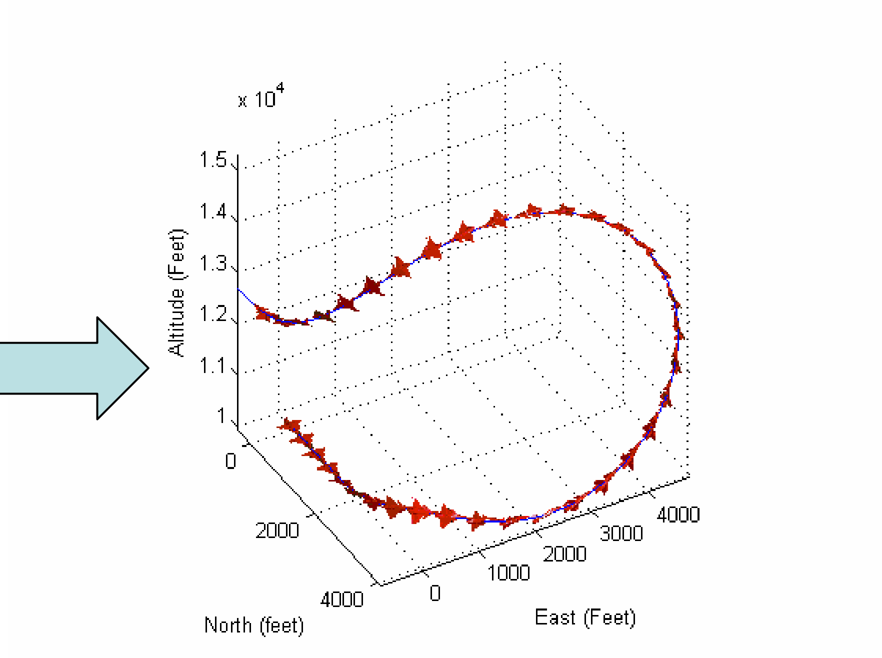
Problem Statement

- **Autonomous Control of Agile Maneuvers over full flight envelope**
  - **Perform agile maneuvers in case of evasive and tactical advantage gain positions**
  - **Output tracking over full flight envelope, especially in extreme cases (high AOA , high g)**
- Design flight trajectory generation algorithms over full flight envelope
  - Agile and competitive maneuvering in dynamically changing and complex environments

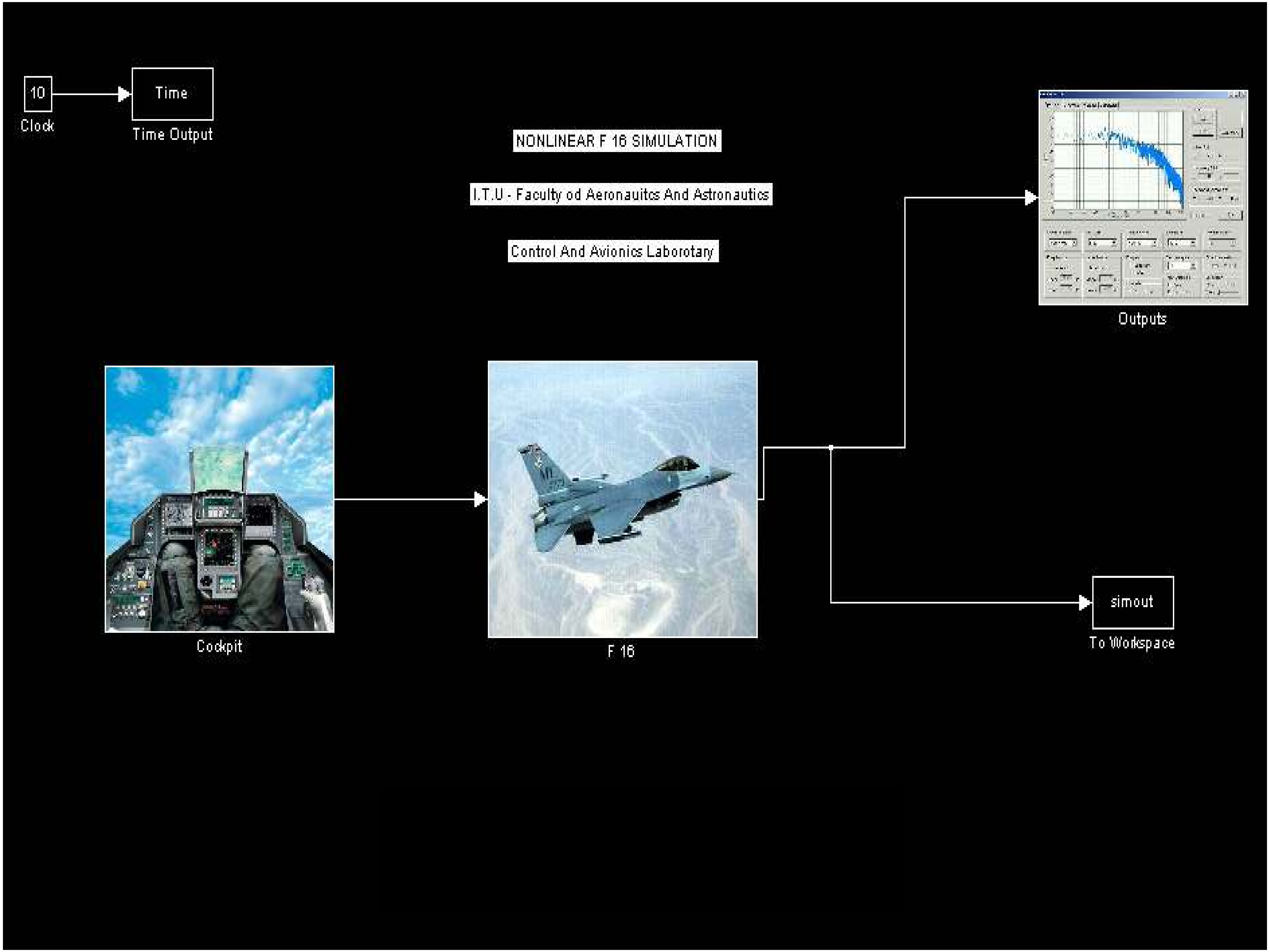
Two Facets of the Problem

- Autonomous design and execution of agile maneuvers





- A low level enabling technology for cooperative control of UAV fleets that driven by performance goals


10
Clock
Time
Time Output
NONLINEAR F 16 SIMULATION
I.T.U - Faculty od Aeronauitcs And Astronautics
Control And Avionics Laborotary
Outputs
Cockpit
F 16
simout
To Workspace

Agile Maneuver Example

Challenges

- Generation of agile maneuvers
  - Lack of general expressions for six degrees of freedom flight dynamics
  - Complexity of decomposing the maneuvers in state space
  - Feasibility constraints on maneuvers
- Execution of agile maneuvers
  - Highly coupled, nonlinear dynamics
  - Demand for high precision tracking on high magnitude angular rates
  - Robustness properties

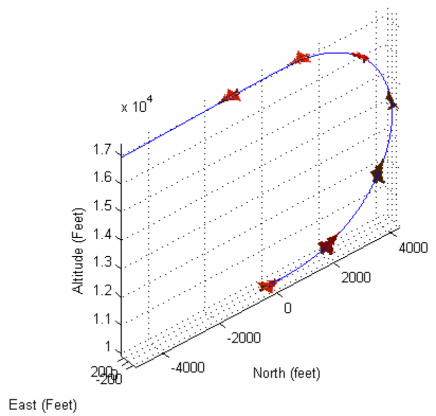
Previous Works

- Hybrid Systems Description for Flight Maneuvering
  - Hybrid and modal representation of single and multiple aircraft dynamics (Tomlin, 1998),(Frazzoli,2002)
- Experimental Work on Agile Maneuvering
  - Gavrilets, Feron (MIT) : outdoors
  - How (MIT) : indoors

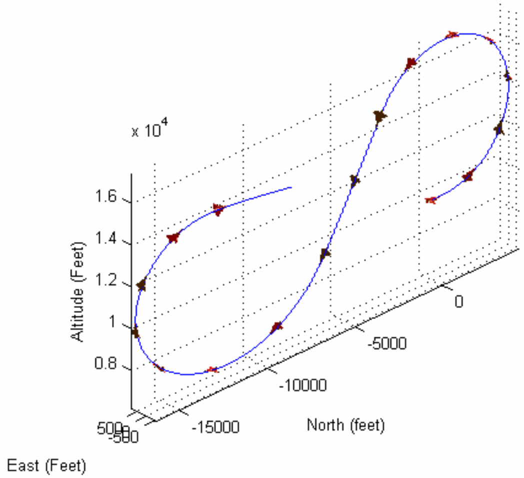
Major issues that is still open…

- Full flight envelope dynamics?
- Trajectory-free controller design?

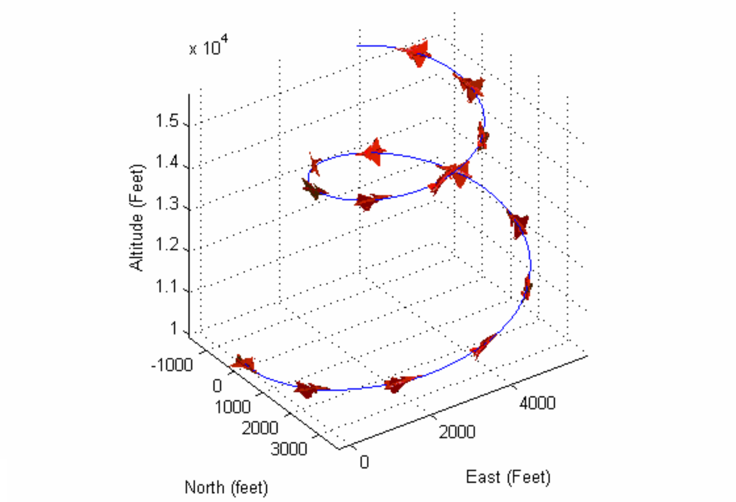
Motion Description for Agile Flight



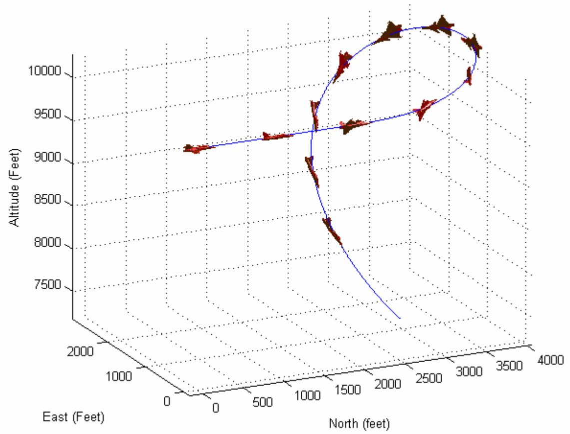
Immelmann



Cuban Eight



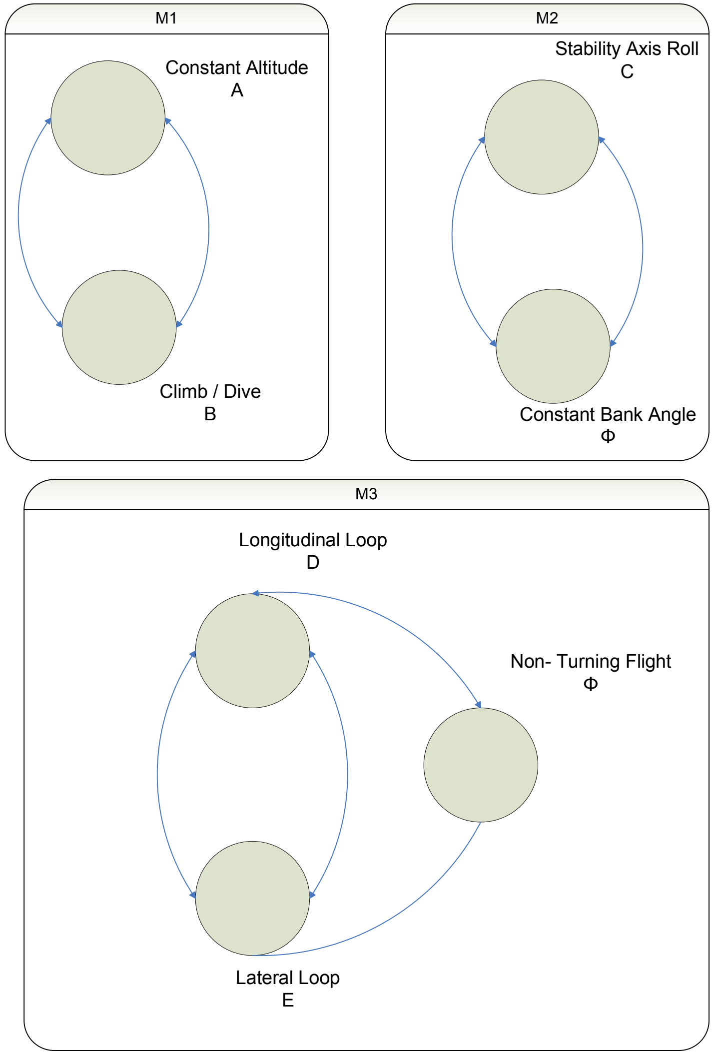
Turning Climb



High Yo-Yo

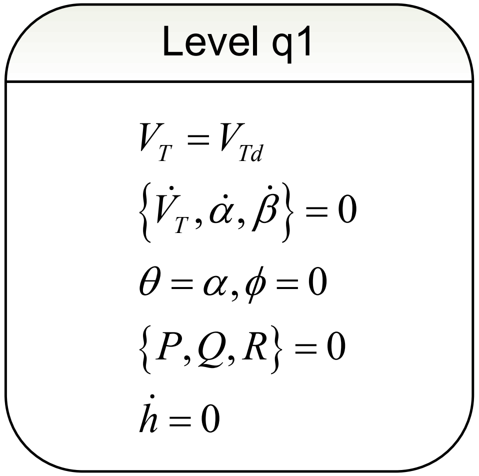
Acrobatic and combat maneuvers is a good starting point….

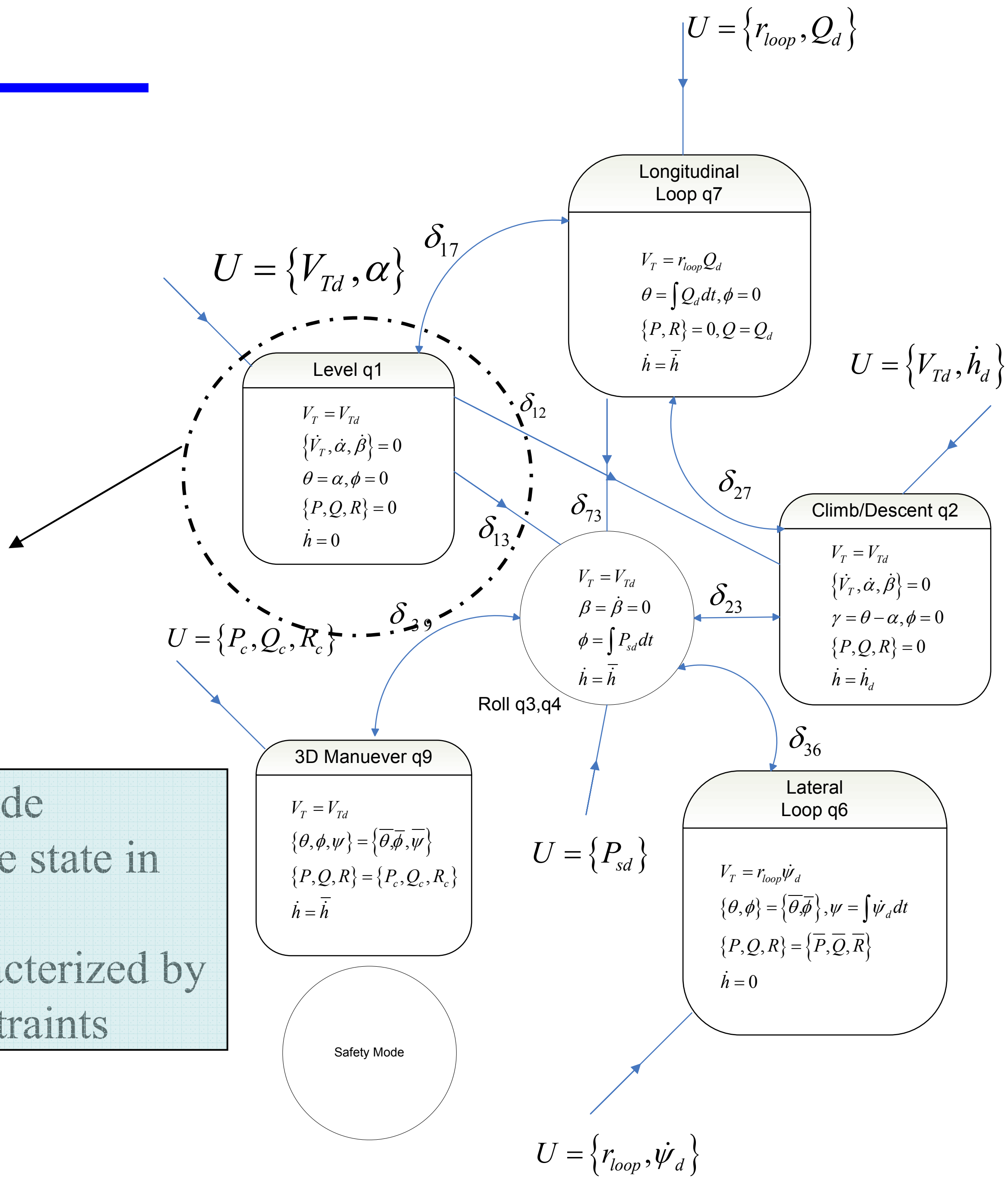
Coordinated Automata Description



	M1	M2	M3	Description of Maneuver Segment
q_1	A	ø	ø	Level Flight
q_2	B	ø	ø	Climb/Descent
q_3	A	C	ø	Straight Rolling Flight
q_4	B	C	ø	C/D Rolling Flight
q_5	A	ø	D	AOA Regulation in Level Flight
q_6	A	ø	E	Coordinated Turn
q_7	B	ø	D	Pitch Up/Down
q_8	B	ø	E	Turning C/D
q_9	B	C	D(E)	Barrel Roll, Helix, 3D Maneuvers
q_{10}	A	C	E	Rolling Circle

Maneuver Modes

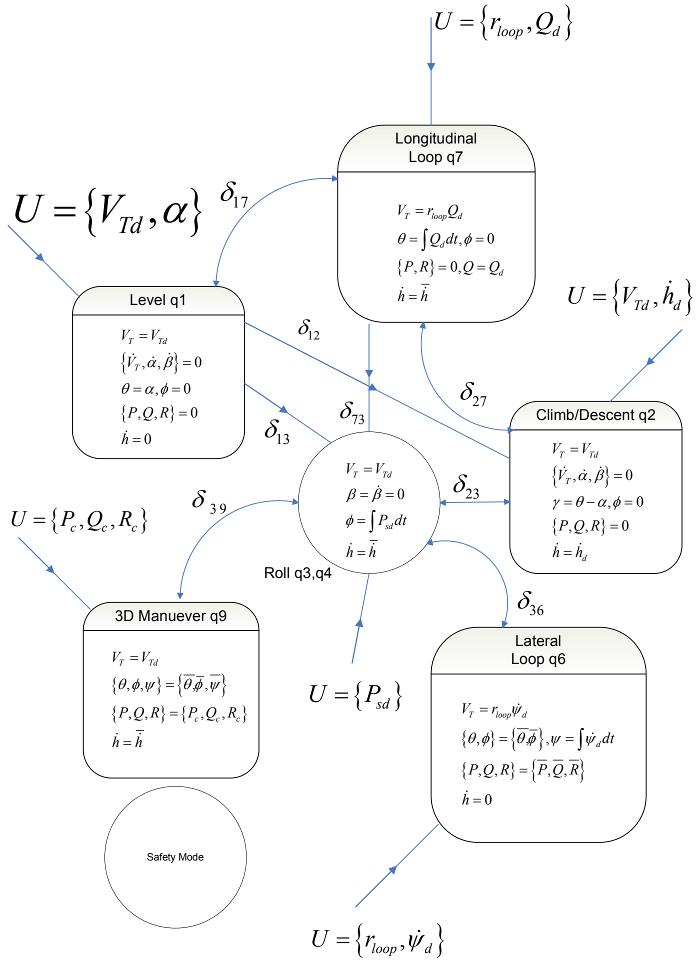


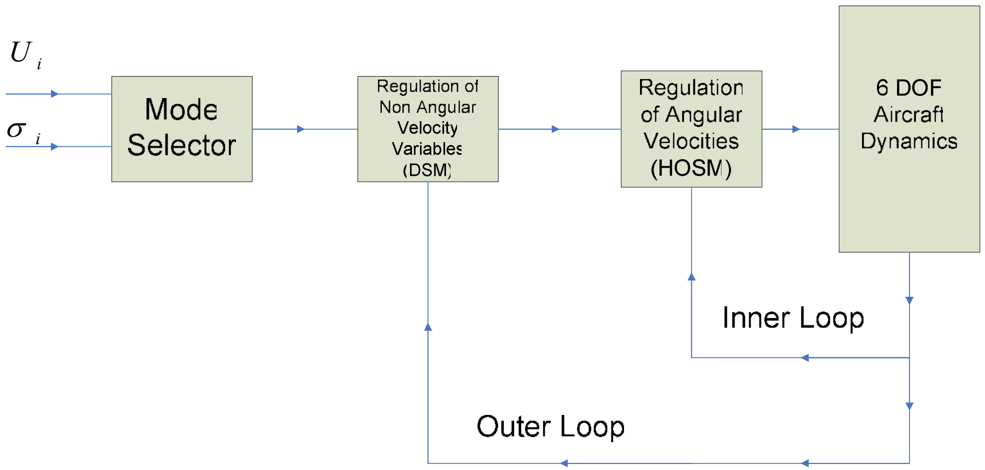


- Each maneuver mode represents a discrete state in finite automata
- Each mode is characterized by different state constraints

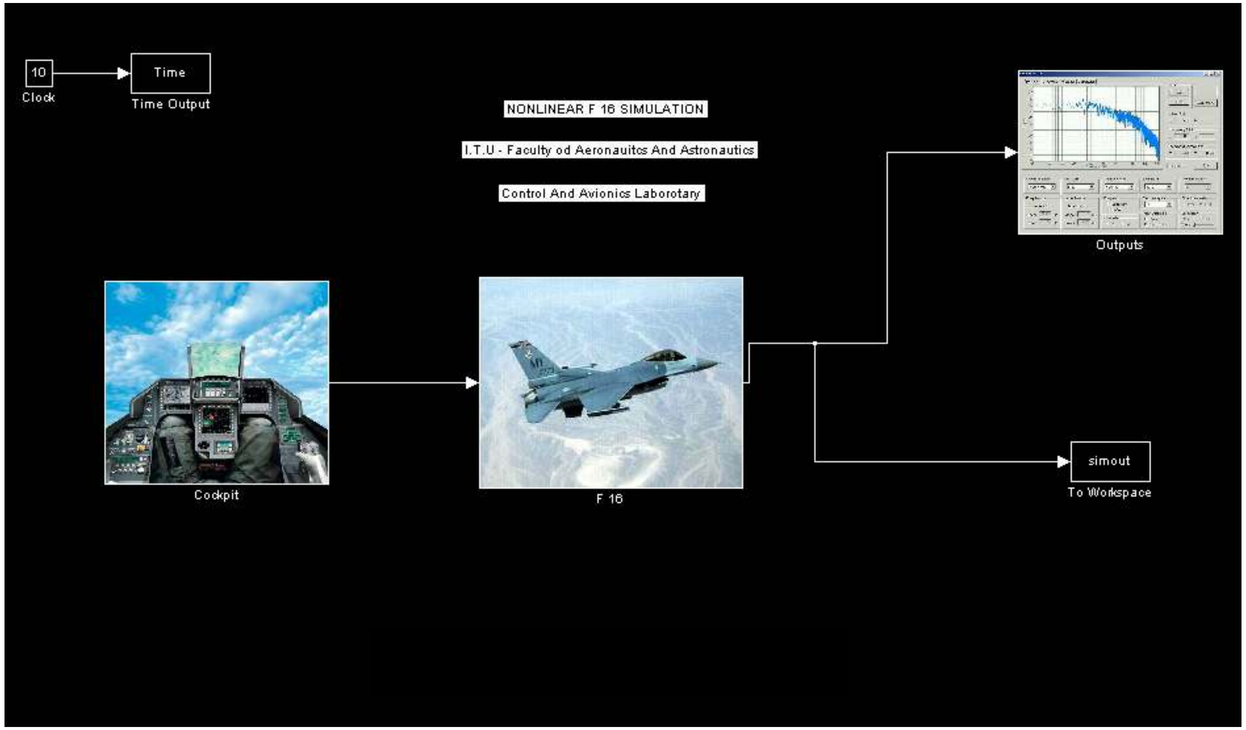
Solution

- A structured finite automaton, spanning full flight envelope
- Nonlinear sliding manifold control system that tracks the outputs of the automaton





Aircraft Model

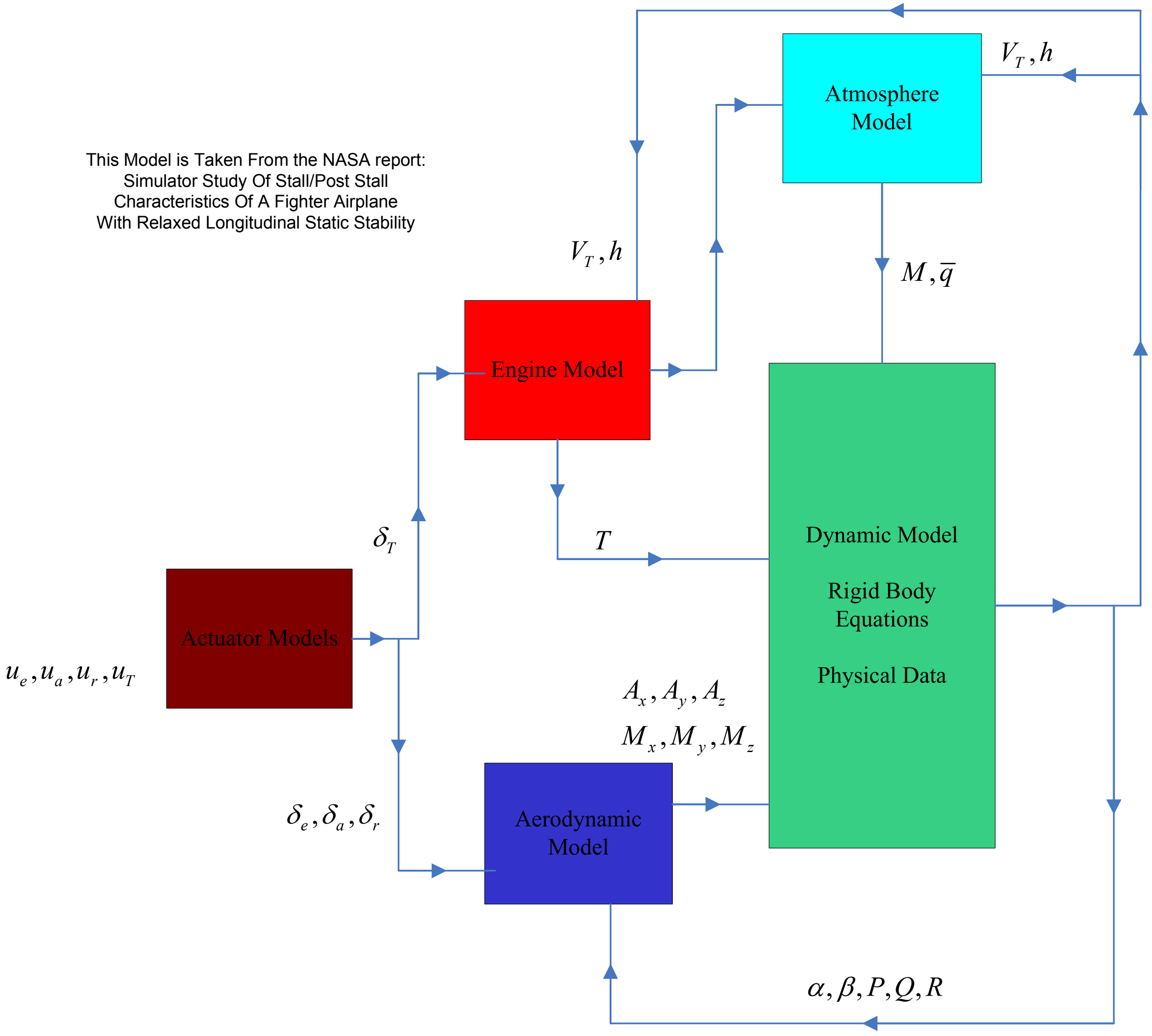


- A Full Scale 6 DOF High Fidelity Dynamic Model
- Highly Coupled Nonlinear State Equations
- 52 Look-up Tables To Build-up Aerodynamic Forces and Moments through control surface deflections (Including Stall Effect)
- Actuator Models with rate limits and saturation
- Afterburning Turbofan Engine Model controlled via throttle

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

Aircraft Model Cont

This Model is Taken From the NASA report:
Simulator Study Of Stall/Post Stall
Characteristics Of A Fighter Airplane
With Relaxed Longitudinal Static Stability



Aircraft Model Cont

Aerodynamic Model

$C_X(\alpha, \beta, \delta_h = 10^o)$

BETA	-30.0	-25.0	-20.0	-15.0	-10.0	- 8.0	- 6.0	- 4.0	- 2.0	
	0.0	+ 2.0	+ 4.0	+ 6.0	+ 8.0	+10.0	+15.0	+20.0	+25.0	+30.0
ALPHA										
-20.0	-.10230	-.10120	-.10800	-.10470	-.10350	-.09910	-.09290	-.09100	-.08840	
	-.08840	-.09070	-.09080	-.09130	-.09180	-.09430	-.09550	-.09880	-.09200	-.09310
-15.0	-.10380	-.10670	-.10570	-.10300	-.09980	-.09980	-.09920	-.09990	-.10060	
	-.10100	-.10070	-.10090	-.10040	-.10000	-.10060	-.10380	-.10650	-.10750	-.10460
-10.0	-.09630	-.10110	-.10130	-.10160	-.10060	-.10130	-.10170	-.10280	-.10390	
	-.10920	-.10400	-.10290	-.10220	-.10080	-.10140	-.10240	-.10210	-.10190	-.09710
- 5.0	-.06640	-.07150	-.07550	-.07800	-.08450	-.08730	-.08850	-.08960	-.08980	
	-.09020	-.08940	-.08840	-.08680	-.08510	-.08210	-.07560	-.07310	-.06910	-.06400
0.0	-.04720	-.04980	-.05210	-.05330	-.05670	-.05780	-.05860	-.05950	-.06020	
	-.06060	-.06000	-.05920	-.05840	-.05660	-.05500	-.05140	-.05040	-.04810	-.04550
+ 5.0	-.01460	-.01340	-.01240	-.01300	-.01700	-.01760	-.01830	-.01890	-.02050	
	-.02000	-.02060	-.01950	-.01840	-.01690	-.01610	-.01210	-.01150	-.01340	-.01550
+10.0	.01820	.02420	.02810	.03130	.03260	.03310	.03220	.03270	.03200	
	.03130	.03130	.03230	.03290	.03280	.03260	.03130	.02810	.02420	.01820
+15.0	.05370	.06020	.06890	.07360	.07850	.08080	.08240	.08360	.08350	
	.08290	.08330	.08290	.08200	.08100	.07850	.07360	.06890	.06020	.05370
+20.0	.08710	.09240	.09070	.08980	.09750	.09960	.09990	.09980	.09740	
	.09710	.09810	.09870	.09920	.09590	.09470	.08700	.08790	.08960	.08430
+25.0	.09160	.10160	.10080	.09960	.10070	.10270	.10270	.09950	.09710	
	.09490	.09600	.09850	.09990	.09840	.09810	.09700	.09820	.09900	.08900
+30.0	.05090	.07140	.07500	.08900	.09530	.10720	.11080	.11130	.11160	
	.11040	.10930	.10960	.10770	.10680	.10460	.09830	.08430	.08070	.06020
+35.0	.04810	.05600	.07050	.07830	.09290	.09870	.11280	.11950	.12070	
	.12010	.11990	.12100	.11880	.11550	.10810	.09350	.08570	.07120	.06330
+40.0	.06640	.07410	.06940	.07850	.09260	.09510	.10540	.10910	.11270	
	.11270	.11390	.11000	.10390	.10310	.09880	.08470	.07560	.08030	.07260
+45.0	.08460	.08110	.08420	.08450	.09330	.09380	.09220	.09460	.09920	
	.09960	.09890	.09780	.09540	.09220	.08940	.08060	.08030	.07720	.08070
+50.0	.09080	.09850	.10110	.09990	.10630	.10610	.10180	.09960	.10210	
	.10710	.10710	.10640	.10700	.10360	.10320	.09680	.09800	.09540	.08770
+55.0	.08420	.08690	.07900	.08820	.10250	.10100	.09930	.09800	.09910	
	.10300	.09720	.08970	.09140	.09690	.10150	.08720	.07800	.08590	.08320
+60.0	.07490	.08230	.08490	.07940	.08310	.08410	.08960	.09080	.09150	
	.09140	.09080	.08930	.08950	.08890	.08680	.08310	.08860	.08600	.07860
+70.0	.05040	.05000	.05040	.04670	.08130	.08110	.09720	.09500	.10750	
	.11900	.11010	.10010	.09670	.09580	.09310	.05850	.06220	.06180	.06220
+80.0	.04210	.03800	.03550	.03970	.04200	.04170	.04240	.04780	.04730	
	.05190	.04840	.04650	.04890	.04720	.04500	.04270	.03850	.04100	.04510
+90.0	.04330	.04040	.03950	.04670	.04950	.04920	.04990	.04840	.05000	
	.05040	.04950	.04630	.04570	.05100	.04820	.04540	.03820	.03910	.04200

Actuator Models

	Deflection Limit (deg)	Rate Limit (deg/s)
Elevator	25	60
Ailerons	21.5	80
Rudder	30	120

Aircraft Model Cont

Dynamic Model

Rigid Body Equations

Physical Data

$$\begin{bmatrix}\dot{x}\\\dot{y}\\\dot{z}\end{bmatrix}=\begin{bmatrix}c\theta*c\psi & (-c\phi*s\psi+s\phi*s\theta*c\psi) & (s\phi*s\psi+c\phi*s\theta*c\psi)\\ c\theta*s\psi & (c\phi*c\psi+s\phi*s\theta*s\psi) & (-s\theta*c\psi+c\phi*s\theta*s\psi)\\ -s\theta & s\phi*s\theta & c\phi*c\theta\end{bmatrix}\begin{bmatrix}U\\V\\W\end{bmatrix}$$

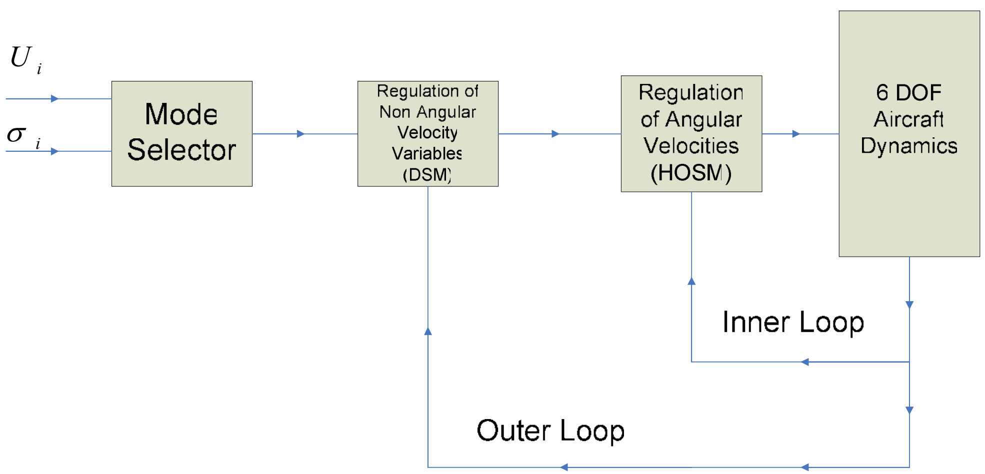
$$m\left\{\begin{bmatrix}\dot{U}\\\dot{V}\\\dot{W}\end{bmatrix}+\begin{bmatrix}0 & -R & Q\\ R & 0 & -P\\ -Q & P & 0\end{bmatrix}\right\}=mg\begin{bmatrix}-\sin\theta\\ \cos\theta\sin\phi\\ \cos\theta\cos\phi\end{bmatrix}+\begin{bmatrix}A_x\\A_y\\A_z\end{bmatrix}$$

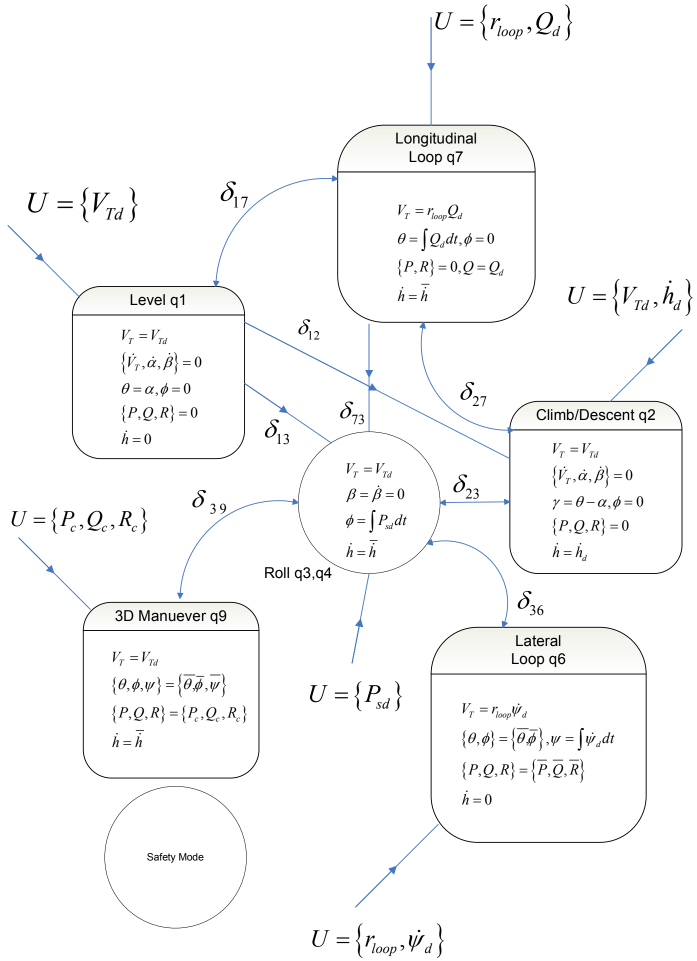
$$\begin{bmatrix}\dot{\psi}\\\dot{\theta}\\\dot{\phi}\end{bmatrix}=\begin{bmatrix}0 & s\psi/c\theta & c\phi/c\theta\\ 0 & c\phi & -s\phi\\ 1 & s\phi*t\theta & c\phi*t\theta\end{bmatrix}\begin{bmatrix}P\\Q\\R\end{bmatrix}$$

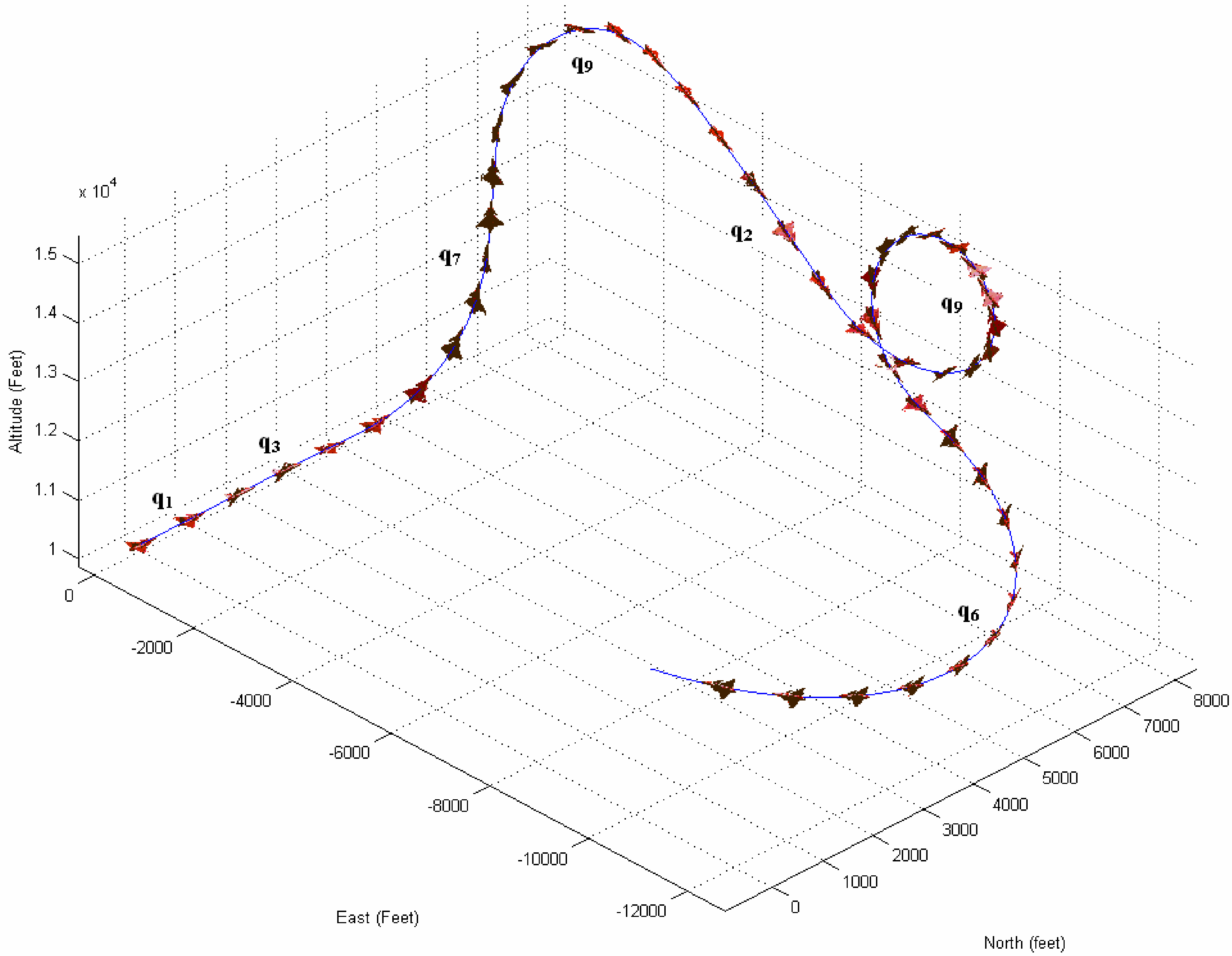
$$[I]\begin{bmatrix}\dot{P}\\\dot{Q}\\\dot{R}\end{bmatrix}+\begin{bmatrix}0 & -R & Q\\ R & 0 & -P\\ -Q & P & 0\end{bmatrix}\times[I]\begin{bmatrix}P\\Q\\R\end{bmatrix}=\begin{bmatrix}M_x\\M_y\\M_z\end{bmatrix}$$

Solution

- A structured finite automaton, spanning full flight envelope
- Nonlinear sliding manifold control system that tracks the outputs of the automaton






x 10^4
1.5
1.4
1.3
1.2
1.1
1
Altitude (Feet)
0
-2000
-4000
-6000
-8000
-10000
-12000
East (Feet)
0
1000
2000
3000
4000
5000
6000
7000
8000
North (feet)
q1
q3
q7
q9
q2
q9
q6

Hybrid System Description for Control Purposes

$$MBMA = \left\{Q, X, U, D, \sum, f, \delta, Dom, Init, \Omega\right\}$$

Set of Discrete States = Modes:

$$Q = \{q_0, q_1, q_2, q_3, q_4, q_5, q_6\} = \{\text{Level,Climb,Roll,Long. Loop,Lat. Loop,3D, Safety}\}$$

Set of Continuous States = Flight dynamics

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

Set of Continuous Inputs = Parameters that generate modal Inputs (state values that create modes)

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

Set of Discrete Inputs = Switching decisions betweens modes

$$\sum = \bigcup_{i=1, j=1}^{i=1, j=7} \sigma_{ij}$$

Continuous Map = The state propagation in hybrid system form

$$\dot{X} = f(X, U, Q)$$

Discrete Transition Functions = Transition conditions between flight modes

$$\delta = \bigcup_{i=1, j=1}^{i=1, j=7} \delta_{ij} \qquad q_j = \delta_{ij}(q_i, \sigma_{ij})$$

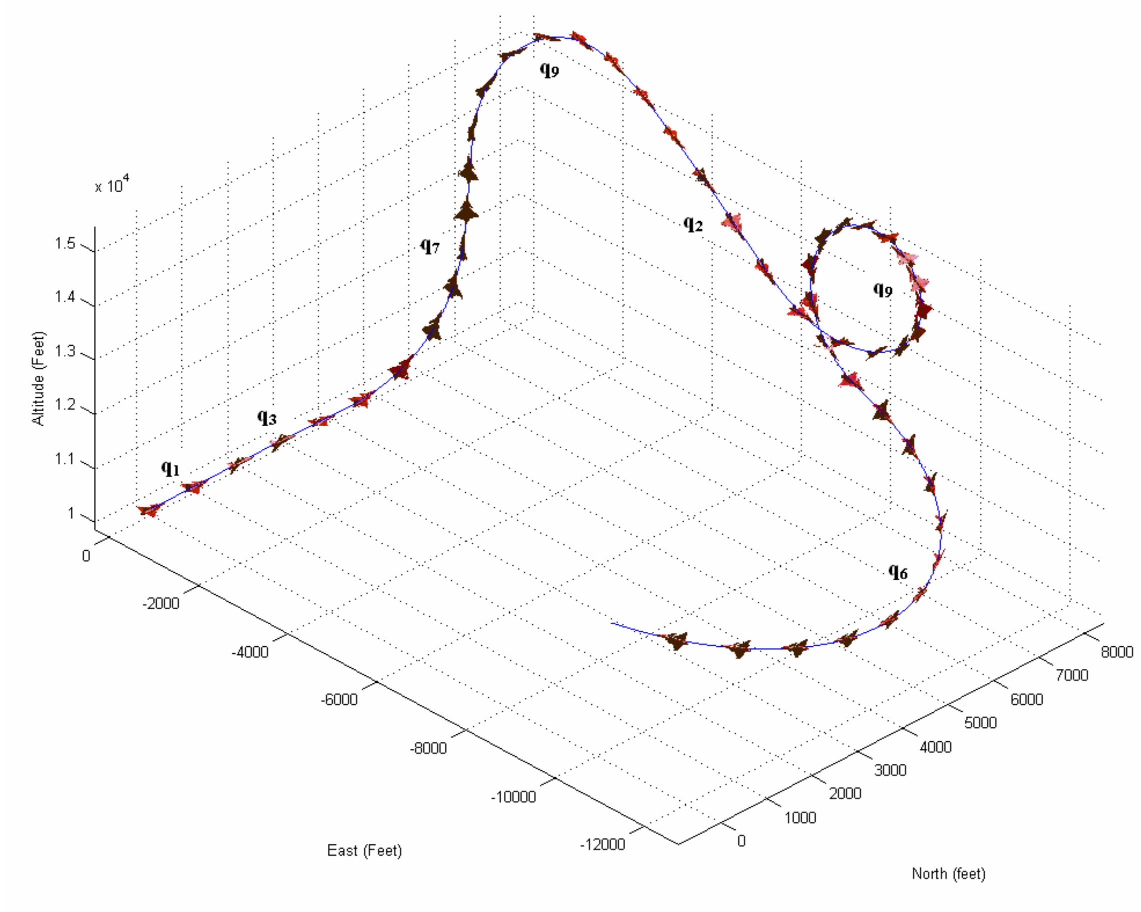
Disturbances = Inputs From Environment (Wind Gusts, Sensor Noises ,..etc)

$$D$$

Maneuver Identification

Mode Sequence = Maneuver Sequence $s = \sigma(1)\sigma(2)\sigma(3)....\sigma(n) \in \Sigma$

Modal Inputs = Maneuver Parameters $r = u(1)u(2)u(3)....u(n) \in U$



Language

- Discrete Input Strings (Mode switching sequence)

$$s = \sigma(1)\sigma(2)\sigma(3)....\sigma(n) \in \sum$$

- Continuous Input Strings (Maneuver Parameters)

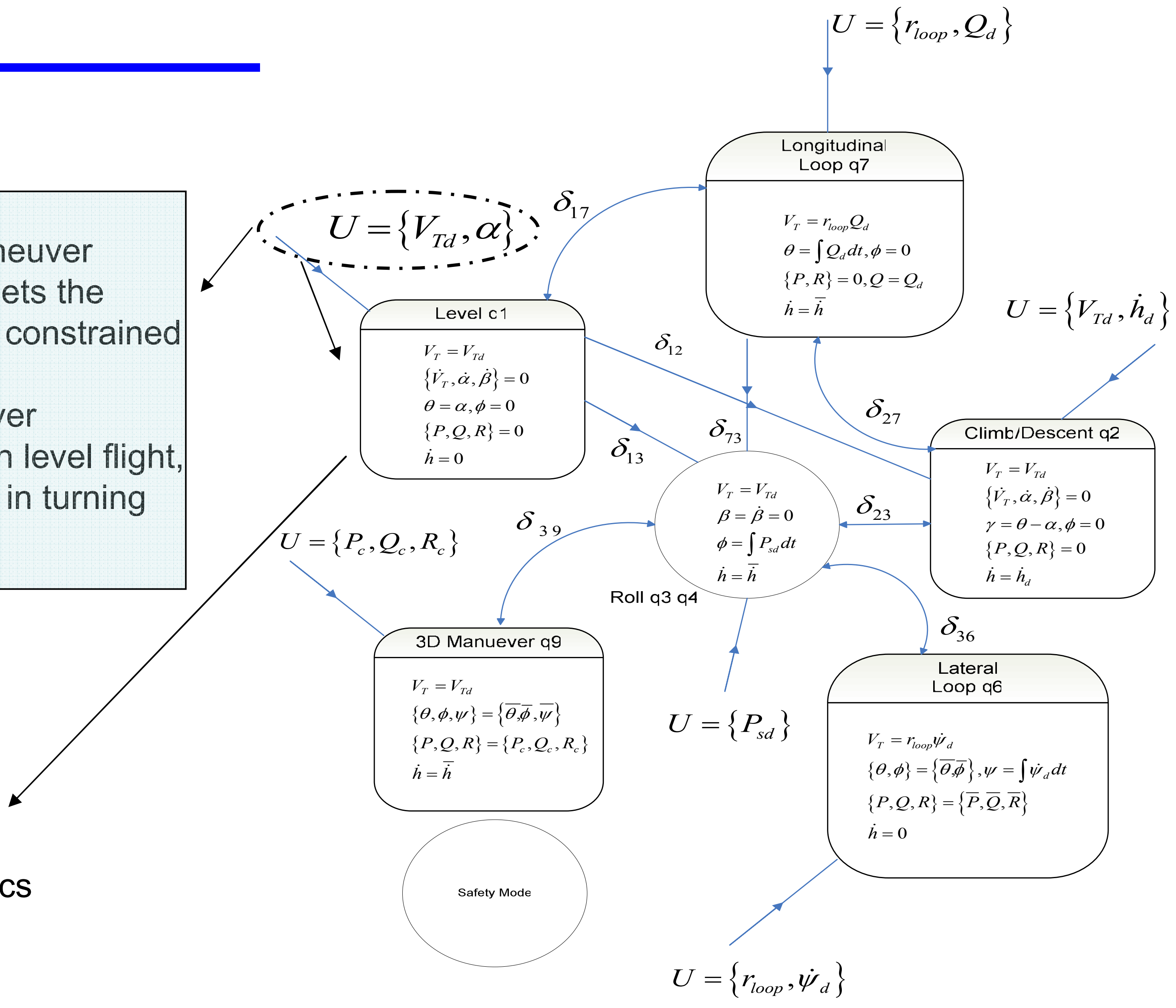
$$r = u(1)u(2)u(3)....u(n) \in U$$

- Trajectory Acceptance Condition

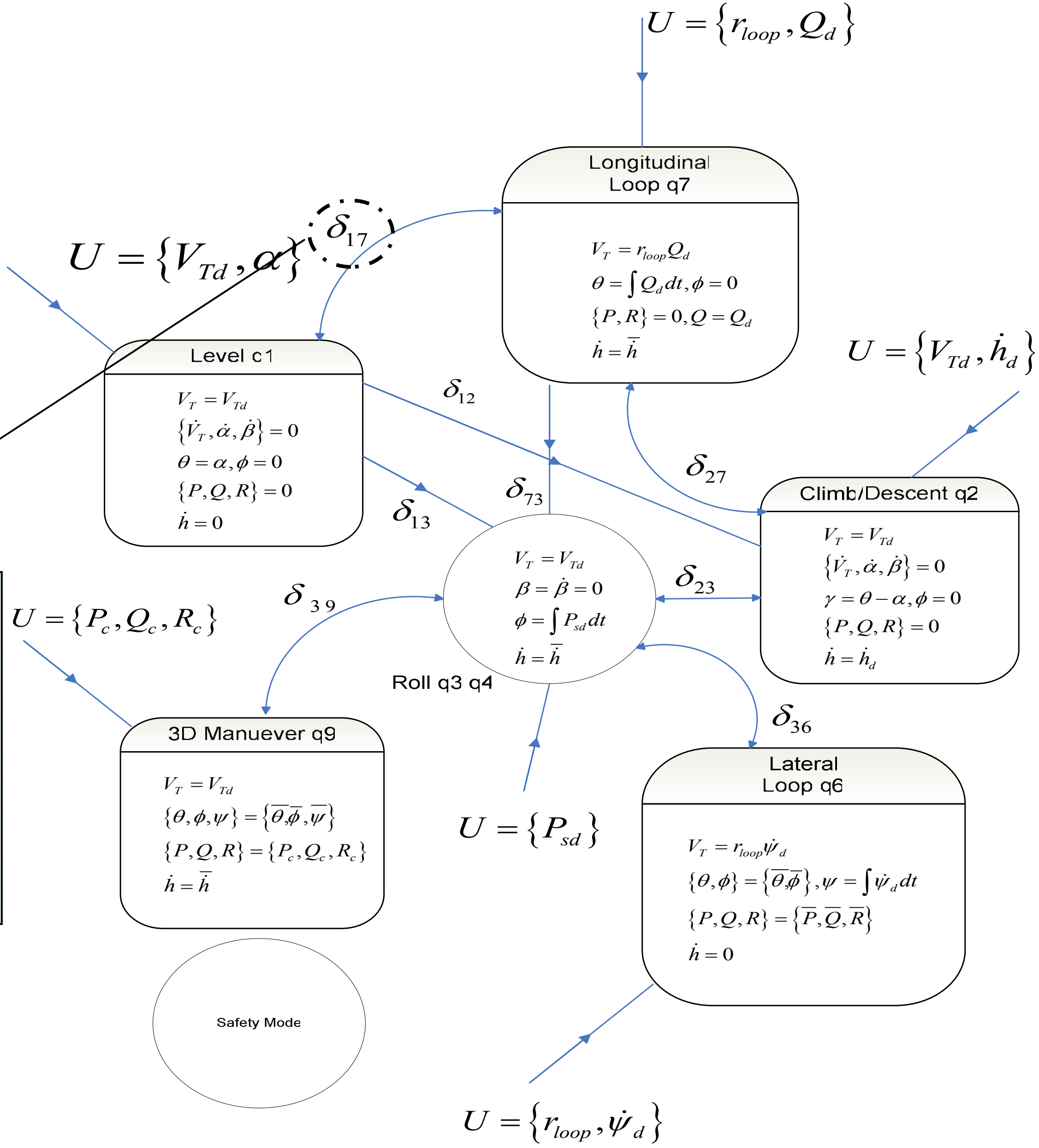
$$\Omega = \left(q_1 \in Init\right) \wedge \left(q_{i+1} = \delta_{i,i+1}(q_i, \sigma_{i,i+1})\right) \wedge \left(q_i, x_i \in Dom\right)$$

This is the starting point for trajectory/maneuver planning algorithms…

Modal input = Maneuver parameters sets the values of the constrained parameters to define the maneuver (such as velocity in level flight, radius of the loop in turning flight)



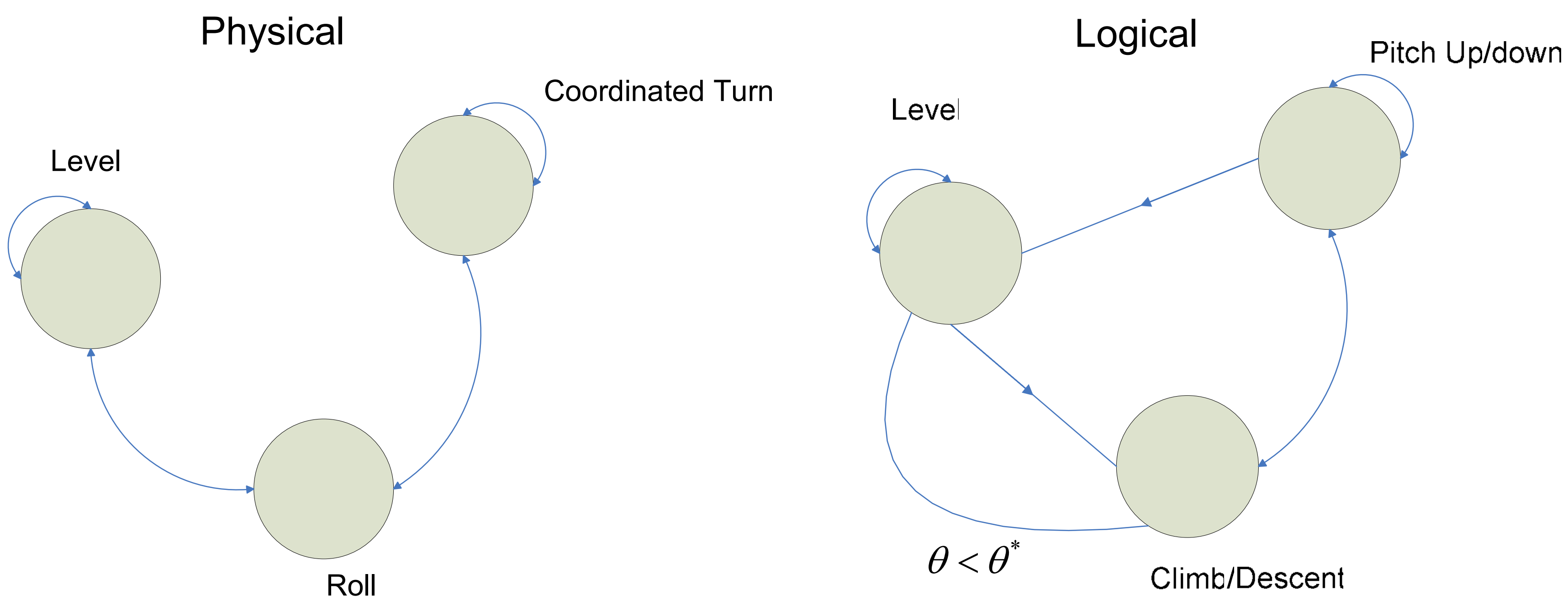
Simplified dynamics



Mode transition functions, set switching conditions between modes. They limit the transitions between two specific modes from both physical and logical constraints
(More on this topic in next slide)

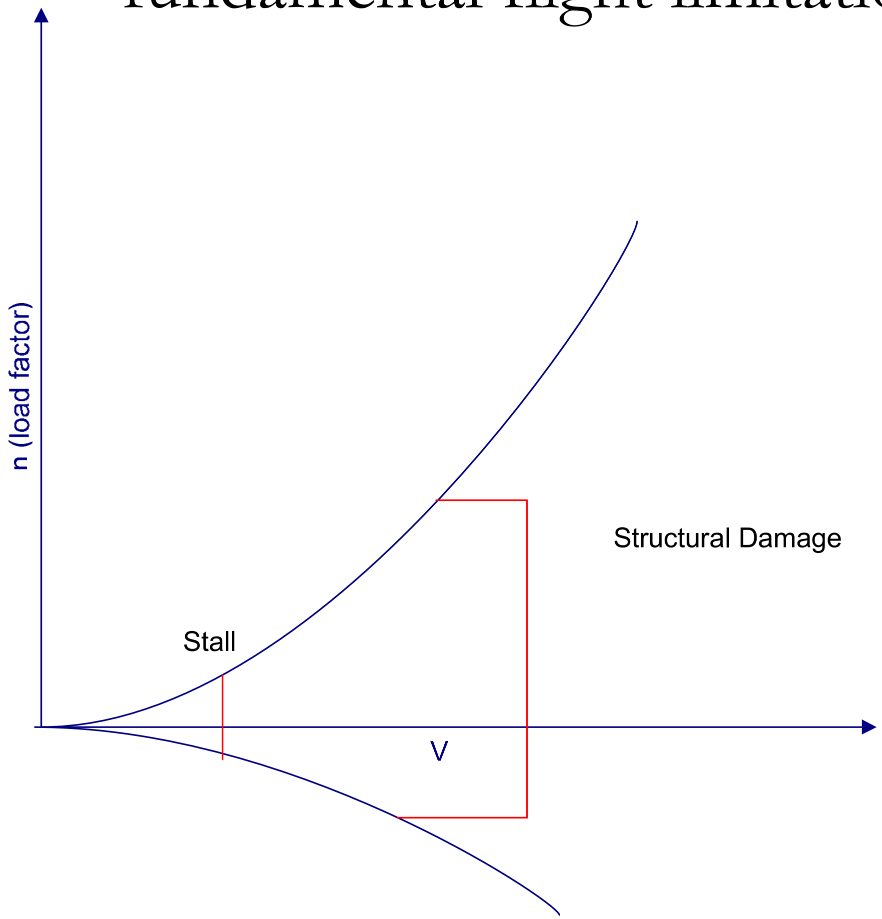
Examples of Sequential Constraints

• Sequences of maneuver modes are not necessarily arbitrary and there can be limitations on when the switch is feasible.

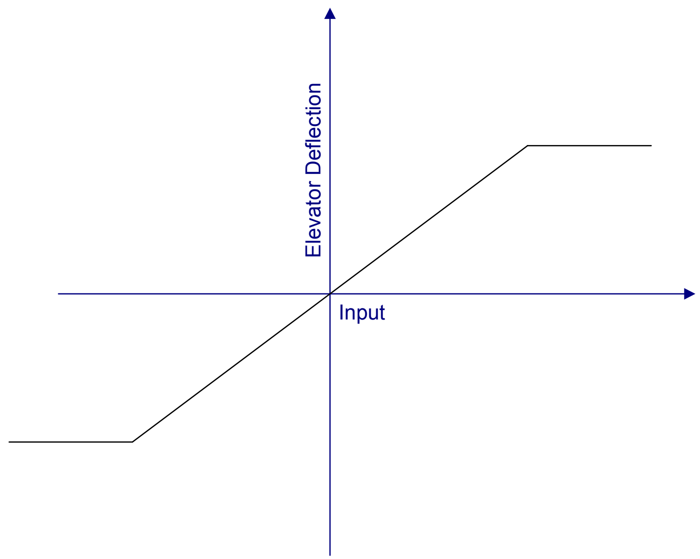


Flight Limitations Also Drive the Mode Transition Table

- Modal Inputs and their transitions must be in line with fundamental flight limitations



Flight Envelope



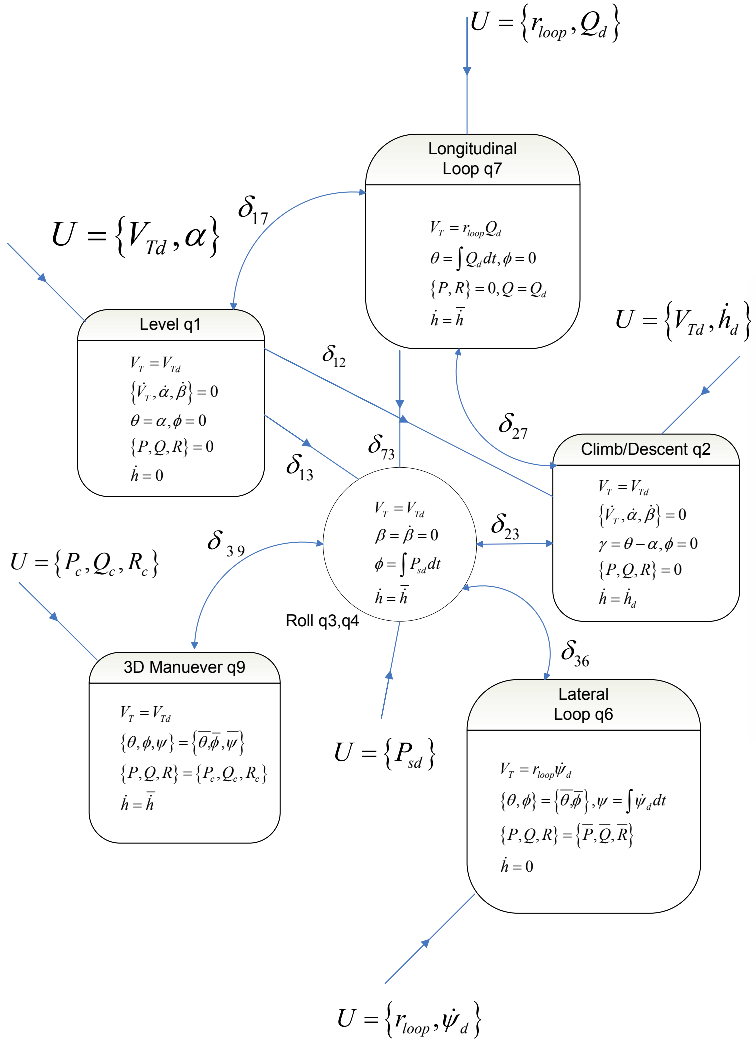
Actuator Limitations

Mode Transition Table!!!

- Either pitch angle or roll angle (sometimes both) must be regulated to a specific value, to translate between certain modes

δ_{ij}	q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9	q_{10}
q_1	1	1	1	1	θ^*	ϕ^*	1	ϕ^*	ϕ^*	ϕ^*
q_2	θ^*	1	θ^*	1	θ^*	θ^*,ϕ^*	1	ϕ^*	ϕ^*	θ^*,ϕ^*
q_3	1	1	1	θ^*	1	1	1	1	1	1
q_4	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	1	θ^*,ϕ^*	θ^*	ϕ^*	1	1	θ^*
q_5	1	1	1	1	1	ϕ^*	1	ϕ^*	ϕ^*	ϕ^*
q_6	ϕ^*	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	ϕ^*	1	ϕ^*	1	1	1
q_7	θ^*,ϕ^*	1	θ^*,ϕ^*	ϕ^*	θ^*	θ^*,ϕ^*	1	ϕ^*	ϕ^*	ϕ^*
q_8	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	θ^*	1	1	1	θ^*
q_9	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	θ^*	1	1	1	θ^*
q_{10}	θ^*,ϕ^*	ϕ^*	ϕ^*	ϕ^*	θ^*,ϕ^*	1	ϕ^*	1	1	1

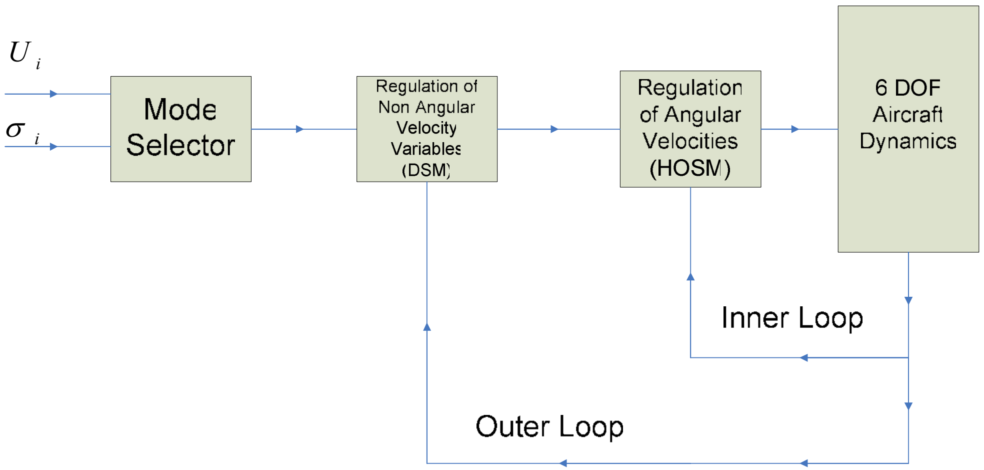
Hybrid System

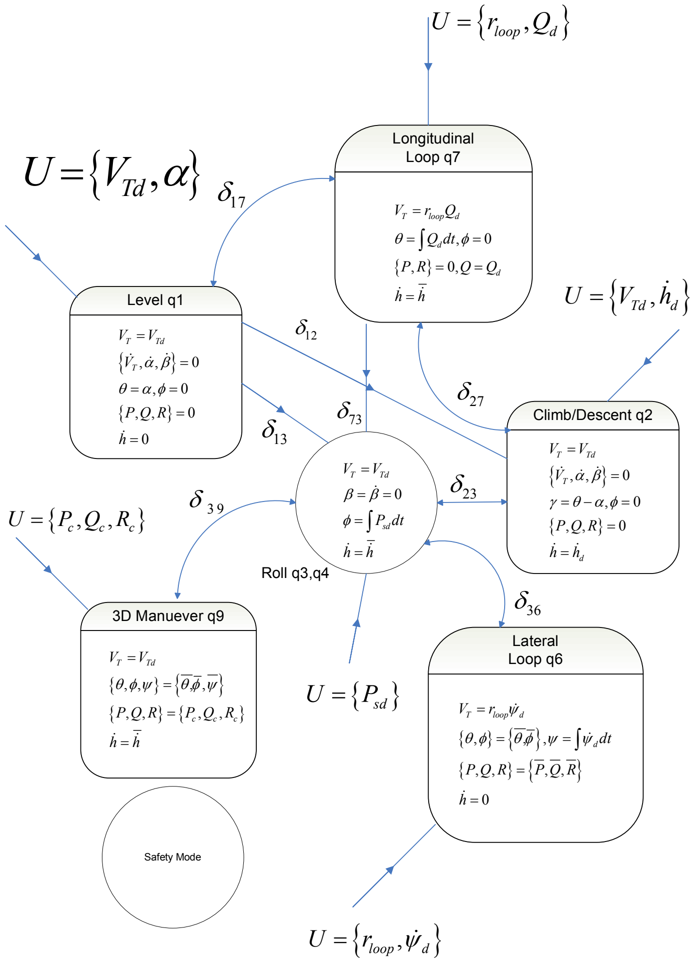


δ_{ij}	q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9	q_{10}
q_1	1	1	1	1	θ^*	ϕ^*	1	ϕ^*	ϕ^*	ϕ^*
q_2	θ^*	1	θ^*	1	θ^*	θ^*,ϕ^*	1	ϕ^*	ϕ^*	θ^*,ϕ^*
q_3	1	1	1	θ^*	1	1	1	1	1	1
q_4	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	1	θ^*,ϕ^*	θ^*	ϕ^*	1	1	θ^*
q_5	1	1	1	1	1	ϕ^*	1	ϕ^*	ϕ^*	ϕ^*
q_6	ϕ^*	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	ϕ^*	1	ϕ^*	1	1	1
q_7	θ^*,ϕ^*	1	θ^*,ϕ^*	ϕ^*	θ^*	θ^*,ϕ^*	1	ϕ^*	ϕ^*	ϕ^*
q_8	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	θ^*	1	1	1	θ^*
q_9	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	ϕ^*	θ^*,ϕ^*	θ^*	1	1	1	θ^*
q_{10}	θ^*,ϕ^*	ϕ^*	ϕ^*	ϕ^*	θ^*,ϕ^*	1	ϕ^*	1	1	1

Solution

- A structured finite automaton, spanning full flight envelope
- Nonlinear sliding manifold control system that tracks the outputs of the automaton

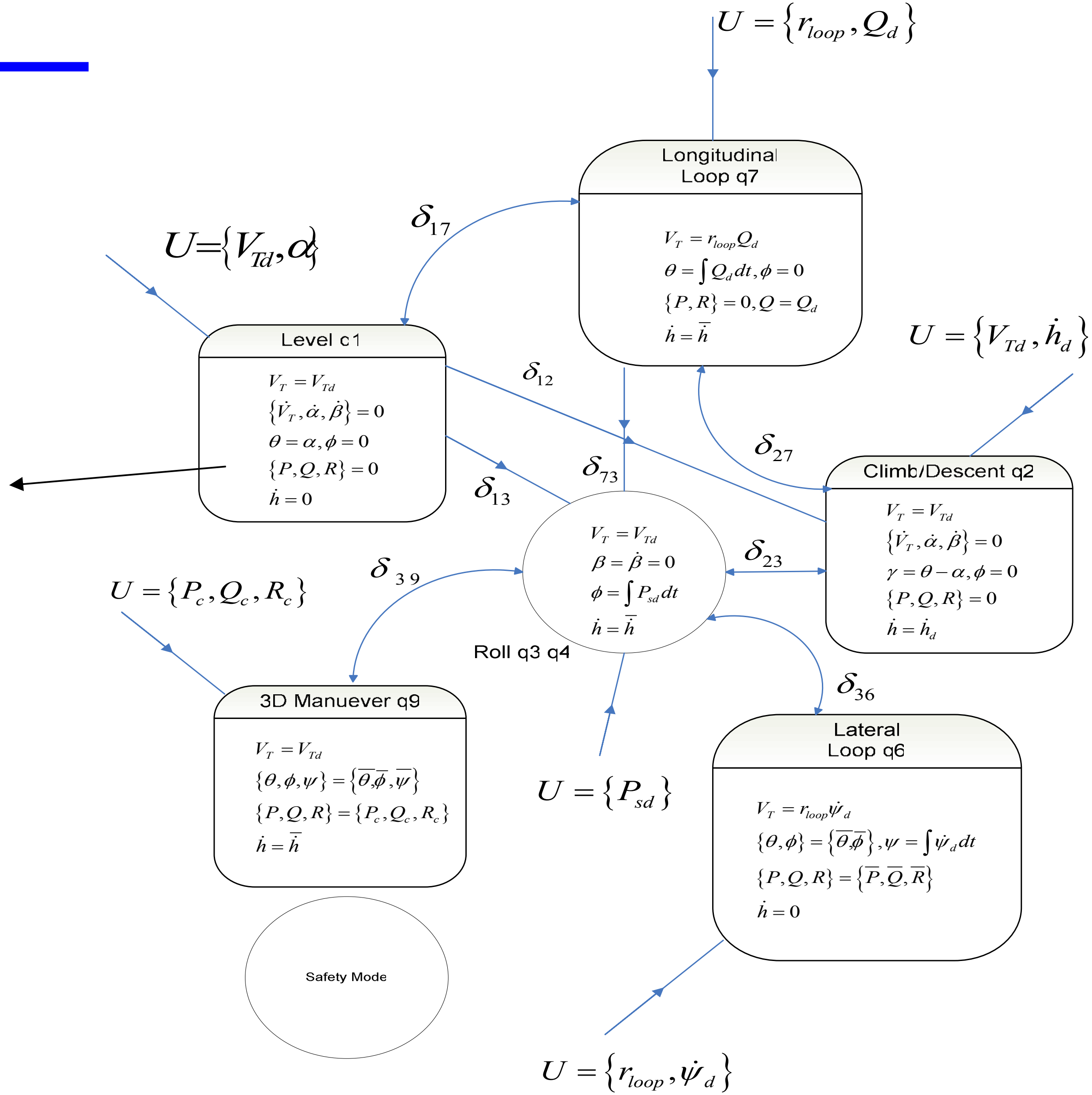




Hybrid Control Plan

- Switching sequence for the modes are already given by motion plan
  - Aim is to track each mode's modal input
- We can define different output variables for each maneuver mode
  - Dynamics are different (simplified ?) for each mode, so even different control strategies can be developed for each mode
- Linear tracking techniques are not adequate! We will rely on nonlinear control techniques of feedback linearization and sliding mode control (robustness?)

Simplified dynamics specific to each mode simplifies the control design procedure (However this is not the Case in 3D maneuver mode)



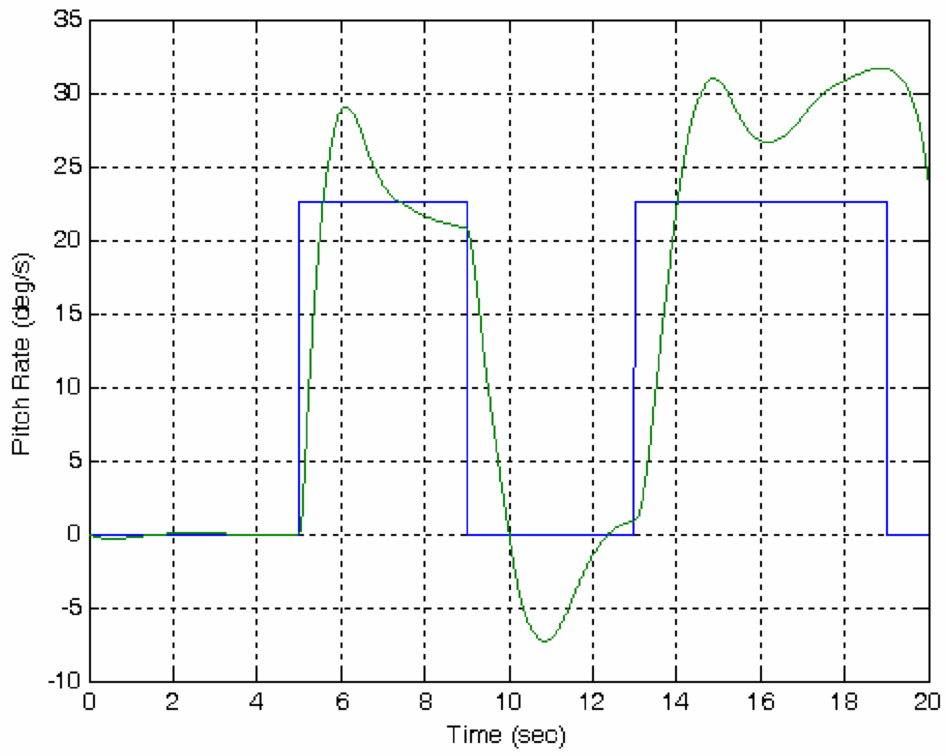
Linear Control ?

•Performance of a robust linear controller designed with parameter space methods

Aggressiveness is defined by:

a. Amplitude of modal inputs
b. Frequency of switching

Performance of the Linear controllers is limited by both “a” and “b” as seen in the example (Actuator Saturation was not taken into account in this example)



Linear control is not suitable for tracking of “non-trimmed” aggressive maneuvers

Aircraft Model for Control Purposes

Dynamic Model

Rigid Body Equations

Physical Data

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{z}\end{bmatrix}=\begin{bmatrix}c\theta*c\psi & (-c\phi*s\psi+s\phi*s\theta*c\psi) & (s\phi*s\psi+c\phi*s\theta*c\psi)\\ c\theta*s\psi & (c\phi*c\psi+s\phi*s\theta*s\psi) & (-s\theta*c\psi+c\phi*s\theta*s\psi)\\ -s\theta & s\phi*s\theta & c\phi*c\theta\end{bmatrix}\begin{bmatrix}U\\ V\\ W\end{bmatrix}$$

$$m\left\{\begin{bmatrix}\dot{U}\\ \dot{V}\\ \dot{W}\end{bmatrix}+\begin{bmatrix}0 & -R & Q\\ R & 0 & -P\\ -Q & P & 0\end{bmatrix}\right\}=mg\begin{bmatrix}-\sin\theta\\ \cos\theta\sin\phi\\ \cos\theta\cos\phi\end{bmatrix}+\begin{bmatrix}A_x\\ A_y\\ A_z\end{bmatrix}$$

$$\begin{bmatrix}\dot{\psi}\\ \dot{\theta}\\ \dot{\phi}\end{bmatrix}=\begin{bmatrix}0 & s\psi/c\theta & c\phi/c\theta\\ 0 & c\phi & -s\phi\\ 1 & s\phi*t\theta & c\phi*t\theta\end{bmatrix}\begin{bmatrix}P\\ Q\\ R\end{bmatrix}$$

Aerodynamic data is usually provided in the tabular form so:

$$\dot{X}=f(X,U)$$

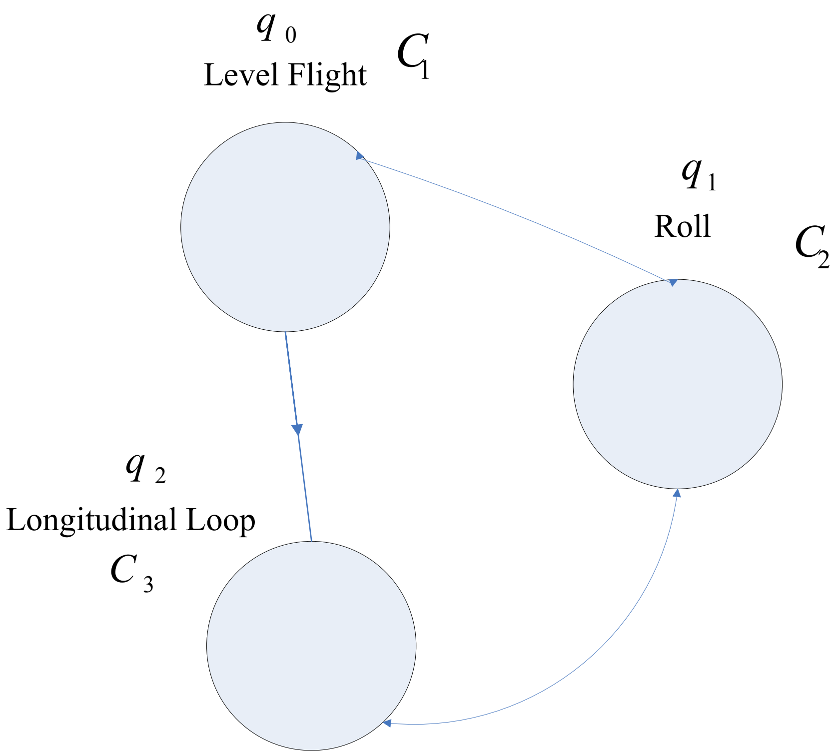
$$[I]\begin{bmatrix}\dot{P}\\ \dot{Q}\\ \dot{R}\end{bmatrix}+\begin{bmatrix}0 & -R & Q\\ R & 0 & -P\\ -Q & P & 0\end{bmatrix}\times[I]\begin{bmatrix}P\\ Q\\ R\end{bmatrix}=\begin{bmatrix}M_x\\ M_y\\ M_z\end{bmatrix}$$

Approximating tables by polynomial functions of (AOA, sideslip and angular rates) and linear multipliers for true inputs (elevator,aileron rudder and thrust)

$$\dot{X}=f(X)+g(X)u$$

Example Hybrid Control Plan

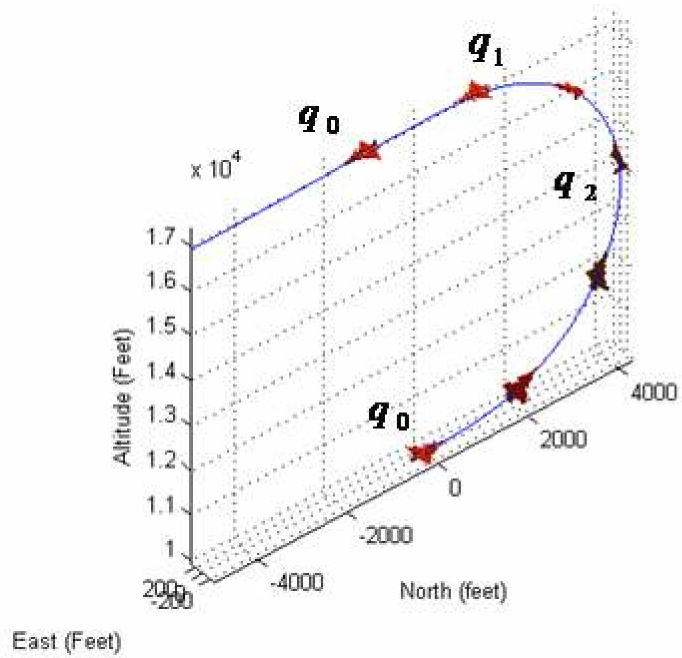
C: Controller



$$C_1 : \{V_T, x, y, z\}\ NMP$$

$$C_2 : \{V_T, P, Q, R\}\ MP$$

$$C_3 : \{V_T, \phi, \theta, \phi\}\ MP$$



Complete Low Level Controller Set

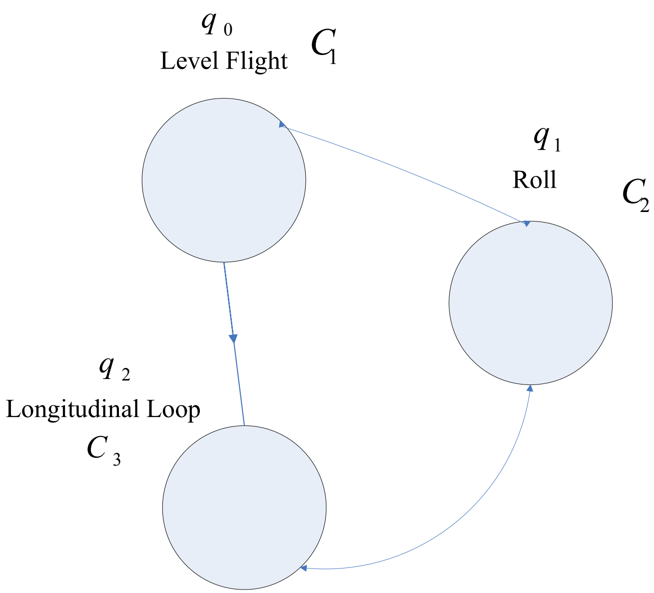
	Mode	State Constraints	Modal Inputs	Controller
q_0	Level Flight	$\dot{h}=0,(\dot{\phi},\dot{\theta},\dot{\psi})=0$	V_T,α	C_2
q_1	Climb/Descent	$(\dot{\phi},\dot{\theta},\dot{\psi})=0$	$V_T,(\dot{h},\theta_w)$	C_2
q_2	Roll	$(\dot{\theta},\dot{\psi})=0$	$\int P_w dt$	C_1
q_3	Longitudinal Loop	$(\dot{\phi},\dot{\psi})=0$	$r_{loop},\dot{\theta}$	C_1,C_3
q_4	Lateral Loop	$\dot{h}=0,(\dot{\phi},\dot{\theta})=0$	$r_{loop},\dot{\psi}$	C_2
q_5	3D Mode	$\{\ \}$	V_T,P,Q,R $V_T,\phi_w,\theta_w,\psi_w$	C_1,C_3,C_4
q_6	Safety	$\{\ \}$	$\{0,1\}$	C_5

	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	$V_T,\{Quaternions\}$	MP

Subscript w
Refers to “wind axes”, this controller regulates the 3D orientation of the velocity vector

Two Problems with SMC

C: Controller

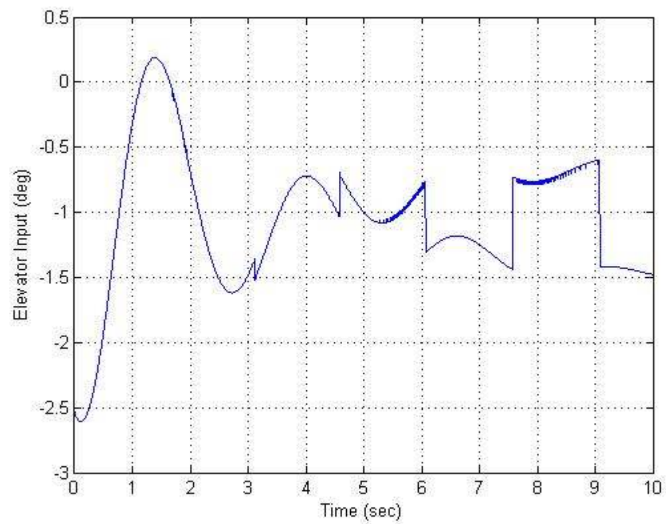


$$C_1 : \{V_T, x, y, z\}\ NMP$$

$$C_2 : \{V_T, P, Q, R\}\ MP$$

$$C_3 : \{V_T, \phi, \theta, \phi\}\ MP$$

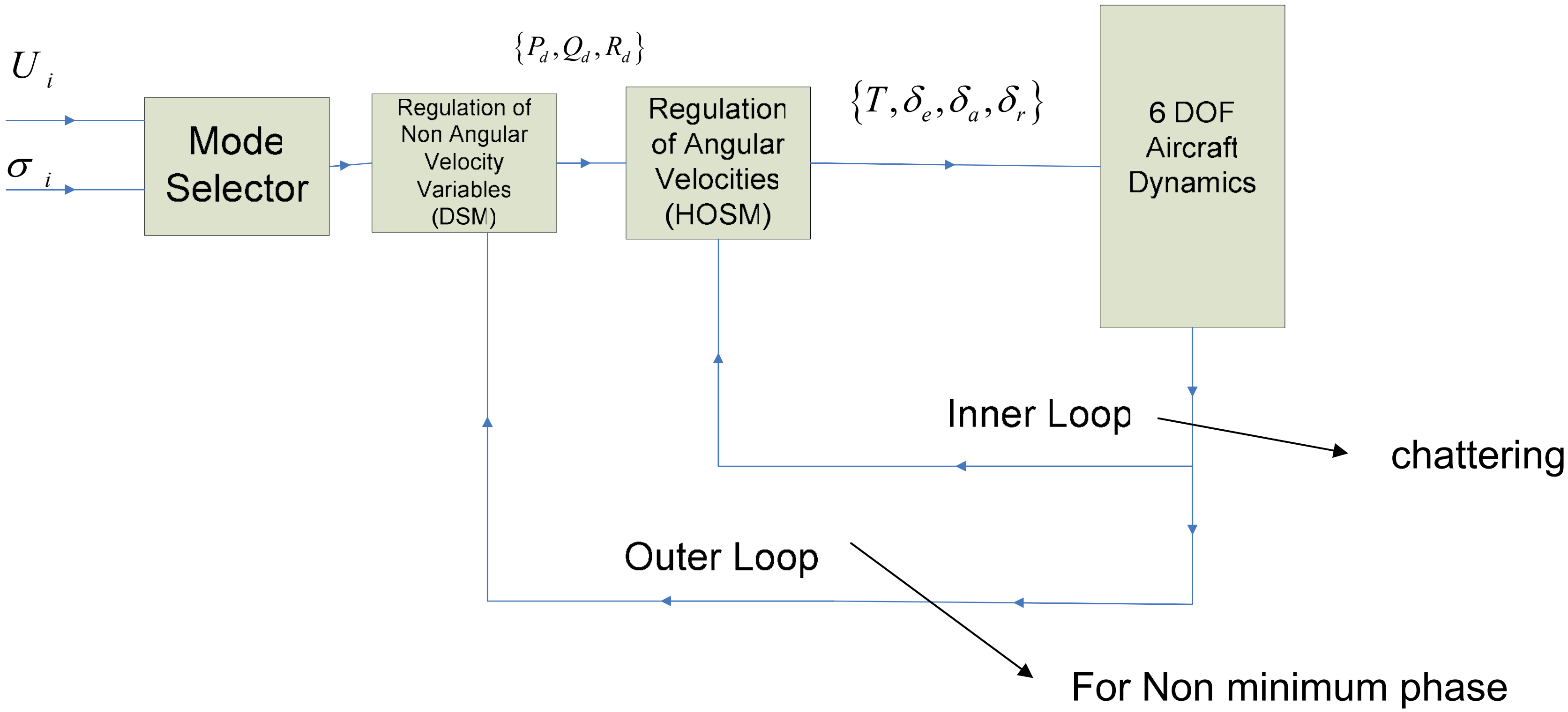
1. Avoid NMP outputs !! In these sets position variables are controlled, which results in unstable attitude dynamics.
But altitude rate is a
modal input, Therefore we must seek a way to stabilize internal dynamics for NMP outputs



2. Discontinuous terms in control law results in chattering, which can be deadly for actuators

Control Architecture

- To separate NMP tracking from the input chattering problem faced at sliding mode control we develop a two loop architecture



Dynamic Sliding Manifolds

- To stabilize rotational dynamics when tracking translational variables we can add integral terms to sliding manifold

$$s(x) = e + v + C\theta$$

- Integral term provides robustness to matched uncertainties, and internal dynamics are stabilized by rotational feedback term

Higher Order Sliding Modes

- Chattering is an important problem in sliding mode control
- Dangerous for actuators
- HOSM keeps the constraint

$$s + \dot{s} = 0$$

- With the following algorithm:

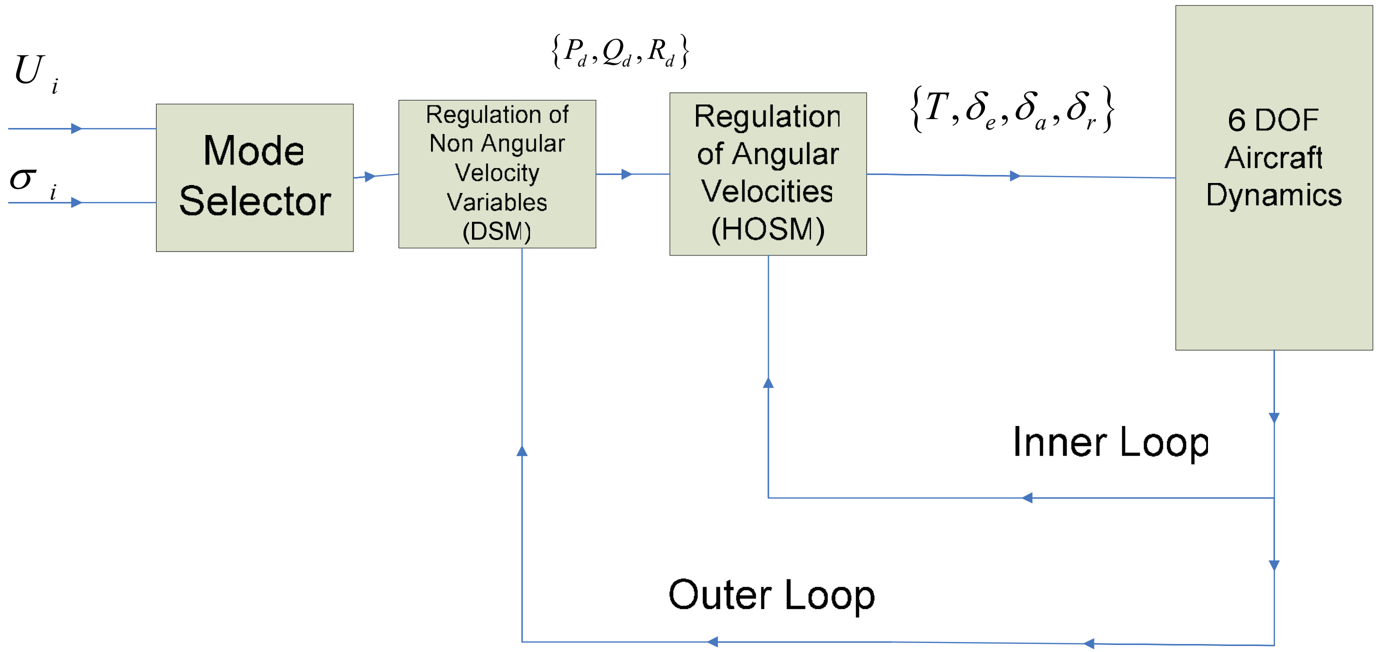
$$u(t) = -\lambda\sqrt{|s|}\,\mathrm{sign}(s) + u_1$$

$$\dot{u}_1 = \begin{cases} -ku & |u| > u_0 \\ -W\mathrm{sign}(s) & |u| \le u_0 \end{cases}$$

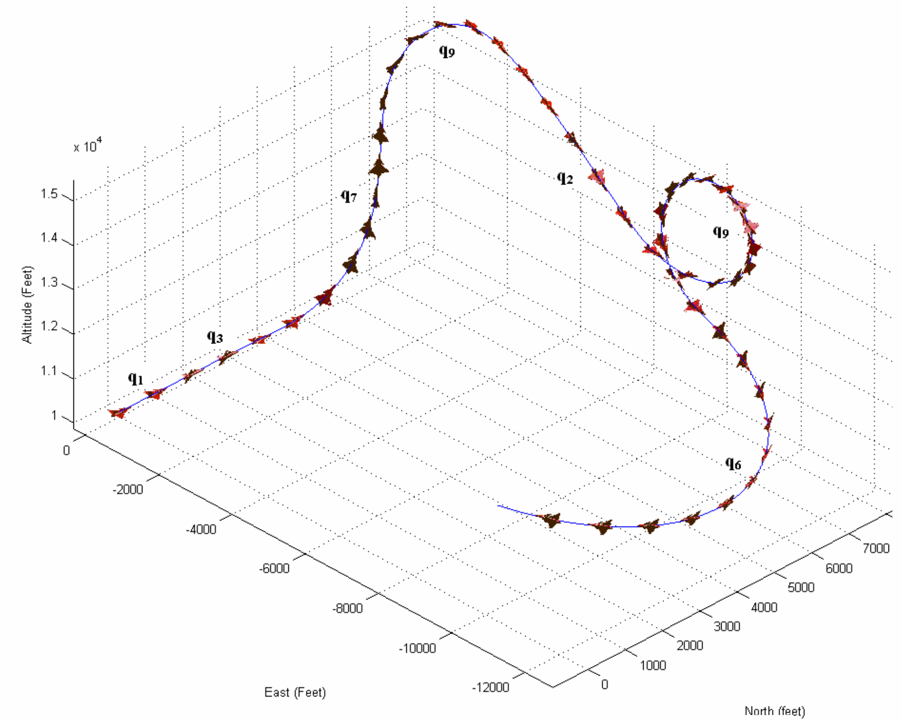
- Fast switching part is moved into derivative of input, therefore actuators are safe

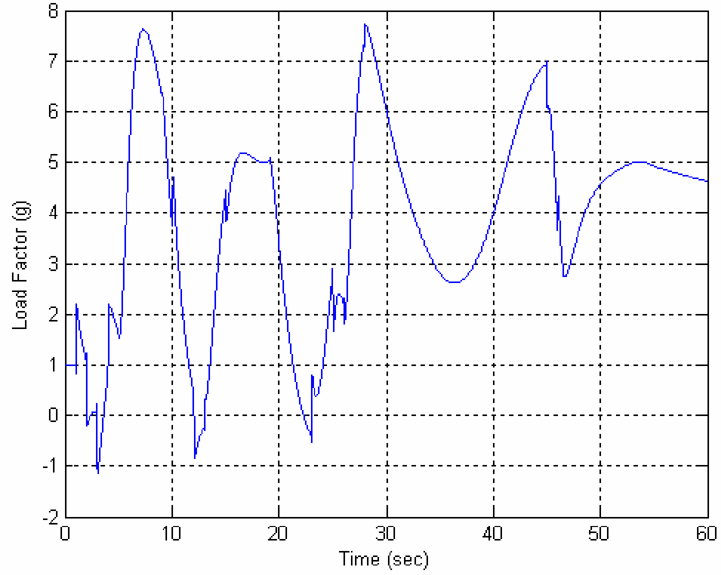
Control Architecture

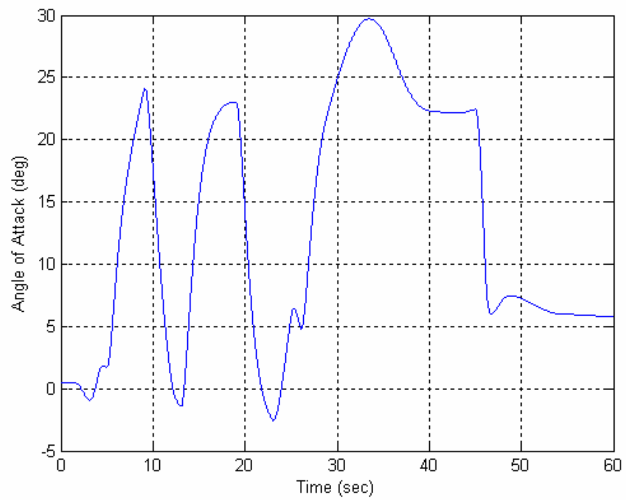
- To separate NMP tracking from HOSM part we develop a two loop architecture

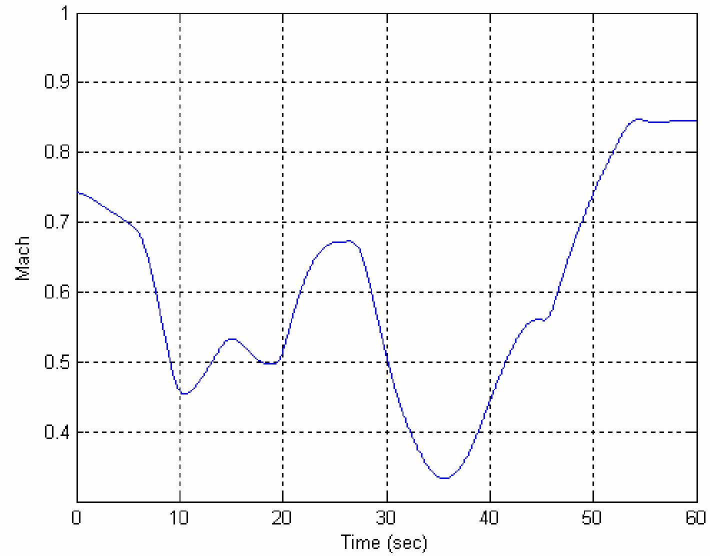


Simulations

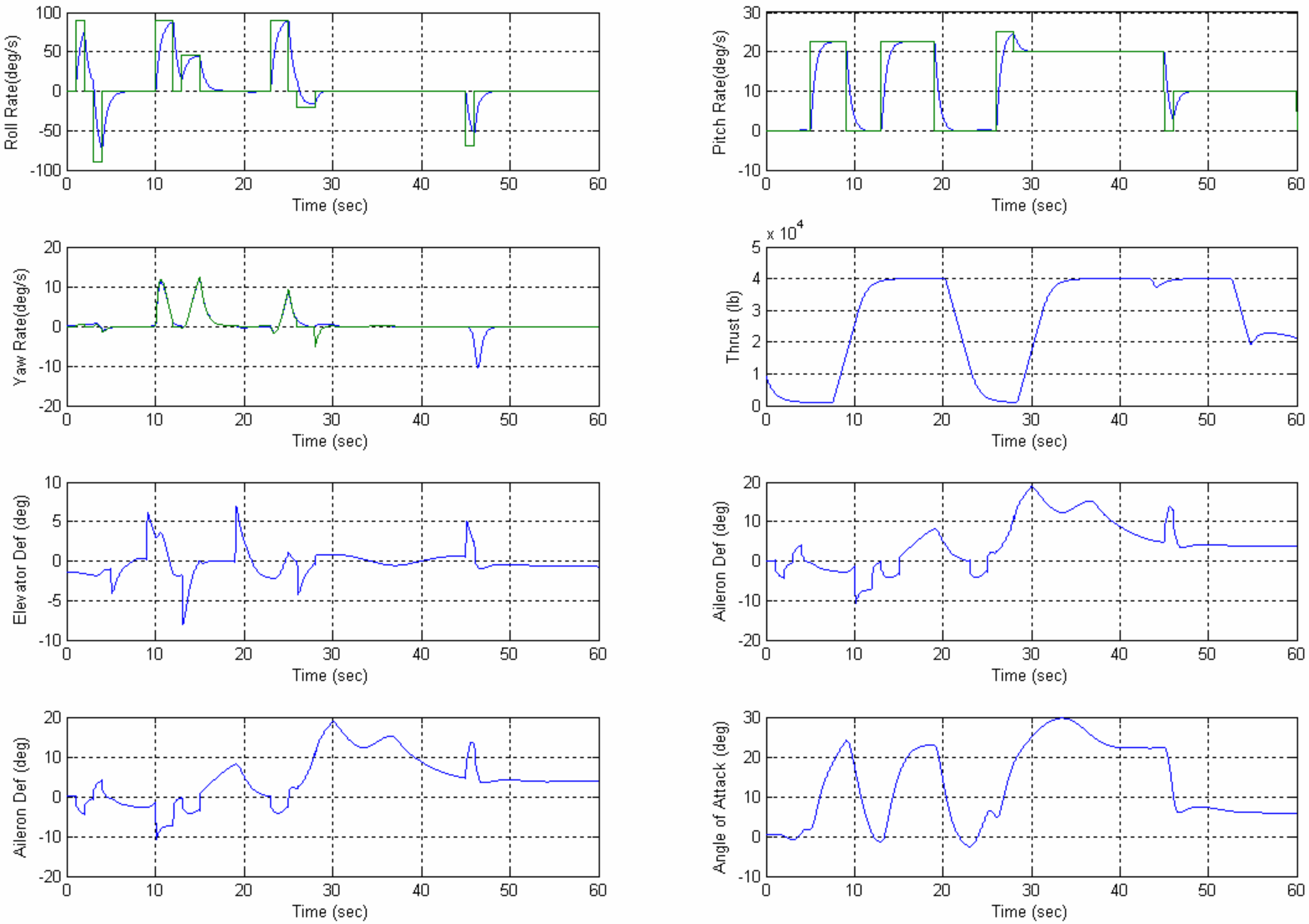








Simulations cont



Conclusion

- We have developed a nonlinear hybrid automata, which describe the dynamics of agile flight with dynamical constraints
- We have developed a mode based control algorithm which tracks the outputs of automaton by sliding control methods
- We now want to define agility metrics to measure the complexity and aggressiveness of maneuvers, we also seek ways to expand coordinated automata by adding coordinated and un-coordinated flight
- Now that we can identify and control maneuver sequences, current research focus on structure of these sequences and planning/synthesis maneuver sequences issues related with the described finite automata.
- Issues such as
  - Reachability : underlying control structure guarantees – Lyapunov approach
  - Safe mode transitions : underlying control structure guarantees – Lyapunov approach