Logic for Mode Transition of Autopilots in Lateral Direction for Commercial Aircrafts

Aparna S Nair, Yogananda Jeppu and C.G. Nayak

Abstract--- *Complexity in autopilot logic design and confusion involved in its mode transition is one of the major reasons for the accidents in highly automated airliner. In this paper we present the usage of a recently proposed array logic based technique for designing the autopilot mode transition logic for a commercial aircraft in the lateral direction. This designing technique helps to reduce the design effort in the development of an autopilot. Ease to understand and very concise way to specify a large number of transitions in simple tabular column is one the highlight of this method. This paper provides some observations about lateral modes and logic concerning lateral mode transition in a less complex way compared to the prevailing methods for autopilot design. Here various mode possibilities of lateral mode transition in an autopilot is mentioned along with specification criteria's that bound these transition and these possible transitions were given a frame work using MATLAB software.*

Keywords--- *Aircraft Navigation, MATLAB, Logic Arrays, Logic Design*

I. Introduction

AUTOPILOTS is a mechanical, electrical or hydraulic system used to guide an airplane with minimal or no assistance from the pilot. The first aircraft autopilot was developed by Sperry Corporation in 1912.It helps to fly an aircraft with less fuel consumption than human pilot, reducing airline cost and increasing flight Safety for passengers. . The autopilots are normally designed around intricate mode transition logics. The designers usually spend significant time and efforts for understanding different modes and their safe transitions. Over the last few decades the development in digital avionic system have added plenty of improvement in air safety sector. This has drastically increased the complexity of the systems and increased the risk of "mode confusion". Anjali Joshi in her paper on Flight Guidance System [1] defined 'mode confusion' as a phenomenon in which pilots become confused about the status of the system and interact with it incorrectly. These designs are further strengthened through rigorous validation. Incorrect mode transitions due to either conflicting requirements or ambiguously defined criteria have led to accidents as reported in Asaf Degani paper [2].

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The world witnessed the most drastic effect of faulty autopilot system in 1983 when Korean Air Lines Flight 007 flying from Anchorage, Alaska, to Seoul, South Korea, deviated more than 200 miles into Soviet territory and got shot down killing all the crew and passengers[12]. When the reason for this navigational failure was analysed it was found that the flight was initially in heading mode later the crew might have forgotten to select inertial navigation system or the crew might have selected inertial navigation, but it never got activated. Autopilot really goes to inertial navigation mode if and only if two conditions are satisfied and they are (a) the aircraft's path must be close to the predefined flight path, specifically, the distance between the aircraft's position and the flight path must be within 7.5 miles for the activation of inertial navigation mode (b) the aircraft must be fly in the direction of the predefined flight path. Only when these two conditions are met, or become True, the autopilot will engage the inertial navigation mode. For constantly checking these two conditions a software routine is used and it is called a guard. A guard is just a logical statement which aids mode transition only if it gives a True value after its implementation [9].[Illustrated in figure below].

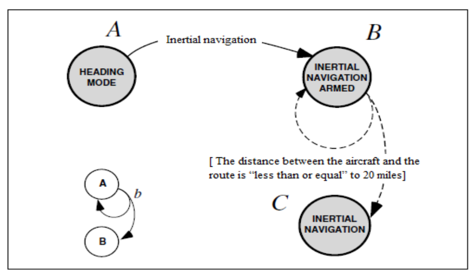

Figure1: Flow Chart for Mode Transition from Taming HAL [9]

Modern autopilot includes complex components that are capable of detecting and avoiding collisions with other objects and can allow aircraft to land in situation where a human cannot see the runway. Several aircrafts accidents and incidents have happened due to autopilot failure. Recently in February 2009 a Turkish Airlines Flight TK1951, a Boeing 737-800 flying from Istanbul-Ataturk International Airport to Amsterdam-Schiphol International Airport got crashed at distance from its runway [3]. An initial investigation results indicated that one of radio altimeter indicated an erroneous altitude of -8 feet when the aircraft was actually at an altitude of 2000 feet, the autopiloting system employed shifted to 'retard flare' mode cutting off the thrust from both the engines to a minimum value which is mainly done during last phase of landing finally resulting in stall and crash of the flight. After this accident a warning was passed in the year 2004 that states that autopilot or autothrottle where radio altimeter is inoperative then they must not be used for approach and landing [5]. Efe Sevin research report on TK1951 [10] is a handy one that aims at developing and improving immediate crisis response strategy in communication which can be utilized by Turkish as well as other airline companies. Reasons for some of the critical failures that occurred were closely related to incorrect selection of autopilot modes. This can be due to conflicting or ambiguously defined transition criteria. Scientists and engineers have spent significant amount of time in designing appropriate and correct mode transition logics. Putting a stress on the importance of correct mode transitions, different aircraft autopilot mode logics are studied and analyzed from the safety standpoint and performance criteria. A framework for validating the mode transition logic will be developed and used for testing.

A few common modes in lateral autopilot such as Roll hold mode (Rah),Heading Hold (Hh), Heading select (Hdg), Lateral navigation (LNAV), Approach mode(APPR) and Go-Around (GA) mode will be studied [6] and [7].

Apart from the accidents cited above one more issue that needs to be stressed is confusion involved in transition logic of the modes. Advanced-technology Aircraft Safety Survey report [4] by the Australian Bureau of Air Safety Investigation (BASI) in 1999 covered a story in which pilots all over the world strongly supported the advanced technology aircraft at the same time expressed worries regarding the confusion of mode selection and mode transition while handling an automated cockpit. Logics involved in Transition of modes are the basics related to the designing of an autopilot .Working of an auto pilot is nothing but various transitions of modes involved in achieving a desired flight plan automatically by an aircraft. Safety specifications and various performance criteria are the vital factors that influence or define the logic involved in a mode transition.

In this paper we use array logic method for designing the modes transition along with the specification criteria’s for autopilot in lateral direction. Main reason for adopting this method is it is less complex compared to the existing methods for autopilot design. More complex the design procedure more time utilized for logic reviewing process. Usually reviewing is done manually so with increase in complexity there will b a proportional increase in time utilized and manual effort. These issues can be solved using array logic technique. Unlike mentioned in Shrikant Rao and Shyam Chetty’s paper [8] that describes array logic based scheme for longitudinal autopilot, this is an effort done to extend this technique to lateral direction of autopilot.

II. Mode Transition of lateral Modes

In lateral mode of autopilot, default mode is the roll hold mode. While using an autopilot if any mode is disengaged or simply when autopilot is engaged, then we can have a default mode. Being in a default mode you can go to any other higher modes of autopilot. For roll hold mode to be active, it have to meet with certain specification conditions (Table 5).For example, specification condition for roll hold mode to be engaged is, bank angle limit +/-60deg during autopilot control and $+6^0$ to $+38^0$ bank angle limit upon initial engagement. If these conditions are met then on engagement of autopilot we get roll hold mode as the default mode. Heading hold mode, as name suggest, automatically holds a particular heading for the aircraft.HDG key is used to select heading hold mode and the condition required for engagement of heading hold mode is engage HDG button at any heading with static accuracy of 1 of engagement heading +/-30deg bank angle limit, +/-5kmph turbulent air and heading must be less than 6^0, if greater than 6^0 then it will go to the default mode. When HDG button is pressed twice then autopilot will shift to default mode. From heading hold mode it is possible to transit to any other modes of autopilot by engaging the respective keys. Heading select mode is nothing but to select the heading by turning the knob While HDG mode is in operation then it is not necessary that the system is aided by any navigation source, it merely flies a specific heading [11]. Lateral navigation automatically moves the aircraft from current flight path to predefined flight path during its voyage. Many sources are associated with navigation mode such as VOR, TACAN, FMS, LOC, ORBITAL GUIDANCE (OG) etc. Lateral navigation mode can be engaged using LNAV key and conditions to be met varies with the source that is being used, that is, for activation of LNAV mode engage LNAV key with conditions mentioned in Table1.

Table1: LNAV-VOR Specification

VOR INTERCEPTABLE ANGLE	BANK ANGLE LIMIT	OVERSHOOT
Upto 45 deg	30	≤2

Table 2: APPR Specification

OVERSHOOT	TRACK	WIND LIMIT		
		TAIL WIND	HEAD WIND	CROSS WIND
$\leq 0.58^0$ when capturing from below GS flight level	Within TBD degree +/-35 micro ampere	15 KNOT	25 KNOT	25 KNOT

Approach mode captures the required data points and maintains a constant heading to track the selected navigation source (like LOC) with greater sensitivity for approach. Approach mode is engaged using APPR key and condition required for the engagement of this mode is mentioned in Table (2).

From above we understand different possible mode transition and criteria are which bounds the transition from one mode to another. So the logic behind mode transition is essential for successful accomplishment of autopilot task.

III. Mode Transition Logic

Mode transition logic explains the entry and exit criteria of various modes in accordance with their performance criteria. This is best depicted in Table 3 and Table 4 where columns represent various modes and rows represent various keys that can be engaged. Initially when we are in a disabled mode and when we engage autopilot by pressing an AP button it goes to a default mode that is roll hold mode if and only if it satisfies the zcondition mentioned in condition matrix that is Table 4 where the condition is clearly elaborated in Table5. For example if we are in roll hold, that is, default mode and if we engage HDG button then we go to a heading hold mode, as shown in Table 3, only if we satisfy condition 3, as per Table 4, where elaboration of condition 2 is mentioned in Table 5.

Table 3: State Transition Matrix Table

Condition No.	Condition For Lateral Autopilot
1	AP engaged with bank angle limit 60^0 during autopilot control; +6 to +38 bank angle limit upon initial engagement.
2	Engage HDG button at any heading with static accuracy of 1 of engagement heading +/-30^0 bank angle limit, +/-5turbulent air.
3	Engage LNAV with VOR interceptable angle upto45, bank angle limit=30, overshoot ≤2overshoot of <5800 from course centerline at distance≥40nmfrom station (no wind).
4	Sync released and ($\theta \leq$ -10 or $\theta \geq$ 25 or $\|\phi\| \geq$ 30) and AP in sync or FD in sync.
5	Engage GA with pitch up speed 1.2Vstall, pitch up angle limit 7^0.
6	Engage approach hkey or NAV key with GS angle error>0 and distance <10000, pitch rate limit max2deg/sec or 1.5G
7	Engage APPR with ≤1 overshoot of ≤35microampere or ≤0.58^0 when capturing from below GS in level flight at an altitude of□ 800 'above GS transmitter datum altitude. Wind limit are Headwind 25 knot Crosswind 25 knot Tailwind 15 knot Wind shear 10 knot per 100' from 500' above touch down to touchdown.
8	Disengage GA with bank angle limit equal to wings level.
9	Enable AP and enable FD.
10	AP is engaged.
11	Bank angle limit 60^0 during autopilot control and +6 to +38 bank angle limit upon initial engagement.
12	With autopilot control heading error 1 of engagement target HDG , bank angel limit 30.
13	Enable AP and disable FD
14	Engage BC with ≤1 overshoot of≤35microampere or ≤0.58deg; Wind limit is headwind25knot, crosswind25knot, tail wind15knot, wind shear 10knot per 100' from 500' above touchdown to touchdown and their associated turbulence as specified in MIL-F-9490.

Table 4: Condition Matrix Table

SL. NO:	MODES	EVENTS								
		AP	FD	Hdg	Hdgsel	LNAV	APPR	BC	GA	SYNC
1	DIS	2	2	0	0	0	0	0	0	0
2	RAH	10202	10202	3	4	5	9	7	8	1
3	Hdg	103	103	1	4	5	9	7	8	1
4	Hdgsel	104	104	3	2	5	9	7	8	1
5	LNAV	105	105	3	4	2	9	7	8	1
6	APPR	106	106	0	0	5	2	7	8	1
7	BC	1	1	0	0	5	0	2	8	1
8	GA	2	1	0	0	0	0	0	1	1
9	GS	109	109	3	4	5	2	0	8	1

Table 5: Conditions for Lateral Autopilot

SL. NO:	MODES	EVENTS								
		AP	FD	Hdg	Hdgsel	LNAV	APPR	BC	GA	SYNC
1	DIS	2	2	0	0	0	0	0	0	0
2	RAH	282231	282231	12	2	3	6	14	5	4
3	Hdg	282231	282231	1	2	3	6	14	5	4
4	Hdgsel	282231	282231	12	1	3	6	14	5	4
5	LNAV	282231	282231	12	2	1	6	14	5	4
6	APPR	282231	282231	0	0	3	1	14	5	4
7	GA	282231	282231	0	0	0	0	0	8	4
8	BC	282231	282231	0	0	3	0	1	5	4
9	GS	282231	282231	12	2	3	1	0	5	4

A. *Logic Array Based Design for Autopilot*

Array logic is a method that is used to design the logic model of an autopilot in a less complex way. In this method first an account of all modes of lateral autopilot was studied and its possible transitions were studied and framed as a state transition matrix (Table 3). This state transition matrix consist of mode as rows and events (or button pressed) as column. Here then various mode transitions were for various modes corresponding to different events is mentioned. If these possible transitions need to be activated certain conditions have to be met and these conditions were written in condition matrix (Table 4).Hence in nutshell we can say that array logic method has two layer, state transition matrix which implies possible mode transition and condition matrix which implies the conditions required for the transitions to take place. This array logic can be implemented in to any required software and at a very low level we can have FPGA based design; all depend upon the requirement of automated cockpit. Here complexity is reduced because logic for mode transition is represented in a simple way in state transition matrix which is easy to understand and analyze. Confusion of mode selection is eliminated by using a condition matrix which will only allow transition if corresponding condition is met. Thus eliminating the confusion whether a mode transition is successfully activated or not.

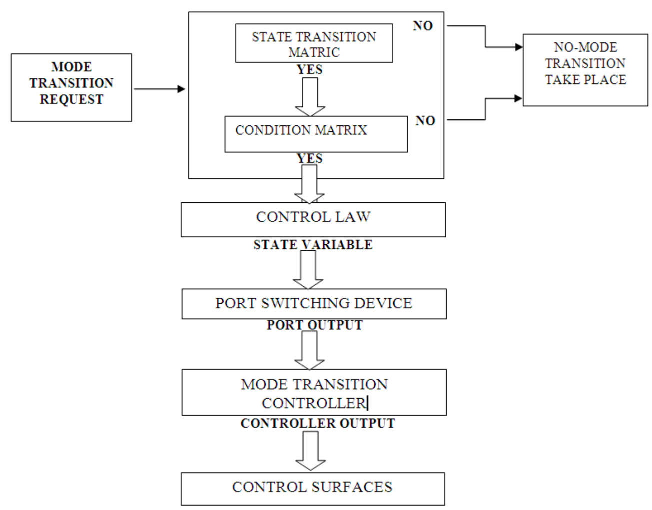

Figure 2: Block Diagram of Array Logic Block

A mode change requesting input is sent into the logic array, which consist of two layers namely state transition matrix and condition matrix. First it goes to state transition matrix and look for whether transition is possible from current mode to requested mode, if transition is permitted then a flag will show true and it will be passed into the second layer of array logic. In second layer or condition matrix, conditions required for transition is checked and only if it is satisfied a flag will show true and a signal goes into mode selector controller and required transition will be taken by giving appropriate instructions to the various control surfaces. If any one of the flag, out of two layers of array logic is false, then no signal will be sent to mode selector controller to control the control surfaces and hence inhibit a change in mode.

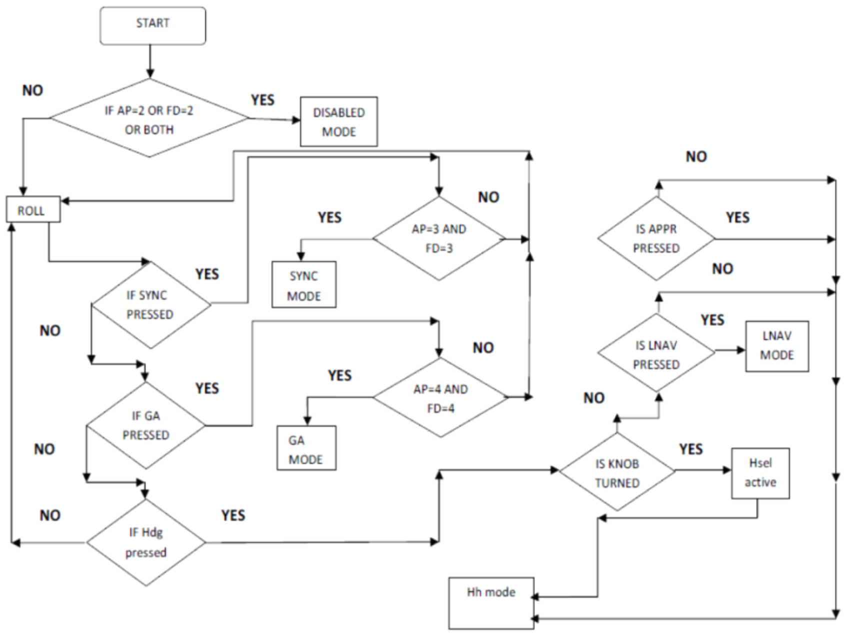

Figure 3: Flow Chart for MATLAB Coding

B. Matlab Code for Structuring a Frame Work of Mode Transition

MATLAB code is created for forming a structural frame work for various mode transition logic which is explained in the above section and executed to obtain results as shown in Table 7. Here Column-1 (C1) represents the various lower modes of the autopilot. This can take different state values such as disengaged state DIS (1), RAH (2), Hh (3) and Hsel (4). Column-2 represent the states of AP button, that is, disengaged(1), engaged(2), sync(3) and GA(4). Similarly Column-3 represent the states of FD button ,that is, disengaged(1), engaged(2), sync(3) and GA(4). Column-4 represent states of Hdg button, that is, ON(1) and OFF(2). Column-5 represent states of Hdgsel button, that is, ON(1) and OFF(2). Column-6 represent states of LNAV button, that is, OFF(1), Hdg(5), Hdgsel(6). Column-7 represent states of APPR button, that is OFF(1), Hdg(7), Hdgsel(8) and Glide Slope,GS(7). Column-8 represent states of BC (back course) button, that is OFF(1), Hdg(9) , Hdgsel(10) and Glide Slope,GS(7). As per the conditions explained in the above section, mode transition logic behavior is converted into MATLAB codes in this section. For example when mode is disengaged mode (C1=1), then AP must be in disengaged state (C2=1) but FD can be in engaged or disengaged state(FD= 1 OR FD=2). Another example is when sync mode is in ON state (C4=2) then both AP and FD must be in their respective sync state (C2=3 and C3=3) and rest of the modes must be in disengaged states. Similarly these mode transition behaviors are converted into MATLAB codes and executed to obtain results that gives us the frame work of valid states of the respected modes we considered, during its various transitions, ('c' matrix), which is shown in Table 8.

IV. RESULT

The matrix which has been computed earlier is now framed to a set of safe states which are completed by using a Table representation of the states and conditions. A safe set of mode transitions that are defining through some assertions as shown below in Table 6. MATLAB code is generated for mode transition and results are executed with various states satisfying our assertions whether it's true or not as shown in Table (7).

Table 6: Assertion for MATLAB code

Sl no.	ASSERTIONS
1	When AP and FD is disengaged all modes are disengaged.
2	When AP and FD are in sync mode then all modes in off state.
3	When AP is in GA mode and FD in GA mode all modes are in off state.

Using array logic techniques lateral autopilot modes transition state matrix (Table 3) and conditional matrix (Table 4) was designed. Rows of matrix indicate modes of lateral autopilot and columns of matrix indicated various possible events. Corresponding to each entry in state transition matrix we have specification criteria or condition mentioned in condition matrix. After analysing both matrices, iff both are true, then only signal will be sent to activate mode selector controller and thus inhibit mode transition. For example, consider the state transition matrix or highlighted row of output of MATLAB code [Table 7]. when it is in roll hold mode(2) and if we press LNAV key then it first analyses state transition matrix to see whether mode transition from roll hold mode to LNAV mode is possible or not. After analysing it, if its true or if mode transition is possible means it goes to condition matrix and analysis condition to see whether LNAV mode activation is possible or not. If true then respective control signal saying to convert current mode to LNAV mode will be given to mode selector controller. This mode selector controller gives necessary command to control surface to exhibit the same.

Table 7: Output for MATLAB Coding

MODES	AP	FD	HDG	HDGSE	LNAV	APPR	BC
1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1
2	1	2	1	1	1	1	1
2	2	1	1	2	6	8	10
2	2	1	2	1	5	7	9
2	2	2	1	1	1	4	1
2	2	2	1	1	1	1	4
2	2	2	1	2	6	8	10
2	2	2	2	1	5	7	9
2	2	1	1	1	1	1	1
2	2	2	1	1	1	1	1
2	3	3	1	1	1	1	1
2	4	4	1	1	1	1	1
3	1	1	1	1	1	1	1
3	1	2	1	1	1	1	1
3	2	1	1	1	5	7	9
3	2	2	1	1	5	7	9
3	2	2	2	1	1	1	1
3	2	1	1	2	6	8	10
3	2	2	1	2	6	8	10
3	3	3	1	1	1	1	1
3	4	4	1	1	1	1	1
4	1	1	1	1	1	1	1
4	1	2	1	1	1	1	1
4	2	1	1	1	5	7	9
4	2	2	2	1	1	1	1
4	2	1	1	2	6	8	10
4	2	2	1	2	6	8	10
4	3	3	1	1	1	1	1
4	4	4	1	1	1	1	1

V. CONCLUSION

In this paper we described basic lateral modes and their transitions from one mode to another. We described autopilots' transitions among the possible mode configurations of the automated flight control system. All the possible mode transitions in the presence of external or internal event and performance criteria are presented using array based logic technique. A model of a autopilot is defined by a set of safe states and is completed by using a Table representation of the states and condition. Assertions were used to compute these safe modes from a set of 288 states. These sets of safe states which is completed by using a Table that represents various states and conditions required for each mode to be engaged and these conditions are converted into MATLAB codes and a frame work was formed for the designed autopilot. Array logic method made design procedure of autopilot a less complex one which was easy to understand and analyse, thereby making manual review with less manual effort. This logic can be implemented into any convenient software according to the requirement of automated cockpit an can be given to control the operation of mode selector controller and hence suitable control provided to control surface to execute mode transmission.

VI. FUTURE WORK

To develop a matrix with more lateral modes incorporated and validate it using MATLAB software. Use optimization to validate the Mode transition logic. Make the design of a controller based on the states. These will be developed using the aircraft plant model and the state transit matrix defined in this paper.

VII. ABBREVIATION

APAuto pilot
FDFlight direct
SYNC Synchronize
Hdg Heading Hold
Hdgsel Heading select
LNAV Lateral navigation
APPR Approach mode
BC Back course
GA Go around mode
1 OFF
2 ON
3 SYNC
4 GA

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