Mode Transition Logic for Lateral Autopilot in Aircraft

Aparna S Nair, Atit Mishra, Yogananda Jeppu, C.G. Nayak and Nagaraj Murthy

Abstract--- Mode confusion is increasingly becoming a significant contributor to accidents and incidents involving highly automated airliners; in the last seven years there have been four airline accidents in which mode problems were present. This paper provides some initial observations about modes and logic concerning lateral mode transition. This paper cover various mode possibilities of lateral mode transition in an autopilot with criteria’s that bound these transition, along with MATLAB implementation and verification and its result followed by its conclusion.

Index Terms--- Aircraft Navigation, MATLAB

I. INTRODUCTION

Autopilots fly an aircraft with less fuel consumption than human pilot, reducing airline cost and increasing flight safety for passengers. 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 aircraft accidents and incidents have happened due to autopilot failure. As an example we have, A Boeing 737-800 (flight TK1951) operated by Turkish Airlines was flying from Istanbul Ataturk Airport in Turkey to Amsterdam Schiphol Airport, on 25 February 2009. During the approach to runway 18 Right (18R) at Schiphol airport, the aircraft crashed into a field at a distance of about 1.5 kilometers from the threshold of the runway. The initial investigation results indicated that the left radio altimeter system had passed on an erroneous altitude reading of -8 feet to the automatic throttle control system (the autothrottle). In response to this, the Board had a warning sent to Boeing on 4 March 2009. This asked for extra attention to be paid to the 'Dispatch Deviation Guide' for the Boeing 737-800, which is a manual of additional procedures and warnings for maintenance crews and pilots to consult before the aircraft is flown. This warning, which was added in 2004, states that with radio altimeter(s) inoperative, the associated autopilot or autothrottle must not be used for the approach and landing [1]. Some of the critical failures that occurred were closely related to the incorrect selection of autopilot modes due to a conflicting or ambiguously defined transition criteria. Till date the scientists and engineers have spent significant amount of time in designing appropriate and correct mode transition logics. Putting an emphasis on the significance 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.

Apart from having a wide variety of modes that define the functionality of an autopilot safety concerns are raised in the field of operations of these various modes and its possible transition logic during the flight of an aircraft. This is indeed serious subjects that need to be in the limelight as failure of these paved major reasons for the accidents of aircraft. For instance considering LNAV mode of autopilot, surveys have revealed that the low levels of use of the LNAV function are primarily a result of the incompatibility between the incompatibility between the tactical operation of ATC and the strategic behavior of the FMS and this led to many accidents in aviation sector. When the ATC environment allowed pilots to use the LNAV function, sixty one percent of the pilots surveyed by BASI agreed that there were things about the automation that took them by surprise. For example, when the LNAV function is used in descent and approach, pilots reported that the function does not perform the task as they had expected. Apart from these were also cases reported of accident of aircraft with autopilot engaged due to defect or malfunctioning of some components within the aircraft [2].

Apart from the accidents cited above one more issue that needs to be stressed is confusion involved in transition logic of the modes. In a survey of 1,268 pilots published in 1999 by the Australian Bureau of Air Safety Investigation (BASI), 73% of the respondents indicated that they had inadvertently selected a wrong mode [3]. 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.

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 it automatically shift into 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 conditions like bank angle limit +/-60deg during autopilot control and +6deg to +38deg 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 it 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, +/-5kmpm turbulent air and heading must be less than 6deg, if greater than 6deg 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. Lateral navigation automatically moves the aircraft from current flight path to predefined flight path during itz 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, engage LNAV with criteria in table 1.

### Table 1: LNAV VOR Specification

<table>
<thead>
<tr>
<th>V or Intercept able Angle</th>
<th>Bank angle Limit</th>
<th>Overshoot</th>
</tr>
</thead>
<tbody>
<tr>
<td>upto45deg</td>
<td>30</td>
<td>≤2</td>
</tr>
</tbody>
</table>

Engage LNAV capture for LOC using criteria in table 2

### Table 2: LNAV LOC Specification

<table>
<thead>
<tr>
<th>Loc Intercept able Angle</th>
<th>Bank angle Limit</th>
<th>Overshoot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upto 90deg</td>
<td>30deg</td>
<td>≤2</td>
</tr>
</tbody>
</table>

Initial overshoot shall be ≤50% of full scale deflection of CDI. Tracking with course maintenance 15deg, bank angle limit upto +/-45deg and cross wind correction 30 and so on. Approach mode captures and track the selected navigation source with greater sensitivity for approach. Approach mode is engaged using APPR key and condition required for the engagement of this mode varies according to the source involved, that is, engage APPR with capture of 0≤1.

### Table 3: APPR Specification

<table>
<thead>
<tr>
<th>Overshoot</th>
<th>Track</th>
<th>Wind limit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tail wind</td>
</tr>
<tr>
<td>≤0.58deg when capturing from below gs flight level</td>
<td>Within tbd deg</td>
<td>15 knot</td>
</tr>
<tr>
<td></td>
<td>+/-35 micro ampere</td>
<td></td>
</tr>
</tbody>
</table>

From above we understand different possible mode transition and criteria 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 4 and table 5 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 condition mentioned in condition matrix that is table 4 where the condition is clearly elaborated in table 6. 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 4, only if we satisfy condition 30, as per table 5, where elaboration of condition 30 is mentioned in table 6.

### Table 4: State Transition Matrix Table

<table>
<thead>
<tr>
<th>SL NO.</th>
<th>MODES</th>
<th>AP</th>
<th>HDG</th>
<th>LNAV1</th>
<th>LNAV2</th>
<th>APPR</th>
<th>BGA</th>
<th>BCAP</th>
<th>FD</th>
<th>SYNC</th>
<th>DECAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dis</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Rah</td>
<td>10202</td>
<td>3</td>
<td>5</td>
<td>9</td>
<td>706</td>
<td>1</td>
<td>3</td>
<td>10202</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Hh</td>
<td>10303</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>706</td>
<td>1</td>
<td>0</td>
<td>10303</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>HDgsl</td>
<td>10404</td>
<td>3</td>
<td>5</td>
<td>9</td>
<td>706</td>
<td>1</td>
<td>3</td>
<td>10404</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>LNAV1</td>
<td>10505</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>706</td>
<td>1</td>
<td>3</td>
<td>10505</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>APPR</td>
<td>10606</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>10606</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>GS</td>
<td>10707</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>10707</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>GA</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>10808</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>LNAV2</td>
<td>10909</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>706</td>
<td>3</td>
<td>3</td>
<td>10909</td>
<td>9</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 5: Condition Matrix Table

<table>
<thead>
<tr>
<th>SL NO.</th>
<th>MODES</th>
<th>AP</th>
<th>HDG</th>
<th>LNAV1</th>
<th>LNAV2</th>
<th>APPR</th>
<th>BGA</th>
<th>BCAP</th>
<th>FD</th>
<th>SYNC</th>
<th>DECAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dis</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Rah</td>
<td>282231</td>
<td>30</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>1612</td>
<td>3</td>
<td>282231</td>
<td>29</td>
<td>3233</td>
</tr>
<tr>
<td>3</td>
<td>Hh</td>
<td>282231</td>
<td>30</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>1612</td>
<td>0</td>
<td>282231</td>
<td>30</td>
<td>3233</td>
</tr>
<tr>
<td>4</td>
<td>HDgsl</td>
<td>282231</td>
<td>29</td>
<td>4</td>
<td>5</td>
<td>7</td>
<td>1612</td>
<td>3</td>
<td>282231</td>
<td>30</td>
<td>3233</td>
</tr>
<tr>
<td>5</td>
<td>LNAV1</td>
<td>282231</td>
<td>30</td>
<td>29</td>
<td>7</td>
<td>29</td>
<td>3</td>
<td>282231</td>
<td>4</td>
<td>3233</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>APPR</td>
<td>282231</td>
<td>30</td>
<td>29</td>
<td>29</td>
<td>7</td>
<td>29</td>
<td>3</td>
<td>282231</td>
<td>19</td>
<td>3233</td>
</tr>
<tr>
<td>7</td>
<td>GS</td>
<td>282231</td>
<td>30</td>
<td>29</td>
<td>29</td>
<td>7</td>
<td>29</td>
<td>3</td>
<td>282231</td>
<td>16</td>
<td>3233</td>
</tr>
<tr>
<td>8</td>
<td>GA</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>21</td>
<td>0</td>
<td>2</td>
<td>7</td>
<td>3233</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>LNAV2</td>
<td>282231</td>
<td>30</td>
<td>29</td>
<td>29</td>
<td>7</td>
<td>29</td>
<td>3</td>
<td>282231</td>
<td>5</td>
<td>3233</td>
</tr>
</tbody>
</table>

### Table 6: Conditions for Lateral Autopilot

<table>
<thead>
<tr>
<th>Condition No.</th>
<th>Condition for lateral autopilot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AP engaged with bank angle limit 60deg during autopilot control; +6 to +38 bank angle limit upon initial engagement.</td>
</tr>
<tr>
<td>2</td>
<td>engage HDG button at any heading with static accuracy of 1 of engagement heading +/-30deg bank angle limit, +/-5kmpm turbulent air.</td>
</tr>
<tr>
<td>3</td>
<td>engage LNAV with VOR interceptable angle upto45, bank angle limit=30, overshoot ≤2overshoot of ≤5800 from course centerline at distance=40NM from station(no wind).</td>
</tr>
<tr>
<td>4</td>
<td>Engage LNAV with TACAN interceptable angle upto30, bank angle limit=30,</td>
</tr>
</tbody>
</table>

overshoot
- ≤2overshoot of <6300 from course center line at distance ≥120NM from station.
- Course accuracy +/-1 of engaged course.
- Cross track accuracy <10% full scale deflection of CDI.
- Crosswind correction up to 45 degrees.
- error; over station band limit = +/-30 with over station course change, +/-10 without over station course change, heading error +/-5 of heading on entry without over station course change.

<table>
<thead>
<tr>
<th>7</th>
<th>engage GA with pitch up speed 1.2Vstall, pitch up angle limit 7deg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>engage approach hikey or NAV key with GS angle error &gt; 0 and distance &lt; 10000, pitch rate limit max 2deg/sec or 1.5G</td>
</tr>
<tr>
<td>19</td>
<td>engage APPR with ≤1 overshoot of ≤35 microampere or ≤0.58deg when capturing from below GS in level flight at an altitude of ≥ 800' above GS transmitter datum altitude.</td>
</tr>
</tbody>
</table>
- wind limit are
  - headwind 25 knot
  - crosswind 25 knot
  - tailwind 15 knot
  - wind shear 10 knot per 100' from 500' above touchdown to touchdown.
| 21 | disengage GA with bank angle limit equal to wings level. |
| 22 | enable AP and enable FD. |
| 28 | AP is engaged. |
| 29 | bank angle limit 60deg during autopilot control and +6 to +38 bank angle limit upon initial engagement. |
| 30 | with autopilot control heading error 1 of engagement target HDG , bank angle limit 30. |
| 31 | enable AP and disable FD |
| 32 | Clutch Closure Monitor trip |
| | Attitude Closure Monitor trip |
| | Motor Current Monitor trip |
| | Pitch Trim Monitor trip |
| | AP Command Comparison Monitor trip |
| | Any Primary Servo Motor Fail. |
| 33 | FD Command Comparison Monitor trip OR Air DATA Inputs Fail OR Inertial DATA Inputs Fail OR Flap Fail |

**IV. MATLAB Code for Validation of Mode Transition**

MATLAB code is created for various mode transition logic which is explained in the above section and executed to obtain results as shown in table(8). Here 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). c2 represents the states of AP button, that is, disengaged(1), engaged(2) and sync(3). Similarly c3 represent the states of FD button, that is, disengaged (1), engaged (2) and sync (3). c4 represent states of sync button, that is, sync ON(1) and sync OFF(2). 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). Similarly these mode transition behaviors are converted into MATLAB codes and executed to obtain results that gives us the valid states of the respected modes we considered, during its various transitions, (‘c’ matrix), which is shown in table 8.

**Table 7: MATLAB Code**

```matlab
c=[ ];
for c1=1:4%dis, roll, hdg, hdgsel
  for c2=1:4%ap, 1off, 2on, 3sync, 4ga
    for c3=1:4%fd, 1off, 2on, 3sync, 4ga
      for c4=1:2%hdg, 1off, 2arm
        for c5=1:2%hdgsel, 1off, 2arm
          for c6=1:3%lnav, 1off, 2hdg, 3hdgsel
            for c7=1:4%appr, 1off, 2hdg, 3hdgsel, 4gs
              ok=1;
              if(c1==1)
                if (c2~=1 || c3~=1 || c4~=1|| c5~=1 || c6~=1 || c7~=1)
                  ok=0;
                  disp('invalid')
                end
              end
              if (c2==3 && c3==3)
                if (c4~=1|| c5~=1||c6~=1||c7~=1)
                  ok=0;
                  disp('invalid')
                end
              end
              if c2==2
                if c3==3
                  ok=0;
                  disp('invalid')
                end
              end
              if c3==3
                if c2==2
                  ok=0;
                  disp('invalid')
                end
              end
              if c2==4
                if c3~=4
                  ok=0;
                  disp('invalid')
                end
              end
            end
          end
        end
      end
    end
  end
end
```

if c3==4
    if c2==4
        ok=0;
        disp('invalid')
    end
end
if c2==4 & & c3==4
    if (c4==1 & & c5==1 & & c6==1 & & c7==1)
        ok=0;
        disp('invalid')
    end
end
if c2==1 & & c3==1
    if (c4==1 & & c5==1 & & c6==1 & & c7==1)
        ok=0;
        disp('invalid')
    end
end
if c3==3
    if c2==3
        ok=0;
        disp('invalid')
    end
end
if c4==2
    if c5==1
        ok=0;
        disp('invalid')
    end
end
if c5==2
    if c6==3 & & c7==3
        ok=0;
        disp('invalid')
    end
end
if c2==1
    if (c6==1 & & c7==1)
        ok=0;
        disp('invalid')
    end
end
if c4==2
    if (c6==2 & & c7==2)
        ok=0;
        disp('invalid')
    end
end
if c6==2
    if c7==2
        ok=0;
        disp('invalid')
    end
end
if c6==3
    if c7==3
        ok=0;
        disp('invalid')
    end
end
if c2==1
    if c5==1
        ok=0;
        disp('invalid')
    end
end
if c4==1 & & c5==1 & & c6==1 & & c7==1)
        ok=0;
        disp('invalid')
    end
end
if c2==2;
    if(c4==1 & & c5==1 & & c6==1 & & c7==1)
        ok=0;
        disp('invalid')
    end
end
if (c7==2)
    if (c6==2 & & c4==2)
        ok=0;
        disp('invalid')
    end
end
if c5==2
    if (c6==3 & & c7==3)
        ok=0;
        disp('invalid')
    end
end
if c7==2
    if lnav in hdgsel n appr in hdgsel then
        if c5==2
            if c6==2 & & c7==2
                ok=0;
                disp('invalid')
            end
        end
    end
if c7==3
    if lnav in hdgsel then
        if c6==3
            ok=0;
            disp('invalid')
        end
    end
if c7==4
    if c3==2
        ok=0;
        disp('invalid')
    end
end
if (c7==2 & & c6==2)
    if c4==2
        ok=0;
        disp('invalid')
    end
end
if (c1==3 & & c5==2)
    if (c6==1 & & c7==1)
ok=0;
disp('invalid')
end

if (c1==4 && c4==2)
    if (c6~=1 && c7~=1)
        ok=0;
disp('invalid')
    end
end

if ok == 1;
c =[c;c1 c2 c3 c4 c5 c6 c7 ]];
end
end

Table 8: Output for MATLAB Coding

<table>
<thead>
<tr>
<th>Slno</th>
<th>Assertions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>When AP and FD is disengaged all modes are disengaged.</td>
</tr>
<tr>
<td>2</td>
<td>When AP and FD are in sync mode then all modes in off state.</td>
</tr>
<tr>
<td>3</td>
<td>When AP is in GA mode and FD in GA mode all modes are in off state.</td>
</tr>
</tbody>
</table>

V. CONCLUSION

A mode transition of autopilot is defined. A set of safe states are completed by using a table which represents various states and conditions required for each mode to be engaged. These conditions are converted into MATLAB codes and executed to obtain valid states of the respected modes engaged.

VI. FUTURE WORK

To develop the complete matrix and validate it using MATLAB software. Use optimization to validate the Mode transition logic. Make the design of a controller based on the states.

REFERENCES


