DEVELOPMENT OF HUD SYMBOLOGY FOR ENHANCED VISION SYSTEM

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Abstract

Head-up display is one of the important sub-systems of aircraft avionics suite for enhancing pilot situational awareness for smooth and safe gate-to-gate operations especially during take-off, approach and landing phases of flight. The Head-up display consist of generic and advanced sets of symbologies mainly categorized as i) conformal: such as local horizon, airport/runway, highway-in-the-sky, pitch ladder, etc and ii) non-conformal: airspeed, altitude, heading, roll, horizontal situation indicator etc. These symbologies can be combined or overlaid with more advanced systems such as Enhanced vision system/synthetic vision system to increase pilot situational awareness in case of poor weather conditions/ degraded visual environment. This paper presents development of generic and enhanced vision system specific Head-up display symbologies based on Gulfstream G450 Head-up display standard and its integration with in-house developed Enhanced synthetic vision system flight simulator.

Keywords: Head-up display; Symbology; Highway-in-the-sky; Enhanced vision system; Synthetic vision system; ESVS flight simulator

Introduction

The Regional Transport Aircraft (RTA) being designed and developed at CSIR-NAL will have capability of autonomous all weather approach and landing at minimally equipped airfields (e.g. without Instrument Landing System (ILS)). Under Instrument Meteorological Conditions (IMC) like reduced runway visibility due to rain, fog, snow or due to low cloud ceiling, Enhanced Synthetic Vision System (ESVS) can be used as Equivalent Visual Operations (EVO) [1] to achieve safe, efficient and reliable flights while keeping in pace with Visual Flight Rules (VFR) operations irrespective of visibility and weather conditions. ESVS is the combination of Enhanced Vision System (EV S), Synthetic Vision System (SVS) and Head-Up/Head-Down Display (HUD/HDD). EVS generates the images in real time from combination of weather penetrating multispectral Infrared (IR) imaging sensors like Short Wave Infrared (SWIR), Medium Wave Infrared (MWIR),
Long Wave Infrared (LWIR) and Millimeter Wave Radar (MMWR). SVS generates a rendered image of the external scene topography from the perspective of the flight deck derived from aircraft attitude and high precision navigation data using onboard database of terrain, obstacles and relevant cultural features [2].

Flight operations with a Head-up display (HUD) can improve situational awareness by combining flight information along with the external view or EVS/SVS to provide pilots with more immediate awareness of relevant flight parameters and situation information while they continuously view the Out-of-the-Window (OTW) external scene. This improved situational awareness can also reduce errors in flight operations and improve the pilot’s ability to transition between instrument and visual references as meteorological conditions change. Flight operations applications may include the enhanced situational awareness during all flight operations or during taxi, take-off, approach and landing. During take-off, approach and landing it improves the pilot performance due to precise prediction of touchdown area, tail strike awareness/warning and rapid recognition of and recovery from unusual attitudes.

There is plenty of research work [3-12] that has been done by scientific community over decades on creation of conformal 3-D perspective view of outside world. The desired path of aircraft is represented by tunnel or series of symbol through pilot has to fly his/her aircraft and has been known by "pathway-in-the-sky", "tunnel-in-the-sky" and "Highway-in-the-sky". An ergonomically designed flight situation display system that replaces the old-fashioned instrument panel is the hallmark of the NASA Advanced General Aviation Transportation Experiment (AGATE) cockpit revolution. The display system is the foundation for NASA’s Highway in the Sky (HITS) initiative, which is developing affordable glass cockpits for single-engine, single-pilot airplanes by the year 2001[13]. Cobham system [14] SVS Electronic Flying Instrument (EFIS) includes Highway-in-the-Sky (HITS) as part of their primary functional display approved for about 740 fixed-wing and rotorcraft models, including many Bell helicopter models, the Eurocopter AS 350 and King Air, Citation 501, Cessna single and twin, Piper single and twin, Piaggio Avanti and Pilatus PC-12 fixed-wing aircraft models [15]. GRT avionics EFIS has HITS feature for approach and Enroute operations [16]. Garmin Synthetic Vision Technology (SVT) on G1000’s primary functional display has pathways, or HITS guidance depicted as 3D "flying rectangles", pathway guidance symbols to help the pilots stay on course when flying en route legs [17].

This paper describes the design, development and integration of HUD symbology with fixed base ESVS simulator. The development includes a generic HUD symbology and one similar to Gulfstream G450’s HUD symbology (Gulfstream has delivered more than 500 aircraft with the certified EVS on its business jet class aircrafts, improving flight safety and situational awareness for pilots). Apart from overall development of generic and EVS specific HUD symbologies, the major contribution of the paper is design and implementation of conformal Highway-in-the-Sky HUD symbology as navigation aid to pilot for curved/straight approach, landing and take-off operations during normal or degraded visual environment (instrument flight conditions). The few advantages of using HITS over conventional 2D display (gauges, needle, dials etc) are, i) reduced tracking error, ii) reduced pilot work load and iii) increased situational awareness.

### ESVS Flight Simulator

ESVS Flight simulator [18] (Fig.1) is a fixed based simulator indigenously developed by CSIR-NAL for the research and development of Enhanced synthetic vision system and its operational concept studies. The simulator can also be used for human factor studies with EVS along with HUD in low/poor visibility environmental conditions during different phases of flights especially the critical one such as take-off and landing phases. The ESVS simulator is designed to have dual mode of operations namely flight simulation mode and playback mode. The flight simulation mode is used for ESVS operational concept studies and for human factor studies by engineers and pilots. The playback mode is used for playing back the pre-recorded EVS and navigation data from ARINC429 based SARAS avionics test rig or EVS field experiments (both ground vehicle and flight) in real-time on the simulator to study SV image rendering and fusion/overlay of EVS, SVS and symbology on the HUD/HDD.

ESVS flight simulator is developed by augmenting the basic flight simulator ‘NALSim’ with EVS and SVS simulation components. The ESVS simulator contains separate computing hardware for EVS, SVS, Symbology and Playback systems with other hardware such video splitters, EzWindow, EzScan Converter and switches such as KVM and Ethernet. The simulator is divided into three components such as NALSim (Rack1), EVS (Rack2) and Cock-
pit Displays and Controls (Pilot station). The ‘NALSim’ consists of

- Three Out-of-Windows (OTW) Workstations (WS) named OTWL (left), OTWC (centre) and OTWR (right),
- Flight Model Computer (FMC) PC,
- Multi Functional Display (MFD) PC,
- KVM switch,
- Ethernet switch and
- Cables

The ESVS part consists of

- SVS-WS,
- EVS-WS,
- Symbology-WS,
- EVS-DAQ Laptop,
- KVM switch,
- Ethernet switch,
- EzWindow,
- EzScan Converter
- Video splitters and
- Cables

The Cockpit (pilot station) consists of

- OTWL, OTWC and OTWR displays
- MFD display
- Rudder
- Joystick
- Throttle
- Pilot seat and
- Cables

Apart from above three main components of ESVS flight simulator (‘NALSim’, ESVS and pilot station), there is common control station consisting of display monitor, keyboard and mouse. Using this control station, all the PCs/WSs and other hardware are programmed and controlled via KVM switches.

HUD Symbology Development

The transport aircraft requires the development of HUD symbology to enhance the pilot situational awareness and to reduce the pilot workload. The HUD is more suitable compared to HDD, because pilot doesn’t have to look down to interface for gathering information such as altitude, speed etc. The HUD symbology is displayed on a transparent glass in front of pilot’s eye looking out of the cockpit. So the pilot can simultaneously see the information on the HUD symbology and outside environment. The HUD concept is very useful in IMC for take-off and landing operations. The paper presents the development and implementation of generic HUD symbology (Boeing 737-832) and Gulfstream G450 HUD symbology [19] and integration of it with ESVS simulator for pilot-in-the-loop studies. The HUD [20,21] symbology is implemented using open graphics library (OpenGL) [22,23,24] and supporting libraries. It is developed on Microsoft visual studio 2005 using C++ win32 console application. The following graphic libraries are used for designing symbology.

Use of Graphics Library Utility (GLU): GLU is the graphics library for the OPENGL. The features included in this library are mapping between screen and world coordinate, drawing of quadric surfaces, tessellation of polygonal primitives, setting up the position of camera and different transformation such as Translation, rotation and scaling.

Use of Graphics Library Toolkit (GLUT): GLUT is the library utility for the OPENGL. The features included in this utility library are window control, window definition, monitoring input from Keyboard and mouse and drawing shapes like cubes, spheres and teapots.

Generic HUD Symbology

The HUD symbology of Boeing 737-832 (Fig.2 (a)) is used as benchmark to develop the generic HUD for ESVS simulator. Fig.2(b) shows the generic HUD implemented on ESVS simulator.

The following symbology labeled in Fig.2(b)) presented in the HUD for ESVS simulator.

1. Airspeed Indicator (Knots)
2. Altitude (feet - above mean sea level)
3. Pitch (in degrees)
4. Flight path vector
5. Tunnel-in-the sky
6. Horizon
7. Roll (in degrees)
8. Heading (in degrees)
9. Longitudinal accelerating cue
10. Latitude and longitude (in degrees)
11. Course over Ground (CoG) in degrees and Ground Speed (GS) in knots
12. Azimuth angle (in degrees)
13. Landing gear indicator (up/down)
14. Pitch reference Indicator
15. Flap
16. Aircraft energy state
17. EVS On/Off
18. Altitude above ground level (AGL)

The Generic HUD symbology is being generated on symbology workstation of ESVS simulator. Symbology code is driven by data received from FMC of simulator using UDP protocol over the Ethernet. Fig.3 shows the symbology generated on CSIR-NAL ESVS Flight Simulator. It can be seen that the artificial horizon is matched with the real horizon in the computer generated image. For the pilot, matching of artificial horizon with the real horizon is the important factor in the transparent HUD screen because it increases the pilot’s confidence and helps pilot while flying the aircraft.

G450 Based HUD Symbology

Gulfstream is the first aircraft manufacturer to successfully deployed and obtained certification for the EVS on its business jet class aircrafts, improving flight safety and situational awareness for pilots. EVS feeds infrared images of runways, approaches and surroundings into the cockpit and onto the pilot’s head-up display, a transparent, drop-down screen between the pilot and the windshield. EVS proves most useful at night or when weather conditions hamper visibility. Now EVS [25] has been proven to the point that the Federal Aviation Administration (FAA) in late 2013 proposed a new Part 91 regulation to allow pilots to touch down and roll out on runways using purely enhanced vision. The current regulation mandated that pilots switch to natural vision at 100 feet/30 meters above touchdown before landing. Gulfstream has offered comments to the FAA on the proposed change and is monitoring progress toward its approval. Fig.4(a) shows the snapshot of G450 HUD used as reference for further advancement in symbology development (Fig.4(b)) on CSIR-NAL ESVS simulator.

The G450 HUD symbologies are divided into non-conformal and conformal categories. Conformality is characterized by those items in a symbology set that overlay and move in unison with similar far domain counterparts in the environment hence adhering to Gestalt grouping principles of proximity, common fate and good continuation. For example runway outline overlapping an actual runway is considered conformal. Likewise a Highway-in-the-Sky (HITS) represents a virtually conformal depiction of the pilot’s flight path. In present work, the methodology used to make the symbology conformal to real-world is explained as follows: The central display monitor of pilot station of ESVS simulator (Fig.1) is used to overlay HUD symbology on top of out-of-window (equivalent to real world) visuals. Based on position of pilot view point the field of view of out-of-window visuals is found to be 50 deg (horizontal) and 40 deg (vertical). Since the HUD symbology development is in pixel coordinates, the real world coordinates need to be mapped to pixel coordinates. In present case central display monitor used to overlay HUD symbology is mapped to max value of ±10 (normalized value) in x and y coordinates with center of monitor in line with pilot eye point. Therefore a factor of 0.5 needs to be multiplied with any angle computed horizontally/vertically to map the real world coordinates to pixel coordinates and hence to make symbology conformal.

Non-Conformal

The non-conformal symbologies (Fig.4(a)) are mainly divided into three major parts, airspeed, altitude and heading indicators. The airspeed part is displayed in left hand and upper side in a form of airspeed dial (Ticks with inset T shape box), secondary airspeed, selected airspeed and airspeed bug. Similarly altitude part is displayed in right hand and upper side in a form of altitude dial (Ticks with inset T shape box), selected altitude, altitude bug and vertical speed. The heading part is represented as i) heading tape on middle and upper side along with heading bug and ii) Horizontal Situation Indicator (HSI) on middle and lower side consisting of heading indicator in dial form and bar indicator for aircraft heading and lateral deviation from designated runway for landing. The other non-conformal symbologies are bank angle, altitude awareness bug, Pitch Limit Indicator (PLI), Course Deviation Indicator (CDI), Instantaneous acceleration caret, Speed error tape, Reference flight path angle, Landing gear etc. Based on G450 HUD symbology norms, some of symbology like HSI, ticks of airspeed and altitude dials gets off (de-clut-
ter) when EVS display on HUD is ON to provide better view of external scene to the pilot.

**Conformal**

The conformal symbologies (Fig.4(b)) include local horizon, pitch ladder, Flight Path Vector (FPV), airport/runway, HITS etc. The methodology to get world coordinates to pixel coordinates to create these symbologies conformal is explained in section-G450 Based HUD Symbology. This sub-section mainly provides the contribution made for the paper in design and development of conformal symbologies for typical airport/runway and HITS of straight and curved types.

**Airport/Runway:** In present case the width of airport and runway is assumed to be 800 and 180 feet respectively. The length of airport and runway is assumed to be 9000 feet. The airport symbol starts appearing during the final approach and landing phase of flight and when aircraft altitude Above Ground Level (AGL) is less than 2000 feet and remain visible up to 350 feet AGL [19]. The runway starts appearing during this phase of flight when aircraft reaches 400 feet AGL and remain visible till final touchdown. It can be noted that both the airport and runway symbols appear together between 400 to 350 feet during this phase of flight. Fig.5 shows the graphical representation of airport to explain the theory behind creation of runway symbology.

Where, ‘L’ and ‘W’ represents the length and width of runway respectively, ‘AD’ represents aircraft ground distance from runway threshold, ‘ATL’ represents aircraft altitude above runway threshold, point ‘A’ shows aircraft current position and runway coordinates are represented by four points ‘C’, ‘D’, ‘E’ and ‘F’ (for e.g.: C defined by \((C_x, C_y)\) in X-Y plane).

In this formulation, it is assumed that aircraft in level flight and is aligned with runway centre line.

The near end points ‘C’ and ‘D’ in pixel coordinate are computed as follows:

\[
C_x = 0.5\times \tan^{-1}(-W/2, AD), \quad C_y = 0.5\times \tan^{-1}\left(\frac{(AD+L)^2 + W^2/4}{2 AD W/2}\right) \tag{1}
\]

\[
D_x = 0.5\times \tan^{-1}(W/2, AD), \quad D_y = 0.5\times \tan^{-1}\left(\frac{(AD+L)^2 + W^2/4}{2 AD W/2}\right) \tag{2}
\]

The far end points ‘F’ and ‘E’ in pixel coordinate are computed as follows:

\[
F_x = 0.5\times \tan^{-1}(-W/2, AD+L), \quad F_y = 0.5\times \tan^{-1}\left(\frac{(AD+L)^2 + W^2/4}{2 AD W/2}\right) \tag{3}
\]

\[
E_x = 0.5\times \tan^{-1}(W/2, AD+L), \quad E_y = 0.5\times \tan^{-1}\left(\frac{(AD+L)^2 + W^2/4}{2 AD W/2}\right) \tag{4}
\]

In case aircraft is not aligned to runway centre line and is maneuvering, then the Eqs.(1)-(4) can be extended to account for aircraft heading, pitch and roll angles and lateral deviation from the runway center line. The same theory can also be used to create conformal symbology to represent airport.

**Highway-in-the-Sky (HITS):** In present work, HITS for straight and curved approach for landing are designed and developed. The HITS symbology is square in shape with its dimensions same as width of runway i.e. 180 feet and can be of different types such as U shaped, Pathway and BOX shaped etc. The concept used in designing airport/runway symbology is also applied for the creation of HITS. As compared to runway which part of ground, HITS is more like of 3D appearance with origin in the sky which gradually (with slope angle typically same as 3 deg glide slope used for smooth landing) vanishes at the touch down point of the runway. Fig.6 shows the graphical representation of HITS to explain the theory behind creation of symbology.

Where, points ‘\(P_0\)’, ‘\(P_1\)’, ..., ‘\(P_n\)’ are the tunnel post points, ‘PS’ is distance between two consecutive post points, ‘AGL’ is the aircraft altitude above ground level, ‘AD’ is the aircraft ground distance from runway threshold and ‘AGL_n’ is the altitude of \(n^{th}\) tunnel points above ground level computed based on tunnel slope and distance of tunnel point from runway threshold. In this formulation, it is assumed that aircraft is in level flight and is aligned with runway centre line. Since square tunnel is considered in present case, only lower points ‘C’ and ‘D’ are calculated and y coordinate of points ‘B’ and ‘A’ are obtained by adding ‘W’ to y coordinates of respective lower points. The \(i^{th}\) points ‘C’ and ‘D’ are calculated as follows:

\[
C_x = 0.5\times \tan^{-1}(-W/2, AD-i*PS) \tag{5}
\]

\[
C_y = 0.5\times \tan^{-1}\left(\frac{(AD-i)^2 + W^2/4}{2 AD W/2}\right) \tag{6}
\]

\[
D_x = 0.5\times \tan^{-1}(W/2, AD-i*PS) \tag{7}
\]
\[ D_y = 0.5 \tan^{-1} \left( \frac{AGL - 0.5 \cdot AGL_i}{(AD - i \cdot PS)^2 + (W/2)^2} \right)^{1/2} \]  

In case aircraft is not aligned to runway centre line and is maneuvering then the Eqns.(5)-(8) can be extended to account for aircraft heading, pitch and roll angles and lateral deviation from the runway center line. Also the curved HITS can be drawn by including the radius of curve (based upon the maximum turn rate given aircraft) into the formulation.

**HUD Control Panel**

HUD control panel is developed for configuring and controlling the HUD symbology pages. Fig.7 shows the GUI of control panel. Using the panel, user can i) On/Off the particular symbology from HUD display page during the simulation running to display minimum symbologies required for a particular phase of flight, ii) select the Lateral deviation indicator mode like CDI or HIS or Auto, iii) select HUD page based on flight mode and there is an option to select Auto mode to enable automatic selection of HUD pages based on phase of flight like take-off / climb / cruise / approach / landing / flare etc. and iv) change the HITS parameters such ‘PS’, radius of curve, tunnel range and visibility etc.

**Results and Discussion**

The conformal symbologies like airport, runway and HITS are extensively evaluated on ESVS flight simulator under different visibility conditions (e.g. day/night) during approach and landing phase. The symbologies are also studied by playing back the real data acquired from ESVS ground experiments at HAL airport’s runway and taxiway on ESVS simulator.

**Playback of EVS Experimental Data**

EVS Ground experiments were conducted on HAL runway/taxiway just before/after sunset and just after sunrise. The test vehicle with experimental setup was driven at around 20 KMPH speed on the runway from one end to the other end and return on taxiway in the same speed. During the experimental run image/video output was captured from both the IR (Max-Viz EVS 600 unit [26]) and EO cameras and recorded on the rugged laptop in time sync with vehicle position and attitude/heading data captured from INS (Ardu Pilot Mega (APM) 2.5 [27]) and GPS units. The recorded data were played back on ESVS flight simulator to carry out the research and development on i) enhanced and synthetic vision system, ii) HUD symbology development specific for EVS/SVS and iii) pilot-in-loop evaluation for human factor studies. Fig.8 (a) and Fig.8(b) show the G450 HUD symbology pages for the real data with EVS OFF and ON respectively. It can be seen from these figures that certain symbologies like HSI, airspeed, altitude dials are not available (i.e. de-cluttered) when EVS is ON to provide better sensor view of external scene to the pilot.

**Conformal Airport/Runway Symbology**

Figure 9(a) and (b) show the conformal airport and runway symbologies during curved approach and landing phase of flight. It can be seen from Fig.9(a) that both airport and runway symbologies are present when aircraft altitude is between 400 to 350 feet AGL. Below 350 feet only runway symbology is present as shown in Fig.9(b).

**Study on Highway-In-The-Sky (HITS)**

Figure 10 shows different HITS types such as (a) U shaped - three sides connected with top open, (b) Rectangle - all four side connected, (c) Pathway - rectangle with path at bottom portion and (d) Box shaped - rectangle with path at both top and bottom portions. The selection of HITS types can be part of human factor study to zero on specific type based on qualitative analysis and feedback given from experienced pilots flown the aircraft on ESVS simulator for different phases of flight especially approach (straight / curved) and landing.

An experiment was carried out on ESVS flight simulator to showcase the importance of HITS as an aid to pilot for approach and landing during Degraded Visual Environment (DVE). Total of 12 flight experiments were conducted during 12 Noon and at 7 PM with/without HITS combinations for curved approach, landing and touchdown of aircraft on VOBG 09 runway of HAL airport. In night the runway lights were kept OFF but airport and runway symbologies were made available for all the 12 experiments. The HITS is of total length of 6 Km with initial 2 Km for curved approach followed by 4 Km for final straight approach and landing. The glide slope of HITS is kept at 3 degree with its size same as width of VOBG 09 runway i.e. approx. 180 feet.

Figure 11 shows plots for: (a) latitude vs longitude, (b) longitude vs altitude (MSL) for entire phase of flight, (c) longitude vs altitude (MSL) for final touchdown phase and (d) longitude vs heading. It is concluded flying with HITS
ON brings following advantages as compared to flying with HITS OFF:

- Increased situational awareness
- Reduced workload
- Consistent following of pre allocated curved and straight path
- Steady descent for approach and landing
- Increased probability of accurate touchdown point

**Concluding Remarks**

The paper provides detail description of work done at CSIR-NAL towards generic and EVS specific HUD symbology development and its integration to ESVS fixed base flight simulator. Some of the advanced symbologies such as conformal airport, runway and HITS are developed on the simulator. The developments of these symbologies are mainly based on Gulfstream G450 HUD standard. The usefulness of HITS in case of Degraded Visual Environment (DVE) is demonstrated using analysis done on data obtained from experiments conducted on flight simulator.

**References**


Fig.1 CSIR-NAL ESVS simulator Views [18]
Fig. 2 Generic HUD Symbology Page (a) of Boeing 737-832, (b) for ESVS Simulator

Fig. 3 Generic HUD Symbology Overlay on ESVS Flight Simulator Display

Fig. 4 New HUD Symbology Page (a) of Gulfstream G450 [19], (b) Similar to G450 for ESVS Simulator

Fig. 5 Real World Graphical Representation for Runway Symbology Creation
Fig. 6 Real World Graphical Representation for Straight HITS Symbology Creation

Fig. 7 HUD Control Panel

Fig. 8 ESVS Simulator in Playback Mode (a) EVS Off, (b) EVS On
Fig. 9 Conformal Airport and Runway During Approach and Landing

Fig. 10 HITS Types (a) U Shaped, (b) Rectangular (c) pathway, (d) Box Shaped
Fig. 11 Aircraft’s Plot (a) Latitude Vs Longitude, (b) Longitude Vs Altitude, (c) Latitude Vs Longitude at Touchdown and (d) Longitude Vs Heading