Integrated Flight Deck Testbed with Next Generation Visual Decision Support Tools

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***Abstract*— This paper presents of novel visual flight deck decision support tools and interfaces utilizing next generation synthetic vision and augmented reality based visualization technologies in order to meet the requirements of the future flight operations defined in NextGen and SESAR 2020+ visions. These avionics are envisioned to aid pilots for conducting their new in-flight tasks such as; collaborative tactical planning with intent negotiation/sharing; fully understanding/analyzing/interpreting solution with their alternatives and proposing modification on the solution subject to negotiation; and aware of required response, execute it or allow collision avoidance module to perform its automated response. Visual Decision Support Tools allow the flight crew to interact with new autonomous systems and provide with visual understanding on the evolving flight operation by fusing all tactical level data and visualizing them. In this paper, two groups of display structure have been proposed. A split head- down Synthetic Vision screen pair aims to support the pilots in managing both low level and high-level tactical tasks with fully understanding the situation in 4D. Synthetic Vision Display (SVD) side provides the pilots synthetic vision and also incorporates required additional guidance and limited operational information. 4D Operational Display (4DOD) provides higher-level operational information giving building enhanced understanding on the states of the operation and results of any modification on processing flight intent. Haptic interfaces allow the flight crew to change demonstrated detail levels in both 2D+time and 3D+time. The other display, which is Head-Up-Display (HUD), provides pilot to efficiently operate flight operation by eliminating the need of looking to head-down screen; and aims to present all essential flight information in the pilot's forward field through augmented reality implementations. For hardware integration and experimental purposes, an integrated testbed including full replica B737-800 Flight Deck Testbed and ATM Testbed has been modified as enabling operational tests subject to human factor validations.**

Keywords-Flight Deck Automation, Decision Support Tools, Next Generation Flight Displays.

I. INTRODUCTION

A paradigm shift from a purely centralized tactical intervention model towards a more efficient strategic planning and more proactive tactical operations is the key concept in both NextGen and SESAR 2020+ visions [1], [2]. Implementing of these concepts will significantly change roles and responsibilities in ATM system by considering best decision place, best decision time and best decision player. For example, controllers will have high-level tactical role to manage the traffic flow, and no longer intervene in the individual trajectories. It means pilots will be more active during the flight in order to monitor the environment, analyze the options and generate a separation maneuver if it is needed. This transformation will not only redefine existing roles of flight crew but also create additional responsibilities inherently affect the human performance requirements. Therefore, future flight deck will require new avionics, operational procedures with adaptive algorithms, automation systems with advanced decision sup- port and human-machine interaction tools enabling the pilot to handle this operation.

Figure 1. B737–800 flight deck platform with experimental visual decision support tools

Monitoring the environment and analyzing the provided solution with their alternatives, in both space and time, within various constraints, is a complex task for the pilots especially under high-level stress. The crew cannot be expected to perform such a complex task without some new form of automation and decision support tools. However, inappropriate levels of automation, for instance, high levels of automation can create a case in which the pilot no longer actively processes information due to over-trust in the system. Such a case effectively diminishes the pilot's ability to recover from failure [3]. When the pilot perceives the automation to be unreliable and gives excessive attention to monitor the sys- tem, situational awareness of the pilot is diminished with a high workload and result in a phenomenon called "attention

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tunneling" [4]. In a transparent system, where the underlying information behind the automation can be fully accessible, the pilot may be led to attend to too much and too low level system information, resulting in high workload and diminished situational awareness [5]. By considering these three cases, an expectation from a good decision support system is that it should provide transparency at a manageable workload level and allows the pilot to be in-the-loop in a cooperative manner [6]. Conflict resolutions experiments are conducted in [7] support this proposition.

Over the last 50 years, systems and instruments on flight decks are getting more automated, and new design philosophies are emerging with crew alerting and situational visualization systems to support the flight crew in monitoring dynamical changes in the environment. These design philosophies and technological improvements are envisioned to provide for improved safety and reduced workload. New functionalities will be integrated in future cockpits such as en-route 4D trajectory implementations; low visibility operations or new data-link implementations (e.g. collaborative trajectory management) are expected to meet future operational requirements. For instance, System Wide Information Management (SWIM) implementations allow the pilot to obtain almost real-time information about the flight operation as to enable decision making for evolving situations. The integration of these new applications on current flight decks will saturate the flight crew with a huge amount of information and interaction loads. Therefore, new interfaces and situational displays should emerge as enabling technologies in the future flight decks. The FAA PARC/CAST Flight Deck Automation Report [8] also emphasizes that the new interfaces should be more understandable from the flight crew perspective and consider to human centered design principles. Through the similar considerations, the ODICIS project [9] performs such studies to develop new cockpit design with a single large, curved, avionic display with tactile interfaces. As a tactical support system, NASA recently conducted a preliminary evaluation of a viable technology to support the Enhanced Vision Operation (EVO) concept for approach and landing operations [10].

In this paper, the authors present novel visual decision support tools and interfaces incorporating next generation synthetic vision and augmented reality based visualization in order to support the flight crew. The presented head-down Synthetic Vision screen pair enables pilots to manage both advanced low level and high-level tactical tasks with fully understanding the situation in 4D. Synthetic Vision Display (SVD) side provides the pilots synthetic vision and also incorporates required additional guidance and limited operational information. 4D Operational Display (4DOD) side aims to present higher level operational information allows understanding the states of the operation and results of any modification on processing flight intent. The interface allows pilots to change demonstrated detail levels in both 2D+time and 3D+time. The other display, which is Head-Up-Display (HUD), provides pilot to efficiently operate flight operation by eliminating the need of continually transition from head-down to head-up; and aims to present all essential flight information in the pilot's forward field through augmented reality implementations. Even in low-visibility operations (e.g. due to fog, clouds, unlighted landing etc.), pilots can easily manage the flight by ensuring following the "visual tunnels" appear in the head up display. The 3D "tunnel-in-the-sky" concept for primary flight display (with synthetic flight map) first introduced in [11]. The paper aims to cover functional structure of these tools considering the future tactical needs of the pilot, and hardware integration into the cockpit by leaving human factor validation issues to the future works.

The proposed visual decision support tools are envisioned to significantly increase situational awareness (SA) of the pilots during the flight operations. Situation awareness (SA) refers to the operator's understanding of the relevant environment state and the operator's ability to anticipate future changes and developments in that environment [12]. Specifically, there are three levels of situational awareness constructed by humans. These levels are perception, comprehension and projection [13]. Progression of these layers, the level of Automation and the extension of SA does not indeed exhibit a simple 1-1 relation. For example, inappropriate levels of the automation can impact SA with results such as automation complacency, automation mistrust, increased workload, and automation transparency [7]. For example, high levels of automation can indeed create cases in which the pilot no longer actively processes information to maintain an awareness of the system state In other words; pilot falls out-of-the-loop due to over-trust in the system. Such fall-outs effectively diminish the pilots ability to recover from automation failure [14]. When the pilot perceives the automation to be unreliable and gives excessive attention to monitor the automation, SA can also be diminished with high workload and result in a phenomenon called attention tunneling [4]. In attention tunneling, all attention is drawn only to the primary task at hand. SA is also reduced while interacting with a decision support system, which requires extensive evaluation of alternatives and choices [15]. The additional workload associated with extensive evaluation and selection naturally reduces the resources available for maintaining SA. A system is transparent when the underlying information behind the automation can be accessible [16]. In a fully transparent system a pilot may be led to attend to too much and too low level system information, resulting in high workload and diminished SA [6].

Figure 2. Airspace Model and ATM Testbed for in-operation experiments

The rest of the paper is organized as follows: Section II introduces integrated testbed system with Flight Deck Testbed and ATM Testbed modules, and explains functionalities of them. Section III gives details about synthetic vision screens. Head-Up-Display module and their augmented reality implementations are given in Section IV.

II. Integrated Testbed: Flight Deck Simulator and ATM Testbed

The integrated system including a B737-800 flight deck testbed and an ATM testbed is envisioned to validate innovative add-on avionics and features come into the flight deck automation systems in order to meet the requirements of the future flight operations. The given flight deck structure uses two different autonomy levels and handles switching these autonomy level modes considering the required response time. These two process cycles at different autonomy levels are represented with Collaborative Mid-term Trajectory Planning and Short Term Collision Avoidance modules where both are involving different tools, procedures and algorithms. The visual Decision Support Systems, allow the flight crew to efficiently monitor the processes, and interact with them at a manageable level. Through these objectives, two groups of displays, head-down Synthetic Vision Displays (including separated Synthetic Vision Screen and 4D Operational Screen) and Head-up-Display (HUD) are integrated into the flight deck to support the pilots and significantly enhance their situational awareness of the pilot. Figure 3 demonstrates whole integrated structure and its add-on modules.

Airspace Model and ATM Testbed involves air traffic management related simulation tools such as: Traffic and Weather Generator, ATC displays and Automated ATC Models. The testbed allows simulating ALLFT+ based historical traffic data set or any custom scenario in the same form. The Traffic and Weather Generator incorporates airport and airspace capacity information from the historical Demand Data Repository (DDR) data set and operational context information comes from the Aeronautical Information Publication (AIP) in order to create complete airspace picture. Similarly, customized scenarios or historical weather effects can be regenerated with the simplified version of the METAR data. The testbed allows to perform both traditional air traffic control operations via ATC displays and voice communication, and fully automated or aided traffic control operations through the hybrid Automated ATC Models which is ongoing research. The software architecture of the entire integrated system with

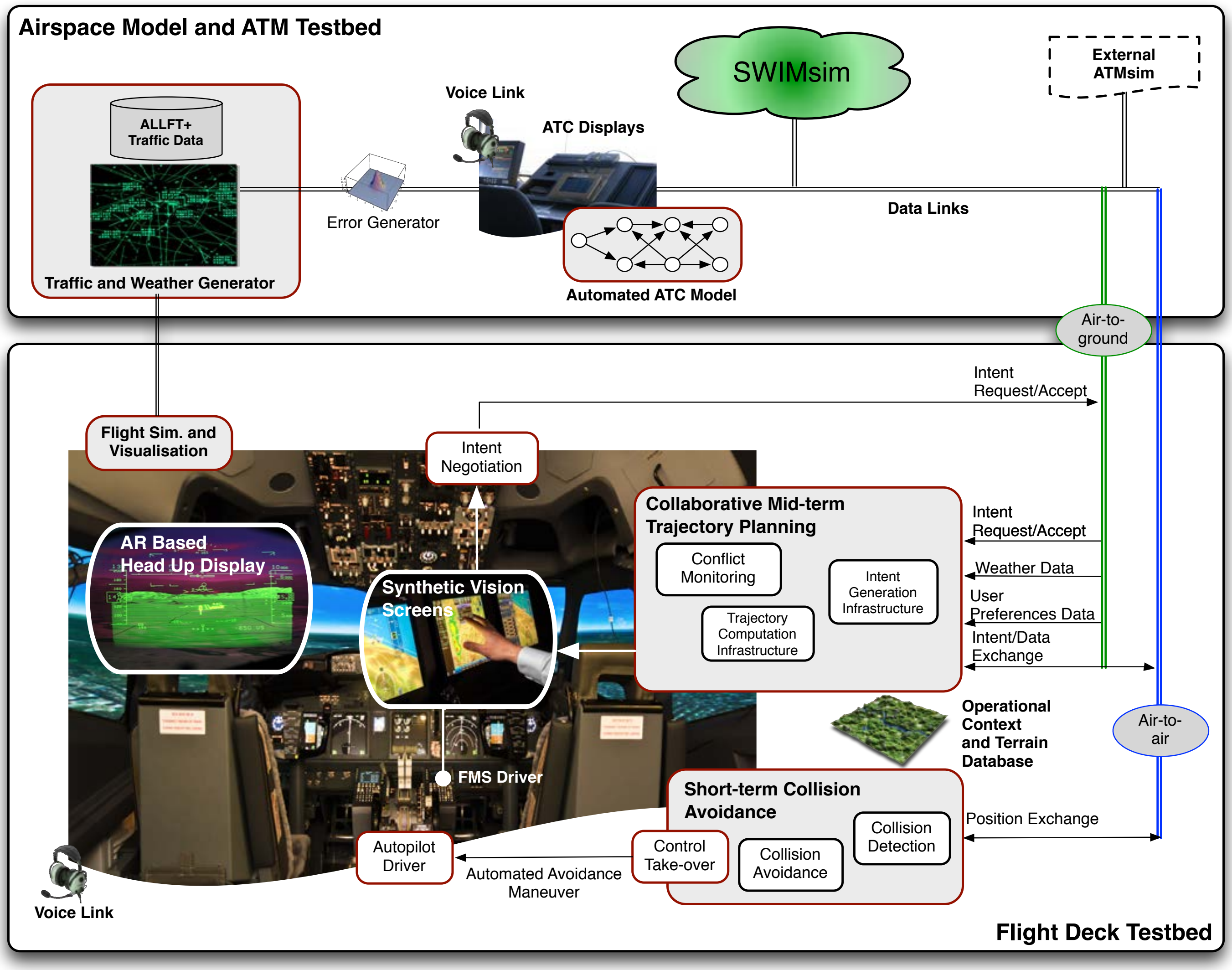

Figure 3. Architecture of the integrated next generation flight deck system with novel add-on modules

their physical links is also given for further understanding in Figure 4.

In the nominal tactical flight operations, it is expected that the pilot cooperates with the ground systems through a data link, and uses decision support and automated tools. In this operation mode, the envisioned system decision support tools incorporates all tactical level information (i.e. weather data, intent data, user preferences data and traffic data) obtained from both on-board sensing (including air-to-air data link) and air-to-ground data exchange. The pilots can also manage Intent Negotiation process via visual Decision Support Tools initiated by either the flight deck or the ground system. The ground based intent negotiation request may emerge in some circumstances such as drastic weather change, change in operational constraints, conflict detection, emergency situations or detection of an aircraft does not conform to the anticipated behavior. During the intent negotiation, pilot can monitor the requested trajectory; modify the solution; or request re-planning through the 4D Operational Screen. Similarly, the flight deck may also create an intent negotiation cycle and pilot can request an acceptance on the modified intent sequence (e.g. direct route to a fix or efficient flight path around hazardous weather). Trajectory Computation Infrastructure (TCI) and Intent Generation Infrastructure (IGI), automatically validates the feasibility of the given intent data, and Conflict Monitoring block checks potential conflicts between the predicted trajectories in the traffic.

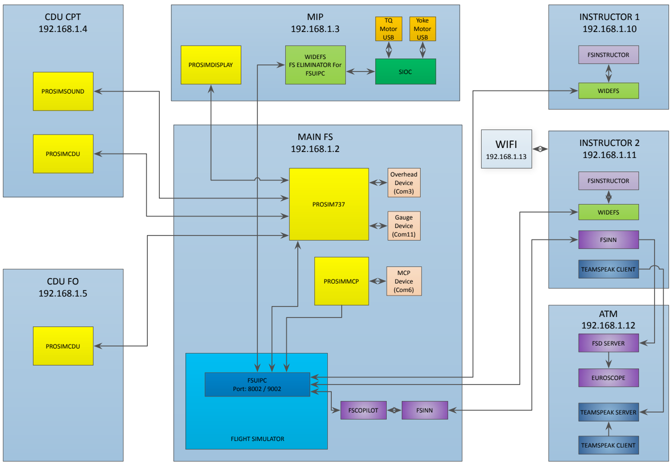

Figure 4. Software Architecture of the integrated System

In both SESAR and NextGen visions, multi-layer structure will also continue to play a major role in ensuring safety for flight operations. Through new concepts that redefine roles of the aircrew, the flight decks must also be equipped with multi-layer safety automation where at least one must work independently from the ground or air [2]. This structure will reduce dependence to the ground and isolate the system from common mode failures such that single data error would invalidate the entire system. By considering these facts, non-intent based collision avoidance (i.e. Airborne Collision Avoidance System – ACAS), which does not require any knowledge on the aircraft intent, will still be crucial when the collaborative separation assurance process fails. The limitation of this method is that the prediction error tends to grow quadratically with time; therefore, these types of tools will still remain in the domain of the immediate to short-term collision avoidance.

The Short-Term Collision Avoidance module (seen in the Figure 3) is an isolated system from the intent data exchange and works independently. Thus, it provides redundancy in the flight deck system. This module only uses position data received from the aircraft in the surrounding traffic obtained via air-to-air data link. The Collision Detection (CD) block persistently monitors occurrence probabilities of potential collisions with other aircraft and terrain obstacles for bounded local region. The CD algorithm uses worst case approach and takes into account both uncertainties in position measurement and pilot actions (e.g. blunders of pilots). Whenever the immediate threat(s) is/are detected (i.e. immediate response is required or late response is detected), the autonomous system takes over the flight control to solve the issue with required 3D avoidance maneuvers which is generated by Collision Avoidance block. The worst-case approaches could produce false alarms often due to their algorithmic natures. To address this issue, the Short Term Collision Avoidance module delays taking-control action until it decides that ”humanly response” may not be achieved within the required response time. Then it switches the system into the higher autonomy level (Parasuraman’s autonomy level 6 [14]) where the avoidance maneuver is performed autonomously. The head-up-display (HUD), Synthetic Vision Display (SVD) and synthetic 4D Operational Display (4DOD) provide the pilot with an appropriate warning about the collision with visual timer countdown for ”pessimistic required response time” before the possible automated avoidance maneuver execution.

Figure 5. Synthetic Vision Display (SVD) and 4D Operational Display (4DOD) screens in the flight deck

III. NEXT GENERATION SYNTHETIC VISION SCREENS

Presented synthetic vision display includes two separate screen; which one for synthetic vision flight and the other for operational management. These screens are envisioned to provide the pilot with full understanding on the evolving flight operation and effects of any intervention. Even in automated nominal flight operations, it is important to keep pilot in-the-loop at a suitable level where the flight crew should recover the flight control from an automation failure. Therefore, on the track of the negotiated trajectory, the flight crew is continuously supported with information about the current state and objectives of the operation (e.g. intent trajectory, RTA objectives, delays, ascending/descending slope and glide slope) and the environment (e.g. surrounding traffic, potential loss of separation, proximity to the terrain). During the intent negotiation process, one synthetic vision screen demonstrates processing flight intent to the pilot and enables required interaction to accept, modify or request re-planning – which are the functions of the collaborative decision making. Through the 4D Operational Display (4DOD), the flight crew can understand the states of the operation and results of any modification on processing flight intent. Whenever the negotiation has been concluded with a success, the negotiated intent can be executed autonomously via FMS (as seen in the Figure 3), or pilot can choose to follow the trajectory manually with guidance of the tunnel-in-the-sky visualization on Synthetic Vision Display (SVD) and HUD.

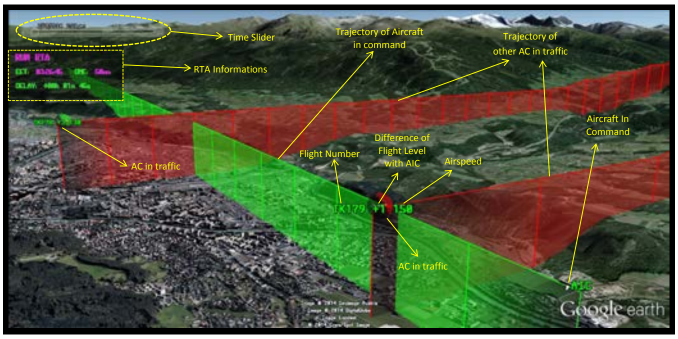

Figure 6. Definitions of the symbology in 4D Operational Dis- play (4DOD)

The 4D Operational Display (4DOD) provides the pilots with high-level information about the whole flight operation and trajectory. Through the 4DOD, the pilot can monitor the flight trajectories (negotiated or processing) of the ownship and surrounding aircraft in four dimensions (including time); environmental effects such as weather, airspace boundaries, terrain obstacles; status of the flight involving required time of arrival objectives, delays, estimated capacity of the airspace; and safety related warnings such as conflict probability predictions. The display gives 3D visualization ability to the pilot as supervisor, and he/she can easily change supervisor look-angle and look-position using haptic interfaces. For experimental purposes, two types of haptic interfaces have been included; an external trackpad and 3D navigator mouse; which both provides better 3D navigation on the operational map overlay. The flight crew can also monitor future projection of the trajectories using the time slider button on the screen, or initiating fast time simulation of the flight. This is where the third dimension (time) perception is provided to the user. Specifically, the flight crew a) can see the flight trajectories of the ownship and surrounding aircraft in 2D map overlay, in a traditional way; b) may choose to go into details using 3D navigation (e.g. around the potential conflict); c) are able to go forward on time to see the projected future; and d) even may chose to perform fast time simulation for entire or specific part of the flight. The Figure 6 gives definition for main symbols in 4DOD.

The 4DOD is envisioned to increase not only ”transient situational awareness” but also enhance fully understanding the entire flight operation. In the context of the 4D trajectory based operation, it has to be handled Required Time Arrival (RTA) objectives and neutralized delays in the air in order to obtain both optimal flight regimes and efficient use of the airspace. The 4DOD also demonstrates these types of information to the flight crew. In the collaborative negotiation with the ground segments, the flight crew can evaluate these objectives and performance scores (both in time and fuel efficiency) of the processing trajectories and their alternatives result in custom modifications. Through this screen, the flight crew can accept the trajectory on which ATC requested negotiation; or can modify existing trajectory by adding or removing fixes and then puts it on the ATC for acceptance. This communication is handled via air-to-ground data link and formal intent languages, which their details can be seen in [17].

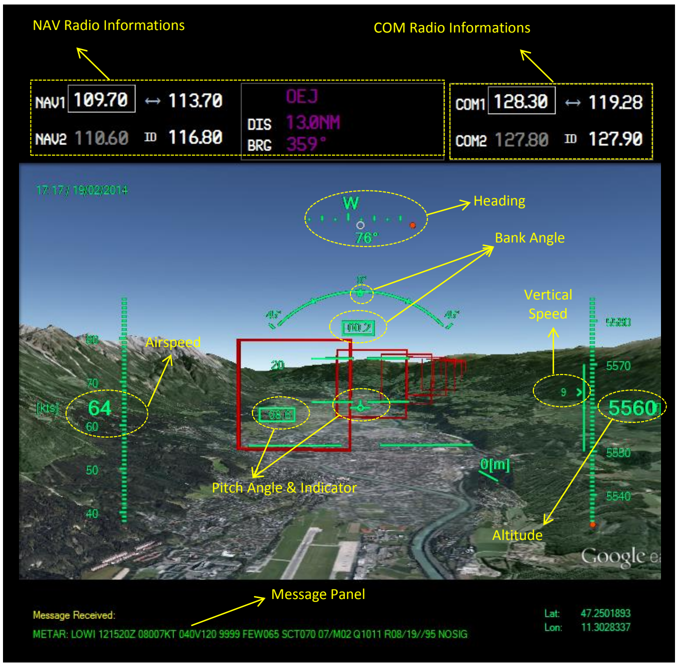

Figure 7. Definitions of the symbology in Synthetic Vision Display (SVD)

The Synthetic Vision Display (SVD) gives the pilots synthetic vision and also incorporates additional guidance and operational information. In addition to standard motion related information such as airspeed, vertical speed, altitude and inertial angles; the envisioned screen also demonstrates planned/negotiated trajectory through the ”tunnel-in-the-sky” demonstration. The pilot can operate the entire flight without having to look up in case of the low visibility flight operations. Tunnel visualization also gives a continuous perception across the whole trajectory from surface operation to landing with glide slope. In addition to synthetic terrain visualization, It also enables to visualize the weather through the METAR data; and other soft obstacles such as closed airspace (segregated for other users), airspace constrained altitude levels and high loaded traffic volumes. The definitions of the symbology in the Synthetic Vision Display (SVD) have been given in Figure 7.

Figure 8. Transparent Screen overlay for HUD augmented reality implementations

IV. AUGMENTED REALITY BASED HEAD UP DISPLAY

The proposed structure of the Head-Up-Display (HUD) seen in Figure 8 aims to present all essential flight information in the pilot's forward field of view eliminating the need of continually transition from head-down instruments to head-up. It is envisioned that HUD provides "informational summary" about the transient status of the flight including near-term objectives. In addition to presenting flight path marking, flight path acceleration, speed and altitude meters, glide-slope angle, and runway aim point demonstrations, similarly as in SVD, negotiated continuous trajectory demonstration is provided through "tunnel-in-the-sky".

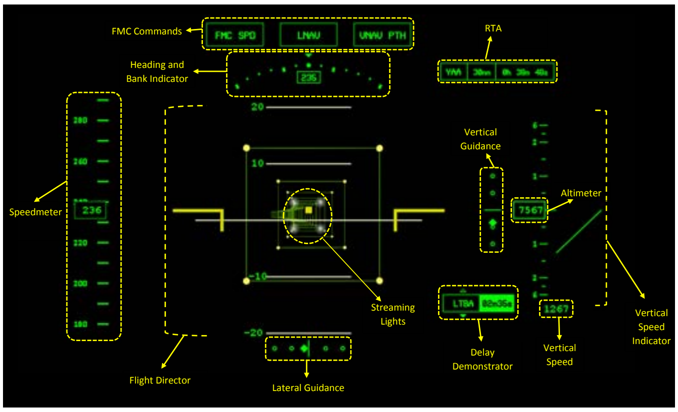

Figure 9. Definitions of the symbology in Head-Up-Display (HUD)

The demonstration of "tunnel-in-the-sky" is obtained through a combination of all tactical level information such as negotiated trajectory, airport location, glide-slope angle, take-off/landing runway with clearance, all come from Flight Management System (FMS). The negotiated trajectory information at all phases (including land operations, take-off en-route and landing) is transformed into virtual tunnel visualization in order to aid the pilot. It is aimed that pilot can operate the entire flight by following the demonstrated virtual tunnel ensuring safety. In addition to path curvature and torsion mostly associated with ascent/descent and turn actions of the aircraft, continuously streaming lights at the corner of the tunnel frames provides the pilot effective flight direction perception. The brief descriptions of the nominal HUD symbology can bee seen in Figure 9.

The transparent head-up-display screen also enables to demonstrate text based pop-up message boxes to give high-level status information. Required Time Arrival (RTA), which is one of the important concepts of the 4D Trajectory management, is demonstrated with the related information such as; next destination fix name, remaining distance and negotiated RTA. In addition to this, another colored message box (i.e. green for positive and red for negative values) shows predicted delay time for the next fixes. It also enables to demonstrate pop-up messages for the check lists according to related situations (e.g. engine start-up, emergency and required traffic and conflict avoidance messages etc.)

V. CONCLUSION

In this paper, a multi-mode flight deck testbed structure with add-on visual decision support tools is presented. The paper introduces an innovative visual flight deck decision support avionics to meet the requirements of the future flight operations. Presented synthetic vision display includes two separate screen; which one for synthetic vision flight and the other for operational management. These screens are envisioned to provide the pilot with full understanding on the evolving flight operation and effects of any intervention. The 4DOD is envisioned to increase not only "transient situational awareness" but also enhance fully understanding the entire flight operation. Through this screen, the flight crew can manage flight intent negotiation by adding or removing fixes and then puts it on the ATC for acceptance. The Synthetic Vision Display (SVD) gives the pilots synthetic vision and also incorporates additional guidance and operational information. The demonstration of "tunnel-in-the-sky" is obtained through a combination of all tactical level information such as negotiated trajectory, airport location, glide-slope angle, take-off/landing runway with clearance, all come from Flight Management System (FMS). Head-Up-Display (HUD), aims providing pilot to efficiently operate flight operation by eliminating the need of continually transition from head-down to head-up; and aims to present all essential flight information in the pilot's forward field through augmented reality implementations. For hardware integration and experimental purposes, an integrated full replica B737-800 Flight Deck Testbed and ATM Testbed has been customized enabling operational tests and validations of these new tools.

As the future work, this research aims to improve the introduced algorithms that are amenable to the rigorous certification process implemented and executed by the aviation agencies in the U.S. and in Europe. Another near future objective is to build a test and validation platform on the integrated Flight Deck and ATM simulation system (Figure 1) of ITU in order to perform human factor related tests to these tools for further improvements.

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