Abstract

Highway-In-The-Sky (HITS) trajectories and symbology were generated for GPS WAAS approach procedures developed for the NASA Small Aircraft Transportation System (SATS) demonstration flights. Aircraft position and attitude data collected using an integrated IMU/GPS were used to render synthetic ground imagery and Highway-In-The-Sky (HITS) symbology using the X-Plane program in real-time. Flight testing showed that synthetic imagery using actual aircraft data can be used for aircraft guidance and for situational awareness, as well as for post flight playback and analysis. The availability of high quality scenery and elevation data as well as the existence of a software development kit allowed use of the X-Plane flight simulation program as a high performance and inexpensive rendering platform. This proved the feasibility of building an inexpensive synthetic vision system to generate synthetic imagery on a low cost head up display (HUD) designed for general aviation type aircraft.

Introduction

In earlier work and as part of the NASA Small Aircraft Transportation System (SATS) project\(^1\), MADL and the Maryland Mid-Atlantic SATS Laboratory have been developing enhanced vision, synthetic vision and combined vision systems for improved aircraft operation in low visibility and for achieving lower landing minimums. An enhanced vision system (EVS) uses imagery from a camera operating in a suitable spectral band (infrared or ultraviolet) which is then displayed on a cockpit display (usually a HUD) to facilitate observation of the scene ahead of the aircraft. The advantage of an EVS is that it can show 'live' what actually lies ahead of the aircraft. The disadvantage is that in some environmental conditions it can not provide enough contrast or resolution to see the scene adequately. Synthetic vision systems (SVS) use knowledge of current aircraft position and attitude to generate an artificial scene based on previously stored terrain and obstruction data. The advantage of an SVS is that it can provide virtually unlimited visibility. However, an SVS can not be used to detect dynamically changing scenery, such as other aircraft or ground vehicles (e.g. runway incursions) or even fixed obstructions that are missing from the terrain / obstruction data used.

A combined vision system (CVS) uses both enhanced and synthetic imagery to reduce the disadvantages inherent to an EVS or SVS system alone. Any of these types of vision systems can incorporate additional symbology, such as a Highway-In-The-Sky (HITS) to display the aircraft state in an intuitive graphical form that can be easily perceived by even a rather inexperienced pilot. While a pilot with experience may be comfortable flying raw ILS or flight director displays, a HITS display provides instant situational awareness and serves as a pictorial 'reality check'.

Development of algorithms for a CVS system is centered on being able to fuse data from a nose mounted EVS camera and synthetically generated imagery. Previously separate development work on EVS and on multi camera video fusion algorithms had to be integrated. Thus for developing a CVS system it was necessary to have a source of synthetic ground imagery that would be fused with actual video imagery from the EVS camera in real time.

There are commercially available synthetic terrain elevation model display systems\(^2\). However, the requirements of the current research program


were to have full control of the SVS and also to be able to interact with it in a tightly coupled way. Thus use of a dedicated SVS system was ruled out. In an earlier program at MADL in the 1990’s an in-house developed graphical scenery rendering engine had been developed, and it was projected that a similar effort would be needed as part of the CVS development.

In another past project involving the design of a new unmanned air vehicle the X-Plane flight simulation program\(^3\) had been used as part of the airframe development effort. This program combines an aircraft flight dynamics simulator as well as a scenery generator which includes a global terrain elevation and land use database. The capability of the program for rendering realistic ground scenery at high frame rates was a factor in using it for the SATS HITS effort. But it was the availability of a software development kit\(^4\) which allowed access to the rendering engine that made X-Plane a good choice for use as a tool in the development of algorithms. The ability to easily draw graphic symbology representing HITS and other symbology was also a criterion in this choice.

### HITS Trajectory Generation

SATS flight testing was performed\(^5\) and demonstration flights were flown at Danville Regional Airport (KDAN) in June 2005 with the participation of aircraft from NASA, FAA and the SATS laboratories\(^6\). During the demonstration the airport was closed to non-SATS traffic and special approach procedures developed for SATS were used. A Self Controlled Airspace (SCA) is defined for the area enclosed by a 15 NM radius around the airport and operation in the SCA is based on specific SATS rules.

Figure 1 shows the SATS GPS WAAS approach procedures for RWY 20 at KDAN\(^7\). There are four administrative hold points outside the SCA (JUBOD, ZUMUR, WODMO, REDNE), holding points at the initial approach fixes (JEDOR, CUNAV), an intermediate fix (WIPIB), and a final approach fix (CUGUR). The four administrative (transition) hold fixes were designed for use in the Danville flight demonstration to coordinate entry of six aircraft into the SCA.

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trajectory to 'round' this corner. Adding to the complexity is the fact that an aircraft is transitioning from level flight to a descent at the same time this 90 degree turn is being made. The HITS locations around this corner have to be calculated as a trajectory in three-dimensional space that has to meet at least a turn radius criterion.

The algorithm for calculating the HITS trajectory uses vector algebra to generate the path around the corner at the intermediate fix. Given the three points in space P1, P2, and P3 corresponding to the initial approach fix, the intermediate fix and the final fix respectively, vectors L1 and L2 are calculated as the trajectories at the beginning and end of the maneuver. Then the tangent points PA, PB and center position of the arc PC are calculated. Finally, individual HITS points along the arc are calculated. The geometric construction and associated equations are shown in Figure 2.\(^8\)

\[ L_1 = \frac{P_2 - P_1}{|P_2 - P_1|}, \quad L_2 = \frac{P_3 - P_2}{|P_3 - P_2|} \]
\[ a = \frac{1}{2} \cos^{-1}\left(\frac{1}{L_1 \cdot L_2}\right) \]
\[ e = \frac{R}{\tan a} \]
\[ P_A = P_1 - aL_1 \]
\[ P_B = P_2 + eL_2 \]
\[ P_0 = \frac{P_A + P_B}{2} \]
\[ L_c = \frac{P_2 - P_1}{|P_2 - P_1|} \]
\[ P_c = P_0 + \sqrt{R^2 + e^2} \hat{u}_c \]

Figure 2. Tangent Path for Radius \( R \) and Waypoints \( P_1, P_2, \) and \( P_3. \)

\(^8\) All calculations are done in three dimensions, but are shown in 2-D for clarity.

A Matlab program called hitsmaker.m was written to calculate the trajectory and locations of the HITS boxes based on waypoint latitude, longitude and altitudes. Figure 3 shows a plot that was output by hitsmaker.m.

**Scene Rendering**

The software development kit provides hooks to various phases of the X-Plane simulation cycle. It also allows a plug-in to override the flight dynamics model, so that a plug-in can take full control of the simulated aircraft. Thus, if the aircraft position and attitude are known, these can be used to set the internal Latitude, Longitude, Altitude and orientation quaternion in the program. Then the terrain scenery as observed from the aircraft’s known position and attitude can be drawn. By setting the weather parameters in the simulation to high visibility daylight conditions an accurate image is obtained. Resolutions of 1024 x 768 at update rate of 30 frames per second were obtained using a COTS laptop computer.\(^9\)

After the external scenery is generated the HITS plug-in draws its own graphic symbology. The HITS symbology drawn consists of a runway outline, an approach path, a series of rectangular boxes along the approach, and a stacked ‘parking garage’ at holding fixes. In addition, the HITS plug-in draws ‘fences’ corresponding to FRZ and ADIZ restricted zones as well as flashing obstruction symbols rising up from the terrain to their appropriate altitude. Figures 4 and 5 show several screen captures with these elements.

When it was desired to display only the HITS symbology, with no terrain scenery, a 99000’ high overcast weather model at nighttime setting was used, thus eliminating any visible terrain features in the rendered scenery.

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\(^9\) X-Plane also has the capability to render objects such as buildings, roads, power lines. But these options (which add significantly to processor load) were turned off, since the HITS plug-in has the ability to draw obstruction symbology.
Figure 3. Plot Generated by hitsmaker.m for KDAN Approaches.

Figure 4. Scenery Rendered of Approach to KESN Runway 04.

Figure 5. Scenery Rendered of Turn to Final for KESN Runway 04.
Aircraft Interface
The system was flown on the MADL C-402 test aircraft (Figure 6), which has an F-16 GEC HUD, with Mi1-553 and Arinc 429 interfaces to a research mission computer, a Honeywell laser ring gyro, multiple GPS receivers, ADS-B data link, an air data computer, video downlink and Ethernet modem connectivity to a ground station. Subsequent flights with the HITS system on the C-402 were evaluated with the Kollsman prototype low cost HUD.

To facilitate installation and testing outside the C-402 aircraft a self contained Inertial/GPS navigation system, a Systron C-Migits III (INS) was used. This was interfaced using a Moxa Netport, which allowed multiple computers to simultaneously access the INS over the Ethernet. Thus, while HITS symbology was being generated aboard the aircraft, the same data could be accessed in real time on the ground via the Ethernet datalink. At the ground station internal or external views were generated independent of the settings used aboard the aircraft.

Cockpit Displays
An 8” liquid crystal head down display was available in the cockpit for inside the cockpit viewing of the HITS graphics. The GEC HUD Electronics Unit in the C-402 creates stroke symbology that is generated by the laser gyro and the mission computer. In addition, both the GEC HUD and prototype Kollsman HUD have an RS-170 video input that is used to display EVS camera imagery. The scenery and symbology rendered by the HITS were converted to RS-170 video and were combined with EVS video using a video mixer and this signal was fed into the HUD raster video input. Thus, the HUD displayed information from three separate sources which were: stroke (artificial horizon, airspeed, altitude, velocity vector, etc.), EVS video, and HITS (scenery and graphics.) Figure 7 shows a photo of the Kollsman prototype low cost HUD display with a HITS approach overlaid with stroke information from mission computer. Photo is from ground looking up the approach and without an EVS video input.

Conclusions
It was shown that a powerful but low cost simulation program, X-Plane, could be used to interface with real flight hardware to generate real-time synthetically generated terrain scenery and Highway-In-The-Sky symbology, as well as symbology depicting FRZ’s, ADIZ’s, and obstructions, and that this could be displayed on a low cost HUD. This means that it is feasible with current technology to build a similar system at a low enough cost to make it available for general aviation use.
Figure 7. HITS Approach Displayed on Kollsman Prototype HUD.

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