Aerospace Cognitive Engineering Laboratory (ACELAB) Simulator for Electric Vertical Takeoff and Landing (eVTOL) Research and Development

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A new generation of aerospace innovators are looking for ways to quickly and efficiently transport people in a safe and environmentally friendly manner. In the not-too-distant future, passengers and goods are expected to routinely fly aboard a new breed of cleaner, smarter air vehicles. This represents a new and significant challenge to the Federal Aviation Agency (FAA) which is responsible for aircraft certification, pilot licensing, operating approval and airspace integration.

To help streamline this process, NASA has formulated its Advanced Air Mobility (AAM) project to provide research capabilities for development and evaluation of these new concepts and an environment where industry and regulators can work together to understand the requirements and work toward consensus standards for the new market.

This paper will describe the development of the Aerospace Cognitive Engineering Lab Rapid Automation Test (ACELeRATE) simulator. ACELeRATE is an adaptable fixed-base aircraft simulator focused on the investigation of the performance and interaction of pilots and increasingly automated aircraft systems. ACELeRATE can be re-configured to support various simulation environments. The simulator includes a simple reconfigurable cockpit placed within a 10-foot spherical dome with a cluster of real-time image generators, high-resolution displays and highly realistic scenery with the surrounding digital terrain and required cultural area details (e.g., hangars, runways, ramp areas, taxiways, test range apparatus, buildings with designated rooftop landing areas, and other man-made 3D structures).

This paper will also describe the various hardware and software tools employed in the ACELeRATE simulator, including engineering tools used by NASA for electric Vertical Takeoff and Landing (eVTOL) vehicle equations of motion, wind-model simulation in an urban environment, as well as the various modeling techniques and tools used to quickly generate highly realistic 3D terrain models for low level flight including urban terrain and obstacle depictions.

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I. Nomenclature

A/C	=	Aircraft
AAM	=	Advanced Air Mobility
ACELAB	=	Aerospace Cognitive Engineering Laboratory
ACELeRATE	=	Aerospace Cognitive Engineering Laboratory Rapid Automation Test Environment
AFRC	=	Armstrong Flight Research Center
CPU	=	Central Processing Unit
COTS	=	Commercial off-the-shelf
eCTOL	=	Electric Conventional Takeoff and Landing
DLL	=	Dynamic Linked Library
DVE	=	Degraded Visual Environment
eVTOL	=	Electric VTOL
FAA	=	Federal Aviation Administration
FDz	=	FlightDeckZ Software
GPU	=	Graphics Processing Unit
GS	=	Ground Speed
HMD	=	Helmet Mounted Display
HSI	=	Horizontal Situation Indication
HUD	=	Heads-Up Display
IG	=	Image Generator
MFD	=	Multi-function Display
NASA	=	National Aeronautics and Space Administration
PC	=	Personal Computer
PFD	=	Primary Flight Display
R&D	=	Research and Development
RVLT	=	Revolutionary Vertical Lift Technologies Project
SF	=	San Francisco
TB	=	Terabyte (i.e., 1000 Gigabytes)
UAM	=	Urban Air Mobility
VMS	=	Vertical Motion Simulator
VTOL	=	Vertical takeoff and landing
WWDB	=	World-wide database

II. Introduction

A familiar vision of the future depicts the common person jumping into their personal air mobility device at their home residence (their "flying car"), and heading off to work or some other nearby destination with grace, ease and little or minimal piloting skills (at least when compared to today's professional pilot that operates a helicopter, rotorcraft, or even a general aviation aircraft). The dream is for any individual to be able to easily navigate and fly throughout a complex environment while almost blindly and automatically avoiding other vehicles, buildings, power lines, towers, bridges, and the terrain beneath until it is time to safely swing into a hover at the destination, and then quickly "hover down" to a safe, comfortable, and environmentally friendly landing (i.e., very quiet engines, no obnoxious fumes, and so on).

Fig. 1 shows a concept rendering of such a fantastic world where advanced air mobility systems have been deployed (https://www.suasnews.com/2017/11/nasa-embraces-urban-air-mobility-uam-calls-market-study). This concept depicts a very busy air traffic environment where many airborne vehicles are maneuvering around the landing pad at the top of a parking garage in a typical downtown urban area. When one considers the safety aspects for each vehicle operating in this scene, it quickly raises safety questions and concerns. Fig. 1 also serves to remind us of how important it will be for the government and industry to work closely together to enable Urban Air Mobility (UAM) while keeping everyone in that future downtown area as well as all occupants on the airborne vehicles safe.

Fig. 1 A Futuristic Concept Drawing for AAM Operations in a Downtown Environment.

A significant challenge for the shorter range eVTOL vehicle operating in the UAM environment is the planned experience levels for the flight crew as anticipated by some operators; i.e., the skills specifically required to operate a future UAM air-taxi service. In some cases, this individual, the air-taxi driver, may be a person with limited previous flight experience since computer automation will be operating the smaller vehicle, perhaps a 4- or 6-person cabin including the pilot. The air-taxi driver will be there to help monitor the flight and coordinate with air traffic control as required.

Today's professional pilot normally has years of flight experience, specialized training, certification requirements, and hundreds or even thousands of hours of qualifying flight time before they are authorized to fly a commercial or military aircraft. Not necessarily so for the air-taxi concept; computer automation is expected to reduce the pilot skill, knowledge and expertise requirements. Even the air-traffic oversight role may become more highly automated due to the expected large number of aerial drones and larger AAM vehicles that may be operating within or near the same urban environment.

Flying a rotorcraft vehicle or any VTOL aircraft is today often complicated by the simple fact that the pilot cannot normally see exactly where the vehicle is going, especially during the final hover down maneuver to an intended landing point. Helicopters often have "chin-windows" down by their feet to aid the crew, but these don't always provide an unobstructed view of the landing point either. Further, it isn't clear if any planned air mobility vehicles will even have chin windows. It also remains unclear what sensors, displays, and visual aids (like nose or lookdown cameras) might be present on these initial flight test vehicles from industry partners.

While many initial AAM operations concepts call for highly trained pilots, as the UAM and AAM [1] technology matures there is an expected transition to reduced skill requirements, commonly referred to as Simplified Vehicle Operations (SVO), and eventually to few or no onboard piloting skills required. As such, NASA is working with the FAA, industry partners, and experienced test pilots to help determine minimum requirements necessary to conduct safe flight test operations to enable a safe transition from highly restrictive pilot requirements through the transition to SVO and beyond.

III. VTOL Simulation

Simulation has long been recognized as a key technology that has proven invaluable over the decades to help engineers and scientists throughout government and industry test new aviation or other advanced system designs and concepts long before the first hardware or software components are constructed. NASA heavily relies on the use of its simulators to achieve its assigned missions.

For eVTOL aircraft developmental testing, NASA and the FAA plan to use a variety of NASA simulators of varying fidelity including ACELeRATE for development and the Vertical Motion Simulator (VMS) for the highest fidelity platform. The VMS is the largest motion-based simulator in the world and has been used for extensive VTOL aircraft research as well as many different aerospace research projects, and for training U.S. Space Shuttle pilots in the past. The VMS is housed in a large 10-story tall building at NASA Ames (Fig. 2).

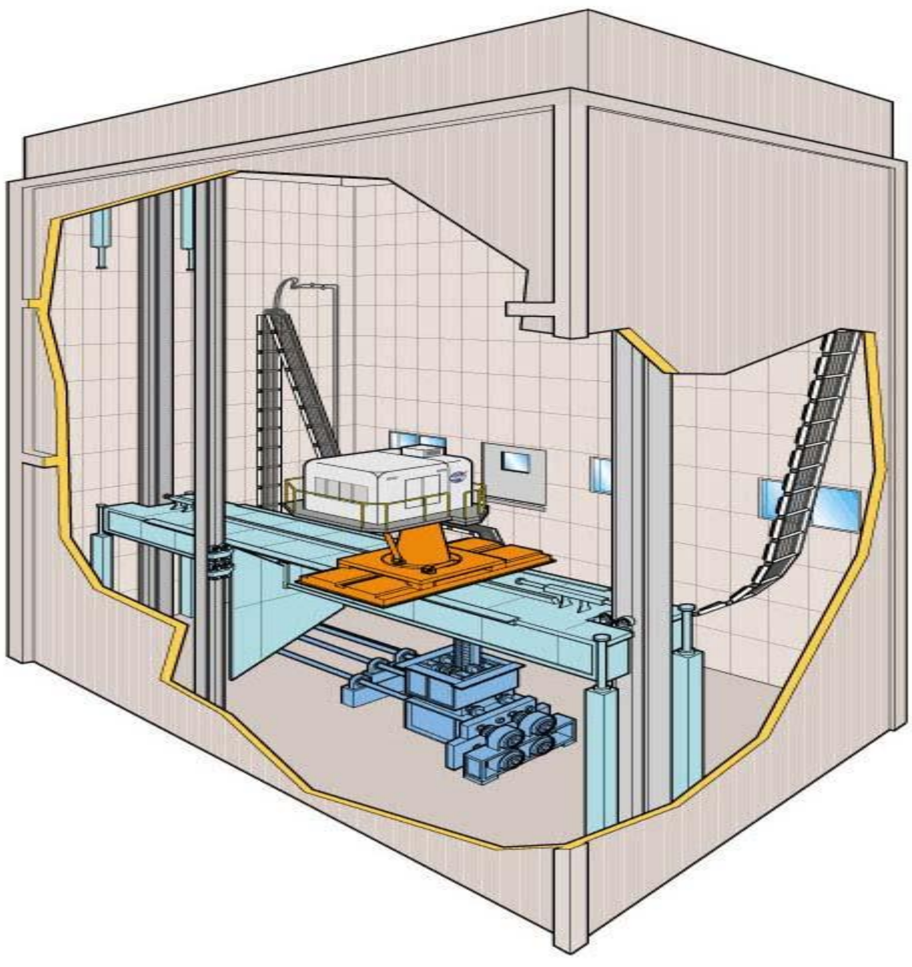

Fig. 2 Illustration / Cutaway Depicting the 10-Story Tall Building Housing the SIMLABS VMS Simulator.

IV. The ACELeRATE Simulator

The need for a spectrum of simulation capabilities to assess the performance of Distributed Electric Propulsion (DEP) VTOL aircraft led to the adaptation and development of existing simulation capabilities, including the creation of the ACELeRATE simulator for increasingly automated VTOL aircraft testing. These needs included development of a medium-fidelity fixed-base simulator for rapid development and test, and a need for compatibility with the high-fidelity research platform (e.g. the VMS) to enable a spectrum of research studies.

The Aerospace Cognitive Engineering Laboratory (ACELAB) has historically been used to study pilot-automation interaction research topics for fixed wing aircraft. A primary goal for this lab has been to help improve safety in the ever-increasing complexity of modern cockpits, and the ever-changing aviation technology. The development of the ACELeRATE simulation capability provides NASA scientists with a highly reconfigurable suite of hardware components and software tools that support scientific research and development for investigating challenges related to VTOL aircraft operations and the transition to Simplified Vehicle Operations and autonomous flight.

A. The FlightDeckZ Vehicle Simulation Environment

FlightDeckZ is a modular aircraft research environment, consisting of three major software components:

- FlightZ,
- DeckZ
- FMSZ

FlightZ implements the vehicle performance, guidance, control and autopilot functions. FlightZ can import aircraft models of different formats, and currently includes high fidelity models of small aircraft, fighter jet, helicopter, regional and large transport aircraft as well as eVTOL models developed as part of the NASA Revolutionary Vertical Lift Technologies (RVLT) project. The eVTOL vehicle currently in use for the studies described in this paper is a six (6) passenger, battery powered, electrically driven quadrotor concept vehicle weighing approximately 6480 lbs. as depicted below in Fig. 3.

Fig. 3 NASA Six Passenger Quadrotor Concept Vehicle [2].

DeckZ implements its own virtual cockpit controls and graphics displays for the FlightZ vehicle model. The DeckZ software generates these displays. These cockpit displays are available on the FDz host computer in addition to the eVTOL displays in the ACELeRATE simulator as described later in section H.

FMSZ implements a Flight Management System (FMS) capability that provides navigation and guidance targets to the FlightZ aircraft models. FMSZ includes automatic takeoff and landing capabilities and is highly modifiable.

B. Visual System

In late 2017, ACELeRATE was re-configured to include a new 10-foot tall spherical dome display surface with three, high resolution digital laser projectors mounted to the ceiling. The visual system provides a near eye-limited resolution display [3] at least for the observer standing or sitting at the design eye location of the visual system. An inexpensive, modular and reconfigurable cockpit enclosure was assembled and installed to support future air mobility experiments, such as for UAM as illustrated in Fig. 4.

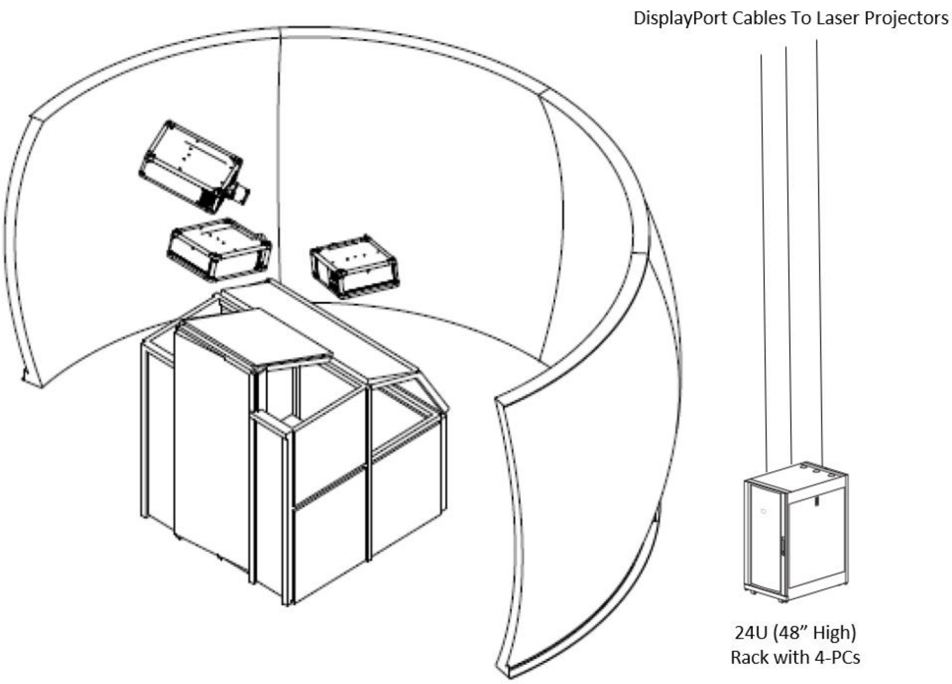

Fig. 4 ACELERATE Fixed Base Cockpit and Dome Visual System Concept Drawing.

The dome structure and projectors were acquired from RSI Visuals Systems. The dome itself is very lightweight but sturdy structure, secured to the floor, and provides a 200° wide x 45°-degree vertical field-of-view on a direct view display surface with a 10° degree overlap region between each adjacent projected image. Each laser projector renders 4096 x 2160 pixels with a 60-Hz refresh rate. For ACELeRATE this represents over 26.5 million pixels (4096 x 2160 x 3) displayed across the entire dome surface with three projectors. Although a 120-Hz refresh rate projector was preferred at the time of acquisition to help reduce motion blur artifacts (i.e., temporal anti-aliasing [4]), in the 2017 timeframe only 60-Hz refresh rate laser projectors with black-frame insertion technology were available to help minimize motion blur artifacts, and which matched available lab budget.

Four dedicated off-the-shelf Windows-10 3-D workstation computers with upgraded Graphics Processing Units (GPUs) were acquired to drive and synchronize the real-time images produced by each laser projector. These visual system PCs are all rack-mounted in a short 24U rack (~48” tall); the rack sits behind the dome structure as shown in Fig. 4. The video cables from the PCs to the projectors are all DisplayPort but require power boost hardware to support the longer cable lengths which go upward from the rack into the ceiling, across the ceiling tiles, then back down to each laser projector to keep them out of the way of foot traffic.

Once the visual system hardware was installed in late 2017, lab managers began to consider what NASA developed and/or COTS software would be required to drive the visual system and meet various planned scientific experiments for ACELeRATE. A major internal goal for NASA Ames was to have a visual system solution that was largely vendor independent so an Ames research scientist could conceivably use any 2-D application or 3-D scene generation software in ACELeRATE, whether commercially obtained or developed internally at NASA.

C. Distortion Correction and Edge Blending Software

Since the ceiling mounted laser projectors cast their pixels downward to the curved display surface below as depicted earlier in Fig. 4, distortion of the pixels (warping) can be expected. Further, artifacts for light overlap at the edges of adjacent projected images will also be present. A sample warped image, where the horizon line should be straight and not bowed, is depicted below in Fig. 5. These artifacts must be corrected by a process referred to as distortion correction and edge blending before the visual system can be successfully used. Thus, the first significant engineering task for ACELeRATE was to devise a software solution to perform pixel level distortion correction, including blending of pixels at the edges of the adjacent projector images to address these artifacts.

The ACELeRATE visual system PC hardware uses Nvidia GPUs (Quadro M6000 which were state-of-the-art in 2017). ACELAB personnel were aware of available distortion correction and edge blending software available from Nvidia in their NVAPI software to address these visual artifacts in hardware. As such, ACELAB personnel developed an OpenGL program called warpBlendGL that uses the NVAPI software and the GPU hardware to address these visual artifacts.

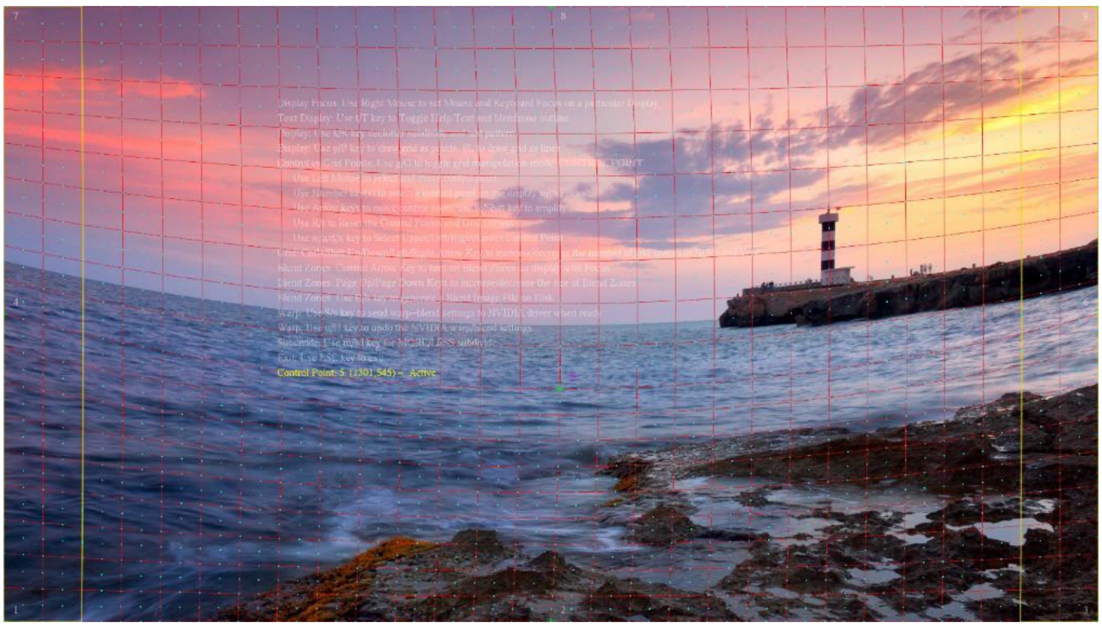

Fig. 5 Warped Pixels from a Non-Uniform Curved Display Surface.

The warpBlendGL program generates a similar scene shown in Fig. 5 on a dome “channel” that has not yet been distortion corrected. The user simply uses the PC mouse and keyboard to click-on and drag select control points from the warp-mesh grid (the colored lines and dots) which overlay an ocean scenery background, until each projected image on each of the three projectors is correct relative to an observer sitting at the design eye location (i.e., cockpit seat). Another major feature of warpBlendGL (not shown) is the elimination or reduction of bright spots between adjacent displays where the light from the left and right projectors overlap with the center projector.

The manual adjustment process with warpBlendGL need only be run once for the lab; the distortion correction and edge blending correction data are saved to disk on each renderer computer and can be later downloaded into the GPU on each renderer computer whenever desired. With the warpBlendGL program, distortion corrections and edge blending can be activated (or totally disabled) with the click of a mouse. Thus, a visiting 3D application program to the lab (or even a 2D desktop program) does not itself need to employ its own warp-blend solutions.

Fig. 6 below shows the previous image from above after alignment; all the pixels on the screen are now distortion free as made possible by the GPU hardware and the warp-blend settings supplied via warpBlendGL. Since these corrections are done within the GPU itself, there is no application overhead and very little (insignificant) GPU overhead when active.

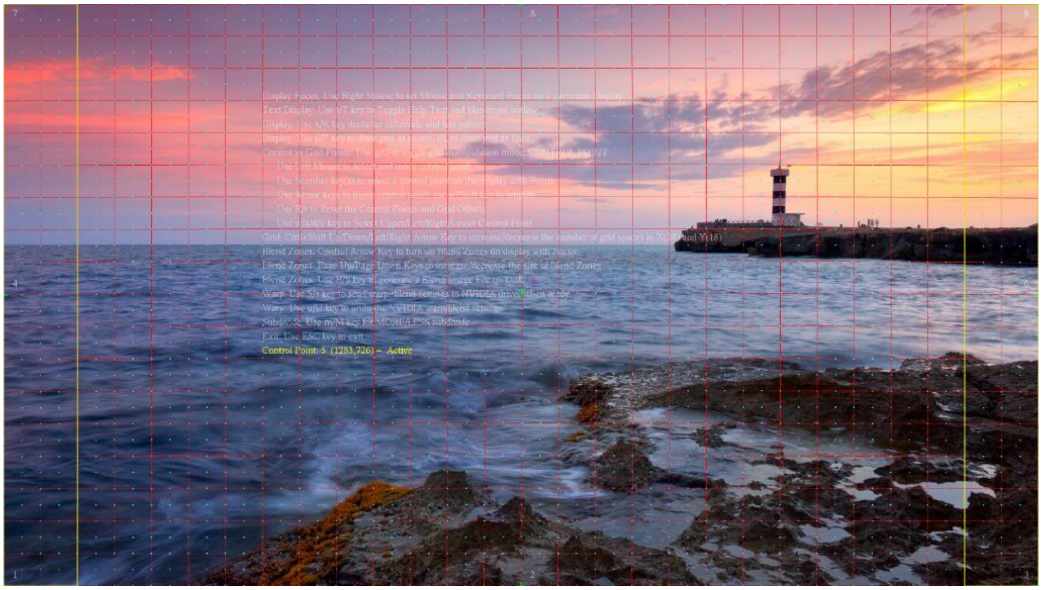

Fig. 6 Sample Image from warpBlendGL after Distortion Correction Settings Applied.

D. 3-D Scene Generation Software

ACELeRATE and the VMS use the RSI Raster XT Image Generator (IG) software. This software includes an extensive worldwide database (WWDB) of the earth modeled with the WGS84 oblate spheroid model; nearly the entire planet Earth terrain surface has been modeled in 3-D with texture imagery derived from geospecific NASA Landsat satellite imagery. The WWDB is supplied with RasterXT and can be stored on a single 2-TB hard drive on each renderer computer (i.e., a “channel” in IG terms). Real-time database paging between adjacent areas in the WWDB provides the ability to fly over long distances such as would be required by a typical commercial airliner or military fighter, or through relatively small and compact database areas such as those required by low level urban flight simulation. The IG channels at each facility are configured as a rendering cluster to provide the requisite edge matched channel geometry where required; for example, in ACELeRATE dome there are three RasterXT channels in that cluster: the left, center and right channels.

Although the base Landsat imagery used within the database is relatively low resolution, it is quite suitable for high altitude views, or distant terrain views outside the key areas of interest when used with the RasterXT scene generation software which includes real-time database paging and a variety of advanced rendering capabilities including but not limited to real-time shadows, atmosphere simulation effects, ephemeris models of the night sky, and many other features generally required for advanced 3-D scene generation. For development environments like ACELeRATE, the RSI IG also allows the end user to add their own “high-resolution insets” into the WWDB using popular visual database development and modeling tools already in use by SIMLABS and ACELAB (such as the popular Presagis Creator 3-D modeling tool). These high-resolution insets that are developed often contain hundreds of thousands or even millions of polygons with higher-resolution texture than provided by Landsat along with 3-D geometry to realistically simulate the outside world. The RasterXT software also includes its own distortion correction and edge blending software so when ACELeRATE is setup for using RasterXT, the warpBlendGL setup described earlier is simply disabled (left off).

E. Visual Database Model of San Francisco Downtown Area

The first major visual database development project undertaken by ACELeRATE development personnel was a highly detailed visual database of select downtown San Francisco (SF) areas. Since urban flights will often be within 500’ of the ground, the database needed to be highly detailed and remain fully compatible between the VMS and ACELERATE simulators. ACELAB personnel used Google Earth 3-D models, where available, and select computer aided design information provided by San Francisco city government offices to help model a large part of the SF downtown area. The principal 3-D database modeling software in use at this time is the popular “Presagis Creator Pro” tool along with other various support tools provided by RSI to integrate each high-resolution inset into the WWDB.

Future vertiport landing pads were added to the database in the SF wharf area along with numerous and accurately sized buildings each with photographic quality in the downtown area. Several select buildings in the downtown area near the SF convention center were also modified to have UAM landing pads on their rooftops. Fig. 7 shows the SF visual environment on the ACELeRATE dome for a sample UAM simulation environment; this scene is intended to be updated 60-times per second. The station off to the far right is the system operator station which is used to control the test scenarios; the person sitting in the open cockpit enclosure (center) is for the UAM Pilot or test subject; the simple cockpit currently includes three COTS multi-function monitors mounted to the cockpit structure that are used to provide the UAM operator with appropriate situation awareness and flight guidance / monitoring displays (see Section H for more information on the concept UAM cockpit displays).

Fig. 7 ACELeRATE Visual System Depicting a Real-Time Display of the San Francisco Downtown Area.

In the VMS, the same SF visual database is also used on similar but newer and faster Windows 10 rack-mount computers from RSI with even more advanced NVIDIA GPUs (all COTS hardware); the same RasterXT rendering software is used by design in both facilities to maintain compatibility. Fig. 8 below shows a VMS simulation that was developed by NASA to investigate ride quality for passengers while on motion for a typical UAM eVTOL vehicle operating in the SF downtown area on a moderately windy day. The test also involved a final approach and touchdown to one of the downtown area landing spots; i.e., the roof-top of a parking garage near the downtown SF convention center complex.

Fig. 8 VMS Air-Taxi, Ride Quality Analysis Flight Test on Motion in Downtown SF.

F. Visual Database of Edwards AFB / Armstrong Flight Research Center Area

In support of the AAM National Campaign, NASA has offered industry partners the opportunity to test their aircraft at the Armstrong Flight Research Center (AFRC) and Edwards Air Force Base (AFB) complex, so a 3-D high resolution database inset of the Edwards AFB test bed and select AFRC cultural detail has been successfully added to the worldwide visual database (refer to Section H that shows concept UAM primary flight displays against an AFRC background). As with the SF database, this Edwards AFB/AFRC database inset will be used on both ACELeRATE and VMS simulators. As NASA continues to evolve the developmental testing plans, these visual databases will be important to help evaluate a number of planned research areas including but not limited to flight handling qualities, air-to-air conflict management, airspace operations interoperability testing, noise evaluation, and a variety of other UAM test scenarios as depicted in Fig. 9.

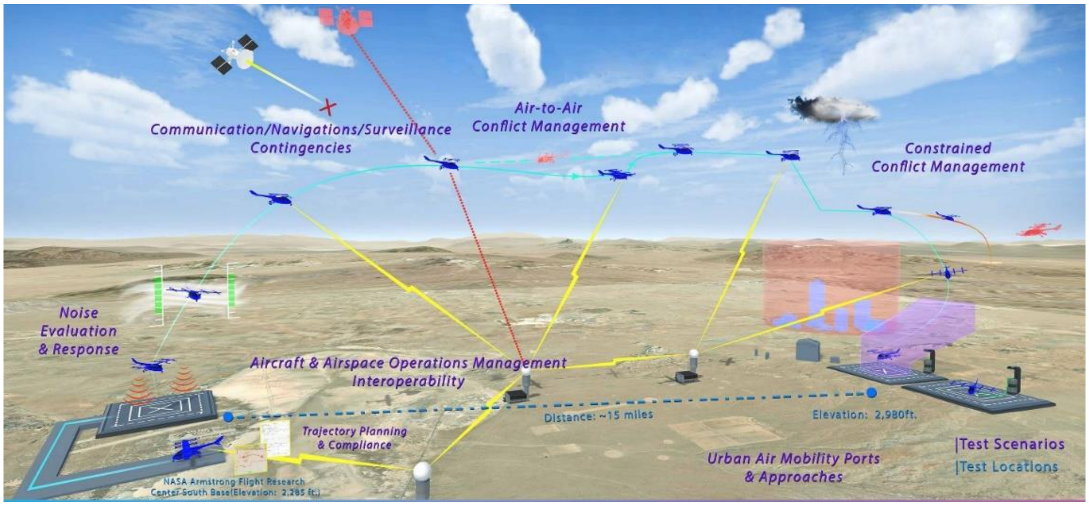

Fig. 9 Flight Test Plans for Armstrong Flight Research Center (AFRC) or Other Sites.

G. Visual Database of Handling Qualities Test Course

To support the FAA VTOL Handling Qualities Evaluation research project, the ACELeRATE team developed a 3-D model of a handling qualities test course for AFRC. This model was derived from definitions and visual specifications in ADS-33E-PR [8]. Fig. 10 shows various pictures of the ADS-33E handling qualities 3-D model that was recently added to the AFRC database; it too is now part of the Ames world-wide database. This section of the AFRC database will later be used by NASA and FAA pilots to help evaluate the handling qualities for each UAM flight test vehicle.

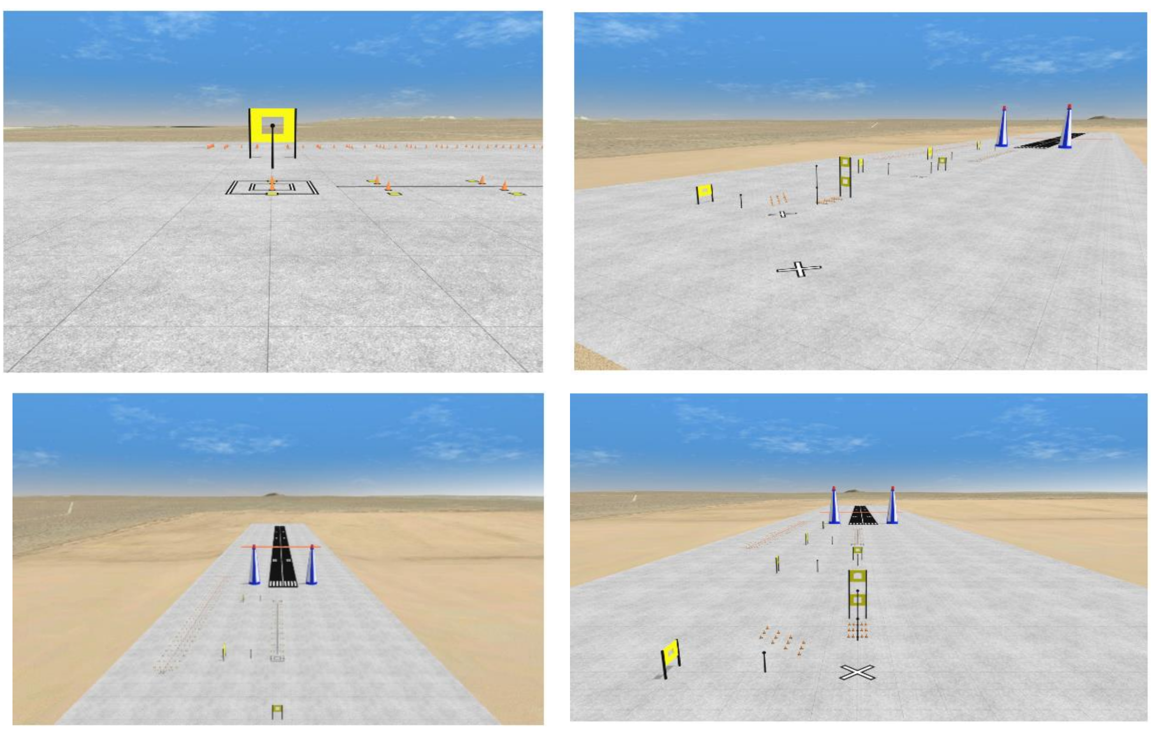

Fig. 10 Several 3-D Model Pictures for AFRC ADS-33E Handling Qualities Flight Test Area.

H. Concept eVTOL Multi-Function Displays

For the past several years, NASA Ames has been actively supporting the U.S. Army Degraded Visual Environment Mitigation (DVE-M) program to study technology solutions that will help mitigate and reduce accidents, injury and even loss of life when operating helicopters in poor or even zero visibility conditions (dust, rain, fog, snow, moonless nights). This program has strong international support within NATO countries as well as numerous international organizations that routinely operate helicopters in dangerous conditions such as mountainous area air-ambulance service at night or flight into reduced visibility conditions; the U.S. Air Force also has a strong interest in this program for its combat search and rescue aircraft (e.g., HH-60W program).

One of the authors for this paper is involved in the development of pilot display software for the Army DVE-M Program to provide computer generated symbols and cues to aid the crew during these often-dangerous, limited visibility conditions. In 2016, this development effort included flight test support as a civilian system operator in the back seat area of the U.S. Army Black Hawk EH-60L research aircraft in support of DVE-M flight trials at the U.S. Army Yuma Proving Ground in Arizona [5]. This R&D program remains active; the EH-60L helicopter is now located at the U.S. Army Fort Eustis base in Virginia where it continues to undergo flight tests there. Since the Yuma flight trials, the helicopter has been modified so that it can now also operate under fully autonomous, computer guidance with coupled flight controls (partial-authority) all the way from takeoff to landing [6].

Fig. 11 is a picture of the U.S. Army EH-60L aircraft (tail number 657) on an approach to a safe, controlled, often near zero-visibility landing at the Yuma Proving Ground. This research aircraft has two front panel mounted multi-function displays that provide cues to the pilot; a helmet mounted display (HMD) is also available as another possible display / cueing device solution under evaluation by the Army. The aircraft has been modified over the years to test various hardware sensors and software solutions that can vastly improve crew situation awareness especially when operating the aircraft close to the ground and often with poor to zero visibility conditions. Over the past decade, the U.S. Army has studied forward looking infrared (FLIR), long-wave radar, laser radar (Lidar), electro-optical, and most recently "bumper radar" devices with 3-D audio spatialization to warn of dangerously close obstacles, all designed to investigate the best technology solutions to provide the flight crew with safety and full 360° situation awareness during all phases of flight (including DVE) without compromising the mission.

Fig. 11 EH-60L Black Hawk Test Aircraft for U.S. Army DVE-M Program.

The future eVTOL vehicle pilot will also face some of the challenges that the pilot of a modern helicopter like the EH-60L faces. Further, the requirement for presenting the flight crew with an easy-to-interpret interface with emphasis on strong situation awareness is also common to both vehicle types. A similar goal for each are to provide onboard tools and automation to help the pilot safely operate the vehicle during all phases of flight, especially as it transitions to and from hover conditions during takeoff and landing; these too represent similar challenges to what the helicopter and UAM pilot will both face. In particular, the transition from forward flight to landing is always more difficult in a VTOL aircraft because the actual landing spot on the ground cannot normally be seen by the unaided eye of the flight crew, since the nose of the vehicle is usually pitched up (raised) to aerodynamically brake (slow-down) the aircraft during the final seconds on approach to a hover, followed by a hover down to the ground (or that building rooftop). As such, the generation of the primary flight display for the developmental testing is another important R&D area that NASA and the FAA will begin to evaluate later in the summer of 2020. Several useful and applicable display concepts from the U.S. Army DVE-M research efforts have been utilized in the initial eVTOL primary flight display concepts.

The current ACELeRATE cockpit display layout concept for an eVTOL vehicle includes at least two multi-function displays (MFDs). Currently, there are three (3) MFDs in ACELeRATE and VMS cockpits; two multi-function displays mounted in a horizontal, landscape orientation and a third mounted in a portrait (rotated) configuration. The first landscape oriented MFD will be used for the primary flight display (PFD) and includes a simulated forward-looking sensor view, providing various viewpoints of the "real-world" as required. The second landscape oriented MFD will be used for a 3-D MAP/ NAV display. The third MFD will be dedicated to the display of System Health and Aircraft Status information; this MFD will be mounted in a portrait configuration.

The PFD and MAP/NAV graphics software were designed and are currently maintained using the DiSTI GL Studio-7 desktop modeling software. GL Studio is a suite of object-oriented interface design tools that enable programmers in any industry to create state-of-the-art, reusable 2-D or 3-D graphical user interfaces for simulation and safety critical applications. Several display concepts where applicable were borrowed from the U.S. Army DVE-M R&D program, and in other cases from NASA developed display concepts. GL Studio allows the displays to be constructed as either a standalone application, or the display software can be packaged and exported as a shareable library; i.e., a DLL in Microsoft Windows terminology. In the ACELeRATE usage case, the PFD and MAP/NAV code are integrated into their respective RSI Image Generator channel and implemented as a user defined graphics callback; i.e., when the IG is finished drawing the 3-D background scenery, it then calls the user defined graphics via the GL Studio generated DLL. In either case, the software exports C++ code with class methods to easily add project specific code to manipulate the underlying graphics symbols and user defined objects, all implemented as C++ classes. This tool also allows the same project source code to be used in either case whether building the code as a standalone program or as a DLL.

GL Studio also offers tools to produce Safety Critical Embedded Code (SCEC++) that is necessary to support the development, validation, and maintenance of safety critical displays that require extremely high availability along with the ability to meet stringent code failure analysis to help ensure the software is free of design flaws that might otherwise cause a safety critical display to fail in flight (or while driving, whatever the usage case demands). Currently, NASA is not employing the SCEC++ tools from the DiSTI Corporation for UAM since the current program emphasis is for R&D and simulation purposes rather than building certifiable, flight worthy hardware and software.

1. Primary Flight Display (PFD)

Fig. 12 below depicts the traditional PFD standalone application case where the background scene is simply represented by a cyan colored sky and a brown-colored ground to better highlight dynamic aircraft pitch and roll. The basic aircraft state information is depicted with familiar cues representing current attitude, altitude, heading, guidance cues, as shown. Fig. 13 on the other hand shows an enhanced PFD which includes a background scene representing a combination of synthetic vision and/or a dynamic sensor supplied image. In the enhanced PFD case, the PFD cues operate like a Heads-Up Display (HUD) when properly aligned with the real-world background scenery. All the PFD screenshots in this paper (including Fig. 13) were generated where the PFD software was being executed as part of the RSI Image Generator user graphics callback (i.e., as a DLL).

As mentioned earlier, the VMS currently uses the PFD from ACELeRATE as a standalone application; the background scenery representing the real-world is then "video-mixed" from a separate RSI channel. In this case, the standalone PFD application is configured to disable the large "Blue Sky" and "Brown Ground" polygons in Fig. 12, leaving a black background scene instead. The VMS video mixing hardware then replaces the black background pixels from the PFD with pixels from the separately generated RSI scene.

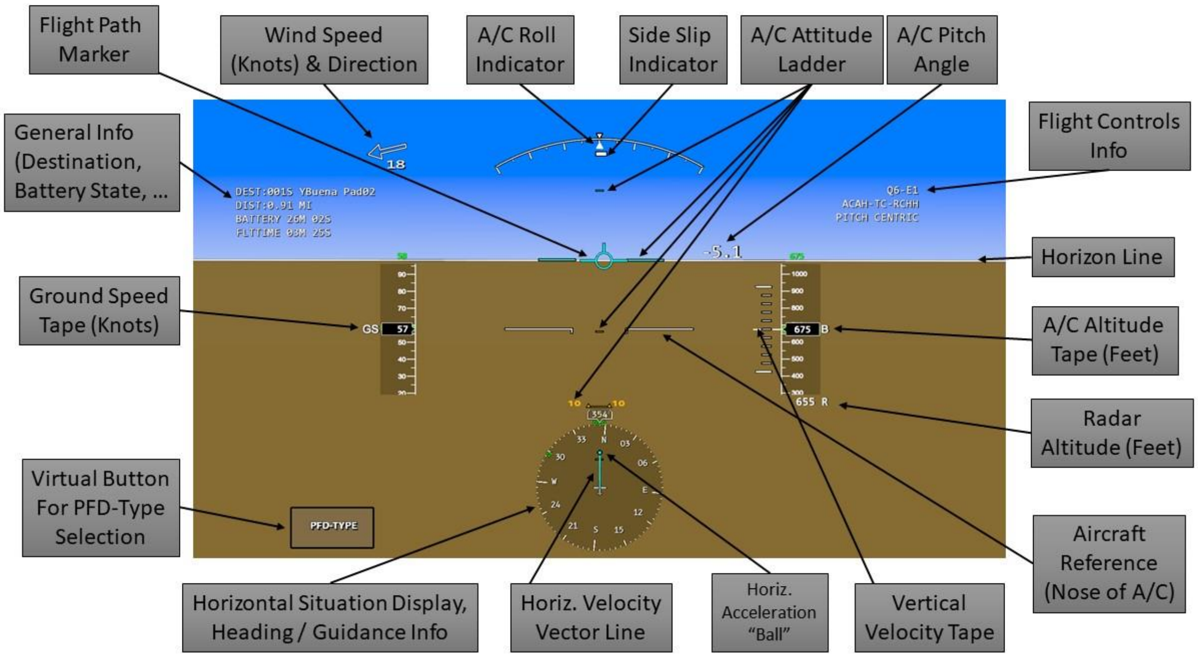

Fig. 12 Traditional Primary Flight Display (PFD).

In ACELeRATE, the preferred method is to render the PFD as an RSI user graphics callback as shown below.

Fig. 13 Enhanced PFD with Integrated Synthetic / Sensor View.

In Figures 12 and 13 above, the guidance controls on the speed tape, altitude tape, and horizontal situation indicator (HSI) are temporarily bright green which indicate the pilot is manually providing inputs to the flight control system. The guidance system will then follow those manual inputs. However, when the pilot operator switches over to a programmed flight plan, the guidance commands switch to a magenta color as shown below in Fig. 14. The small magenta diamond shows the intended landing point location, in this case “0001S YBuena Pad02” as indicated in the upper left general text information. The cyan flight path marker (FPM) symbol has changed to a white diamond shape as a reminder to the pilot the flight path angles are now derived for low airspeeds which can often be less accurate. The FPM is currently offset way to the left of center (within the GS tape) which indicates a relatively strong, quartering headwind is pushing the aircraft at the present time to the left (not an ideal approach, this close to a landing).

Fig. 14 Approach to Landing near Downtown SF Convention Center.

Fig. 15 Approach to Landing near Hangar 4833 at Armstrong Flight Research Center.

Fig. 15 above depicts an approach to landing near Hangar 4833 at Armstrong Flight Research Center. In this case, the command speed and command altitude targets are currently satisfied; the brown rectangle on the altitude tape shows the currently approaching ground which is located at approximately 2,300 feet MSL (i.e., 293-feet below the UAM aircraft as indicated by the radar altitude readout).

Fig. 16 below shows the magenta diamond in the compass rose area is larger now indicating the landing point is getting very close (only 542-feet away); when the ownship is within 800-feet of the landing point, a bright magenta "home plate" cue appears on the HSI-compass rose which provides horizontal (look-down) alignment information relative to the ownship vehicle. So long as the pre-programmed landing point remains visible to the crew, the magenta diamond corresponding to that 3-D position on the ground will also remain visible.

Fig. 16 Approaching Hover Condition; 3-D Landing Point Still Visible to Flight Crew.

In Fig. 17, as the eVTOL aircraft continues to approach the landing point; the ground speed shows nearly zero (0.8-knots, moving slowly forward). The actual target landing point on the ground is no longer visible; the magenta diamond is no longer present. In fact, the landing point is now almost directly below us, but we remain 101-feet away from the target landing point and are 30-feet above the ground. Note the brown highlight on the altitude tape; this representing the ground which is now only slightly below us. The acceleration ball on the HSI is colored cyan indicating we are still moving slightly forward, not backwards as desired. The velocity vector line is very short (nearly gone) since we are nearly at a zero-ground speed hover condition. If the vehicle starts to drift backwards at any time, the velocity vector line and acceleration ball will change to a red color to alert the crew to this situation.

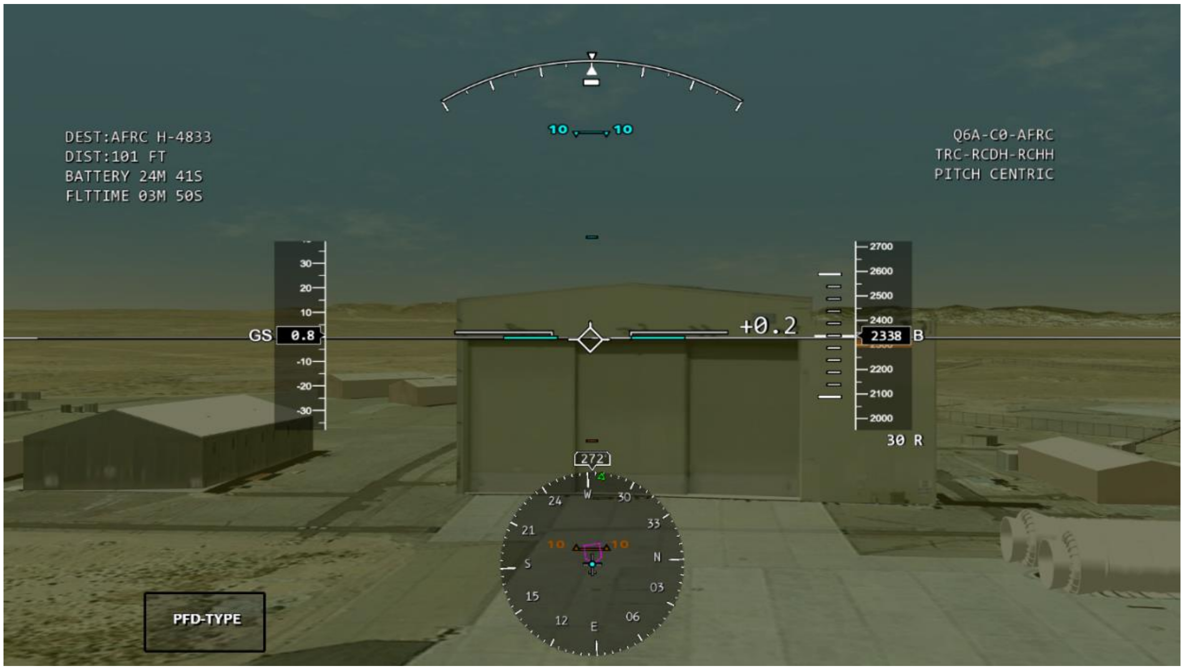

Fig. 17 Approaching Hover Down Condition; 3-D Landing Point No Longer Visible to Flight Crew.

In Fig. 18 below our eVTOL vehicle has arrived within 10-feet of the landing point; the home-plate on the HSI compass rose turns bright green indicating it is now safe to hover down to a landing. The horizontal axis acceleration ball is also larger now (and bright green) indicating our lateral accelerations are very close to zero, if not exactly zero.

Fig. 18 UAM Vehicle Has Arrived at Landing Point and Now Safe to Hover Down to a Landing.

Figures 19 and 20 depict the proposed FAA Handling Qualities maneuver course. The orange painted cross-section on the runway indicates one of the evaluation test-points for landing and/or hover operations.

Since there is no detectable wind in the environment below from the simulated avionics, the wind cue has been automatically decluttered from the PFD/HUD for each of these approach to landing pictures.

Fig. 19 Handling Quality Maneuver Course.

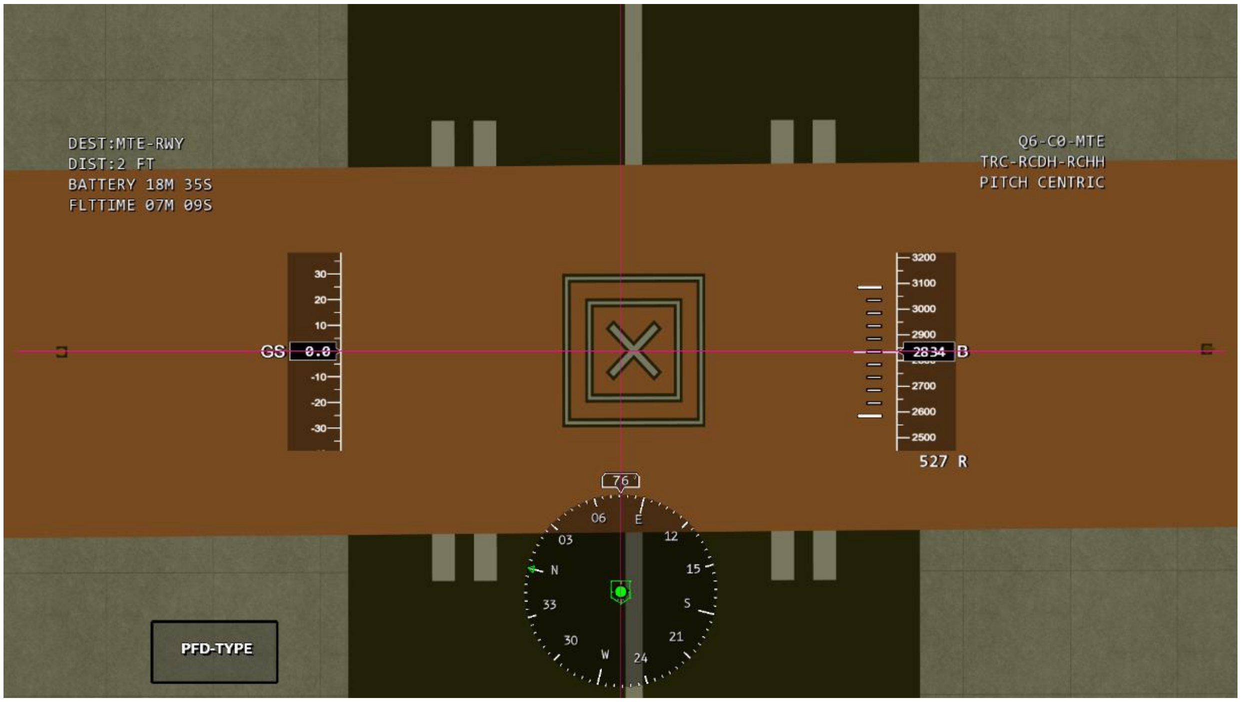

Fig. 20 Look-Down Camera View Concept at ~500-Ft Directly Above the Target Landing Point.

In Fig. 19 above, note the eVTOL aircraft is traveling backwards; this is evident because the ground speed (GS) tape shows negative nine knots, and the velocity vector line and acceleration ball on the HSI are now red in color indicating the vehicle is moving backwards, not forward.

In Fig. 20, the pilot has arrived at the target landing point which is 527-feet below the vehicle, and the pilot has depressed a trigger button on their flight controller (side-stick) to request a temporary "look-down" view on the PFD; this view remains so long as the pilot continues to depress the designated trigger button. When commanded, the PFD display will declutter most of the attitude information since we are looking straight down (even from our 527-feet location above the ground). This concept view may be relatively inexpensive to implement in a UAM aircraft with a downward facing camera, perhaps gimbled to counteract aircraft pitch and roll angles while the look-down is active.

In Fig. 20, the UAM aircraft is within 2-feet laterally of the landing point although the aircraft is 527-feet above it. The "home plate" cue is now green indicating the A/C is within 10-feet of the landing point so it is now safe to hover down to a landing (even from 500 feet up if desired); the horizontal plane acceleration ball is also green and larger indicating near or zero horizontal acceleration (perfect hover). The vertical velocity tape would show a brown downward moving tape during descent or a cyan colored rectangular tape when climbing.

Pitch Centric vs Flight Path Centric Viewpoints

Consider the Bell Helicopter aircraft (A/C) state as depicted below in Fig. 21. This attitude is not uncommon in a VTOL type vehicle as they accelerate forward, especially accelerating from a low airspeed toward a higher one. The A/C is pitched down -10° degrees but is climbing (slightly) since the flight path angle represented in the green pointer below is greater than zero (a conceptual horizon line). The blue viewpoint pointer below represents the classic "pitch-centric" viewpoint that is normally displayed on an electronic PFD. In this case, the pitch angle is relative to the actual real-world horizon. The green pointer on the other hand would depict a viewpoint that instead shows where the aircraft is actually going (in this case, a slight climb angle relative to a zero-climb reference point represented by the horizon line in this case).

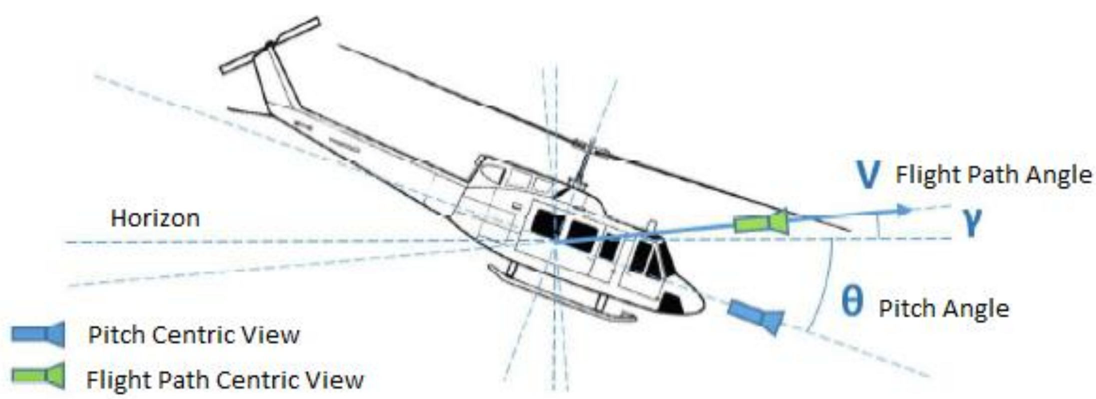

Fig. 21 Pitch Centric vs Flight Path Centric Viewpoints.

In Fig. 22 below, and all previously shown PFD/HUD figures above, the display is setup to show the classic "pitch-centric" display type where the aircraft reference symbol remains fixed at the center of the display and always indicates where the nose of the aircraft is pointing. The attitude ladder in these cases can be referred to as a "pitch ladder" since it represents and depicts "pitch-angle" in the vertical axis; the ladder also rotates to represent A/C roll angle (as it will in a flight path centric display). The vertical placement of the pitch ladder relative to the aircraft reference symbol shows the A/C pitch angle and will match the text displayed on the horizon line itself for quick situation awareness of the A/C pitch angle. For negative pitch angles, the pitch-ladder shows orange-brown markers and text to represent "downward"; positive pitch ladder markers and text are cyan in color to represent "upward". The flight path centric PFD in Fig. 23 also shows pitch-angle but the aircraft reference symbol has moved down to align with the current pitch angle. The A/C is climbing as indicated by the cyan vertical velocity tape indicator next to the altitude tape; the white FPM is also above the cyan blue ref. lines on the pitch-ladder further indicating the vehicle is climbing (slightly).

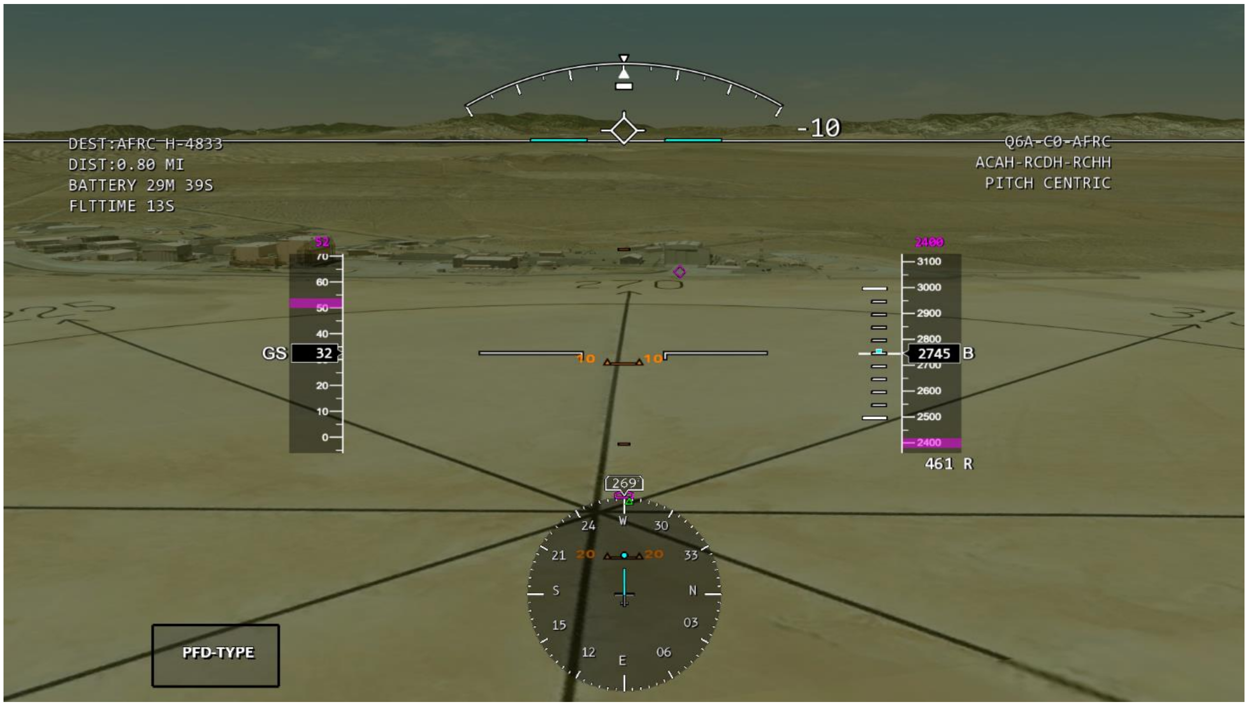

Fig. 22 A Classic Pitch-Centric Type Display.

Fig. 23 PFD Reconfigured to a "Flight Path Centric" Display.

Fig. 23 depicts nearly the same aircraft state from Fig. 22 but with the PFD re-configured to show a "flight path centric" display. The attitude ladder can now be referred to as a "flight path ladder" since the ladder rotates in the vertical axis with A/C flight path angle (not pitch angle); the background 3-D scenery also no longer rotates with pitch angle for the vertical axis, but is re-configured to also rotate in the vertical axis using the A/C flight path angle (i.e., where the vehicle is going) instead of A/C pitch angle. The physical A/C remains pitched downward, but the PFD and the background scene now show, by design, principally where the aircraft is traveling. The pilot can still see where the A/C nose is pointing using the dynamic aircraft reference symbol relative to the ladder bars as shown.

With the Flight Path Centric PFD case, the white horizon line with the pitch angle text readout from the classic pitch-centric PFD is automatically removed to avoid confusion; the aircraft reference symbol is no longer stationary at the center of the display but as indicated earlier translates up and down (vertically) to show where the nose of the aircraft is pointing relative to the flight path ladder. The two cyan colored horizon bars (without digits) on the flight path ladder represent zero flight path angle, and thus zero vertical velocity. Placing the FPM to remain in line with these cyan bars (even while turning), will keep the A/C at the current altitude in both display types.

A flight-path centric display might also eliminate the need for a look-down type display previously shown earlier in Fig. 20 where the pilot must continuously depress a button to "look-down" to see the landing zone. With a well behaved inertial sensor that provides accurate velocities and accelerations even at zero, low or negative ground speeds, a flight-path centric viewpoint may actually prove more useful and intuitive to a future UAM or other eVTOL operator with minimal flight experience since this PFD display configuration would show the crew exactly where the aircraft is going rather than simply where the nose of the aircraft is pointing.

A flight-path centric display will certainly not be as intuitive, at least initially, to the experienced pilot in today's VTOL world since the PFD display and background have remained pitch-centric. The flight path centric vs pitch centric display concepts will be further explored by NASA and the FAA. It is possible the flight-path centric display concepts might offer an improved and more intuitive viewpoint to a future UAM air-taxi driver. This may especially be true during the complex "hover-down" maneuver for the eVTOL aircraft where the aircraft pitch angle will often be close to "zero" or slightly nose-up, but the flight path angle (where the aircraft is going) will gradually move from 0° toward -90° degrees (straight down) during the approach to landing and the final hover-down to touchdown.

2. MAP / NAV Display

A concept eVTOL MAP/NAV display has been mechanized as described earlier in Section H and depicted below in Fig. 24 and Fig. 25. The MAP/NAV MFD has been designed to logically mimic but greatly expand the conceptual operation of the PFD compass rose/HSI. Like the PFD HSI, the MAP is intended to provide horizontal situation awareness but will also include a highly detailed background scene (i.e., satellite imagery or 3-D computer-generated scenery) behind the symbology. The MAP/NAV display will help orient the pilot to their current location while providing additional graphical cues such as the flight plan, location of departure and landing points, location of nearby airports or helipads, nearby dangerous obstacles, nearby airborne traffic, and so on. Similar information may also be present where applicable on the PFD in later versions.

As such, the concept eVTOL MAP/NAV display provides a top-down view of the immediate geographic area beneath the vehicle. The software also presently implements a continuous scan of a FlightDeckZ world-wide landing aids database (select parts read into memory). This database contains all the commercial and military airfields and helipads in the world. The MAP software automatically displays all nearby airports and helipads. Additional guidance and obstacle avoidance cues on this display will likely be added to the MAP soon, such as flight plan information from FlightDeckZ guidance software.

As shown in Fig. 24 for SF downtown, three commercial (green) heliports were found in the FDz database. The magenta line from the ownship aircraft reference symbol at the center of the map shows the current bearing to our selected landing point "001S"; the landing point is 0.36 miles away. The Oakland International Airport icon (KOAK) is outside the current map field-of-view; the relative bearing to KOAK is shown at the lower left corner of the display (thus, the "X" through the icon); similarly the bearing to the SF International Airport (KSFO) is at the upper left corner of the display; it too is outside the current map field-of-view. The cyan colored velocity vector line shows the vehicle is flying straight ahead; the acceleration ball shows the vehicle is accelerating slightly forward and starting a right turn since the ball is no longer attached to the velocity vector line.

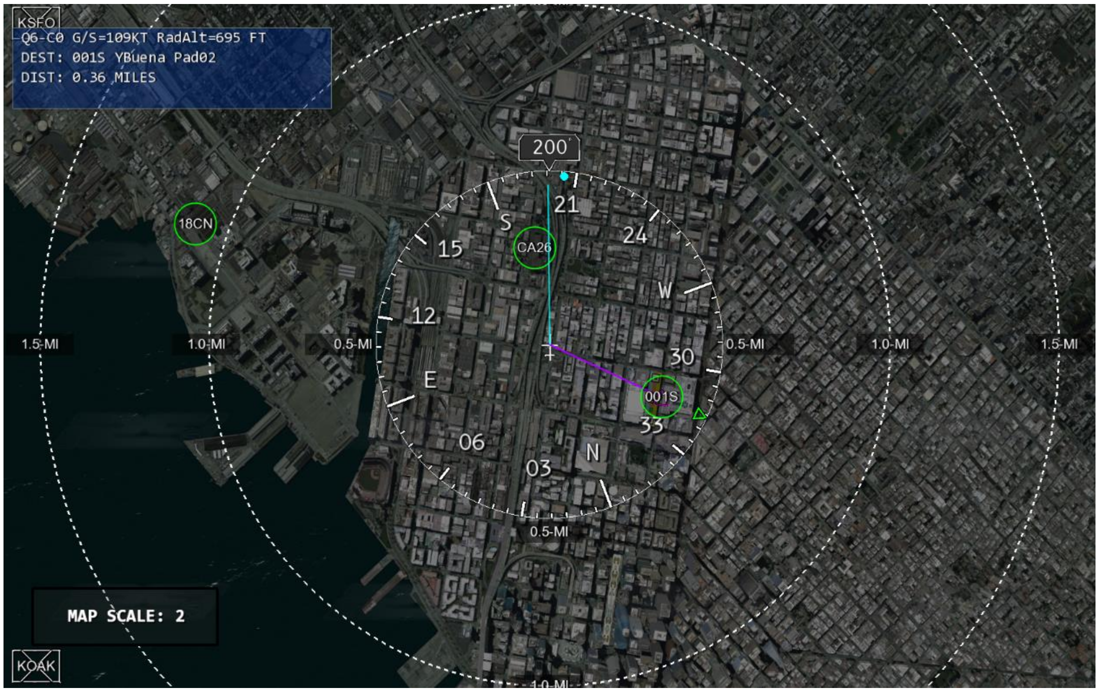

Fig. 24 San Francisco Downtown Area on MAP/NAV MFD.

Fig. 25 shows a concept MAP display at AFRC where the vehicle has been setup for a very short flight; from one landing pad to another (only 403-feet away) at the old AFRC X-33 Flight Operations Center area. The MAP has been scaled to the maximum "zoomed-in" scale (i.e., MAP SCALE: 0) using the software virtual button.

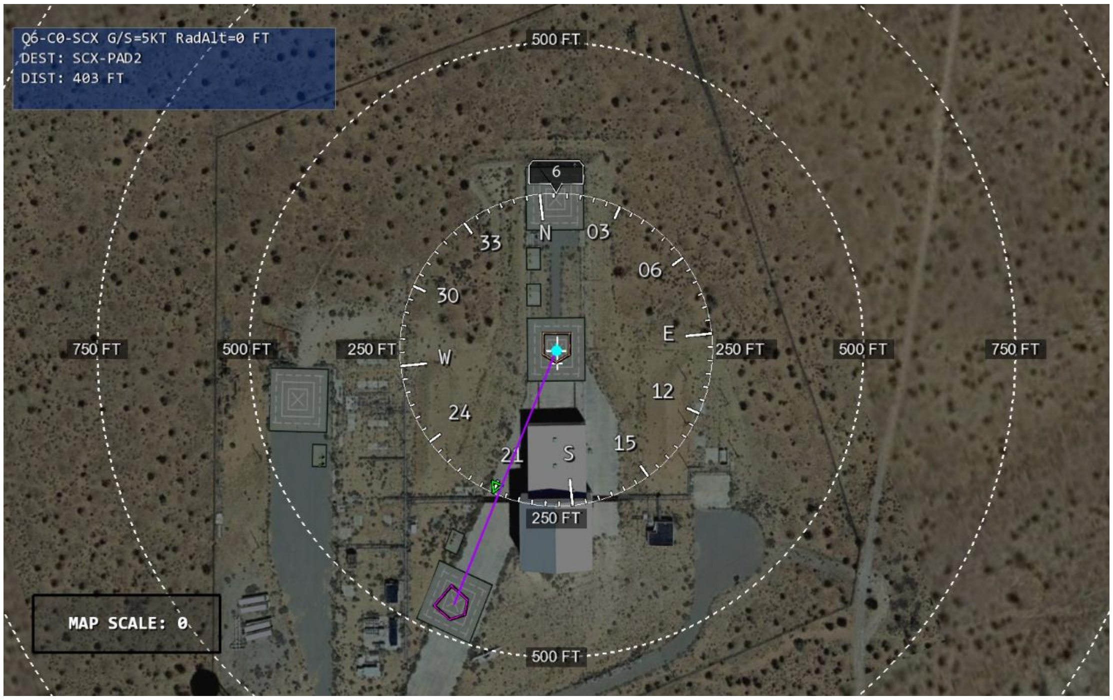

Fig. 25 AFRC X-33 Flight Operations Center on MAP/NAV MFD.

3. System Health Display

A future "System Health" Multi-Function display is planned but not yet implemented in ACELeRATE. Select aircraft and vehicle subsystem status will be available on this MFD.

I. Wind Modeling

Accurately modeling wind for use within an aircraft simulator has historically not needed high precision; in many advanced simulators, wind is often implemented as a constant, or a near constant wind speed and direction with perhaps some minor variability in each component. These wind settings can then be easily setup or modified by a simulator operator as part of training. For example, adding a variable cross wind component for a flight simulator environment will certainly help the pilot learn to safely land the vehicle if the cross winds remain within the design capabilities of the aircraft.

In the case of a dense urban environment, such as the SF downtown area, landing a relatively lightweight vehicle on the top of a building can be expected to be quite difficult on windy days because the wind can vary greatly due to "urban microclimate wind" phenomenon. Tall buildings disturb airflow; they may deflect, slow high winds, or produce venturi-like "urban wind canyons" where wind accelerates in other areas. Further, wind simulation models often don't accurately represent pronounced and random wind gusts. As such, a typical urban skyline like San Francisco along with high building density of different shapes throughout the city can be expected to present a challenging environment to accurately model a realistic wind simulation in real-time.

NASA scientists from Ames traveled to nearby SF and measured wind speed and direction at key points throughout the downtown area. These measurements were collected, stored and then modeled to roughly represent the highly variable wind and turbulence caused by urban microclimate wind effects. This model quickly demonstrated how difficult and dangerous it might be to manually fly a UAM-like vehicle too low in certain areas of the city, especially near tall and wide buildings in the Market Street section of the city. Although the SF city wind model has currently only been developed in ACELeRATE at this time for the San Francisco UAM efforts, it remains another area of interest that NASA and the FAA will have to investigate as part of its developmental testing plans for AAM.

J. Simulation of Flight Dynamics, Controls and Guidance

For the past year, NASA Ames personnel have been extensively modifying its in-house developed "FlightDeckZ" software, also referred to as FDz, to add VTOL capabilities. These complex aircraft equations of motion, aerodynamics, flight controls, and guidance simulation software were historically developed to simulate large commercial airliner and other conventional vehicles. For AAM, FDz has recently been significantly enhanced to also support smaller eVTOL UAM type aircraft that seat only 4- to 6-people in the vehicle along with a variety of different flight control configurations [7] that are being tested in ACELeRATE and VMS simulators to help determine which man-machine interface design works best.

As one can imagine, the future AAM vehicle may not be restricted to the historical, conventional aircraft flight controls with a joystick, rudder pedals, and a throttle assembly, or even a helicopter type vehicle with its cyclic and collective controller. Instead, there exist other possible flight control configurations that might be better suited to a future lightweight eVTOL type aircraft, especially when one considers this vehicle may someday be operated by that individual (air-taxi driver) with little to no flight experience. As such, NASA's FDz team are actively investigating alternate cockpit flight control configurations with the FAA; perhaps one flight control stick in some test cases; multiple side-stick controllers in another; perhaps a configuration with rudder pedals, and another without, and so on.

Further, recent and novel flight control layouts for flying small (personal) air drones, or even remotely piloting larger aircraft sized vehicles are all possibilities that must eventually be studied to help determine how these future UAM and AAM vehicles can be safely and intuitively controlled with minimal training.

K. Other

The ACELeRATE visual database development team is currently adding a high resolution 3-D inset for the Dallas/Fort Worth (DFW) area, with specific high detail planned near and around the Fort Worth Alliance Airport. The Alliance airport is about 20-miles west of the DFW International Airport and will be added to the WWDB once completed. This area of Texas is expected to represent another target market area of interest for future U.S. UAM operators.

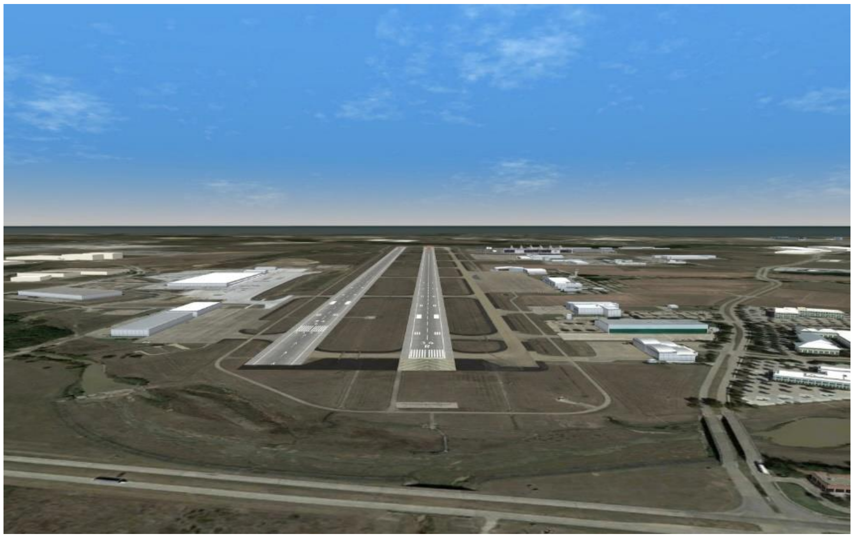

Fig. 26 Prototype Fort Worth Alliance Airport 3-D Inset Model (In Development).

V. Conclusions

The aviation community is developing new technologies to support a transition to increased use of autonomy, vertical flight and new operational environments. ACELeRATE is a new highly reconfigurable simulation capability that will enable support investigation of the pilot-automation interaction to support the safe transition to autonomous flight.

Acknowledgements

This work has been supported by FAA agreement 692M15-19-N-00010 and the NASA Advanced Air Mobility (AAM) and Transformative Tools and Technologies projects.

References

[1] Thipphavong D., Apaza R, Barmore B., Battiste V., Burian B., Dao Q., Feary M., Go S., Goodrich K., Homola J., Idris H., Kopardekar P., Lachter J., Neogi N., Ng H., Oseguera-Lohr R., Patterson M. and Verma S. “Urban Air Mobility Airspace Integration Concepts and Considerations”, NASA, May 2018 https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20180005218.pdf,

[2] Silva, C., Johnson, W. R., Solis, E., Patterson, M. D., and Antcliff, K. R., “VTOL Urban Air Mobility Concept Vehicles for Technology Development,” 2018 Aviation Technology, Integration, and Operations Conference, American Institute of Aeronautics and Astronautics, 2018. doi:10.2514/6.2018-3847.

[3] Archdeacon, J., Sweet, B. Iwai, N. and Kato K. “Achieving Eye-Limiting Resolution: The Devil in the Details”, Royal Aeronautical Society Autumn Flight Simulation Conference, London, UK, November 2012

[4] Sweet, B. and Kato, K. “120 Hz – The New 60 for Flight Simulation?”, Image 2012 Conference, Scottsdale, AZ USA, May 2012

[5] Szoboszlay Z., Davis B., Fujizawa B., Minor J., Osmon M. and Morford Z. “Degraded Visual Environment Mitigation (DVE-M) Program, Yuma 2016 Flight Trials in Brownout”, AHS International 73rd Annual Forum & Technology Display, Fort Worth, Texas, USA, May 2017

[6] Takahashi M., Fujizawa B., Lusardi J., Whalley M., Goerzen C., Schulein G., Mielcarek N., Archdeacon J., Cleary M., Carr J. and Waldman D. “Autonomous Guidance and Flight Control on a Partial-Authority Black Hawk Helicopter”, AIAA Aviation Forum Proceedings, Reno, NV USA, June 2020

[7] Lombaerts T., Kaneshige J. and Feary M., "Control Concepts for Simplified Vehicle Operations of a Quadrotor eVTOL Vehicle", AIAA Aviation Forum Proceedings, Reno, NV USA, June 2020

[8] Anon., ADS-33E-PRF, Aeronautical Design Standard Performance Specification: Handling Qualities Requirements for Military Rotorcraft, March 21, 2000