SYSTEMS TECHNOLOGY, INC.
13766 Hawthorne Boulevard, Hawthorne, California 90250-7083, Phone (310) 679-2281, Fax (310) 644-3887

STI Paper No. 841

A Mixed Reality Simulation Tool for In-Flight Evaluations (STI Paper Series)

June 2020

David H. Klyde
Justin R. Gray
George Park, Ph.D.
Systems Technology, Inc.

Published as AIAA-2020-0668
AIAA SciTech Forum
6-10 January 2020, Orlando, FL

B. System Integration with the Calspan Learjet In-Flight Simulator

This section features material summarized from Reference 1.

1. System Integration with the Test Aircraft

The integration of the Fused Reality® Flight system into the Calspan Learjet required three primary items and a few supporting pieces of hardware. The primary items include the IR cameras, the Fused Reality® head set with its associated HMD and camera, and a laptop computer. Aircraft state information was transmitted from the Learjet variable stability system (VSS) to the system laptop where it computed the proper view for integration into the evaluation pilot's HMD. Fig. 6a shows the positioning of the IR cameras just above the cockpit windshield and Fig. 6b shows the head set as it was worn by each pilot with the associated camera to capture the near-field imagery and HMD. Secondary items included an IR camera hub, a DVI recorder and repeater, and an HMD controller box.

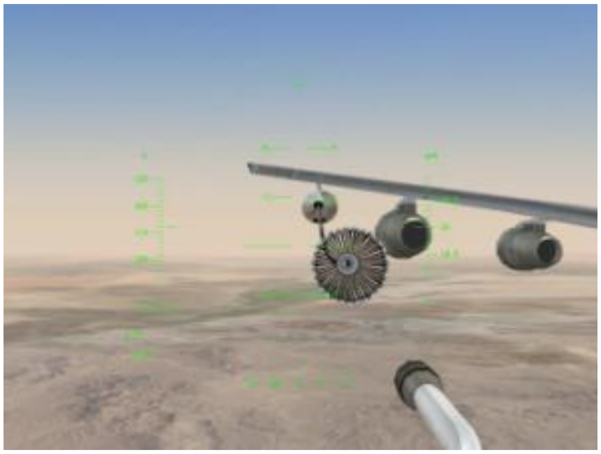
a) IR cameras

b) Helmet with camera and HMD

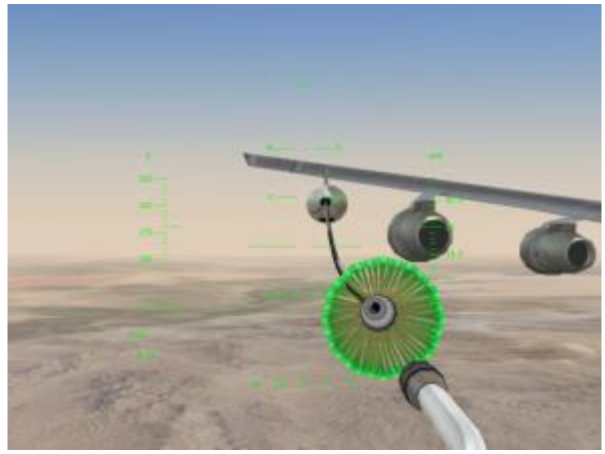
Fig. 6 System integration with the Calspan Learjet cockpit [1].

2. Flight Test Demonstration Task

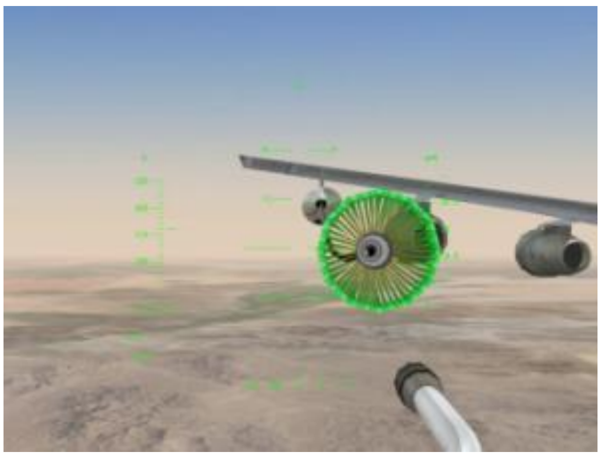
For the Fused Reality® Flight demonstration that was conducted with the Calspan Learjet in-flight simulator, only the drogue tracking portion of the demonstration maneuver defined in Reference 1 was used. Because the task was conducted using a virtual visual scene, enhancements were included to improve the ability of the pilot to discern task performance and evaluate various aircraft configurations. Furthermore, visual enhancements were made to the drogue, so that the pilot can adjust his or her tracking position relative to the basket. When the task begins, the drogue appears as shown in Fig 7a. The proper tracking distance is 6 to 10 ft aft of the basket. The first time the probe enters this vectored distance the basket turns "green" as shown in-line (Fig 7b) and slightly below (Fig 7c). If the probe gets closer to the drogue than 6 ft, the basket turns "red" (Fig 7d). These basket color changes provided the evaluation pilot a powerful visual cue to assess task performance.



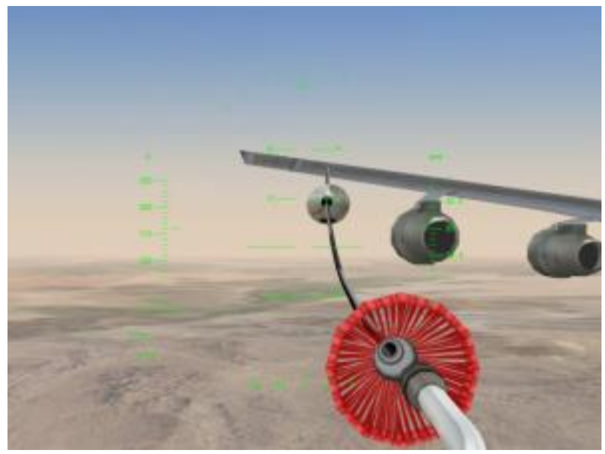
a) Aft of the tracking zone



b) Within the tracking zone



c) Within the tracking zone, probe below the drogue



d) Probe too close to the drogue

Fig 7 Visual scene for drogue tracking task.

3. Summary of Results

Three evaluation test pilots, two from NASA Dryden Flight Research Center and one from the US Air Force Test Pilot School, participated in the first Fused Reality® Flight demonstration evaluations. One flight was conducted on 18 May 2012, while the other two took place on 21 May 2012. All sorties originated at Mojave Airport, California.

Three longitudinal configurations were used in the initial evaluation of the Fused Reality® Flight system. The configurations were all based on models that have been used in previous flight test [4,5] and/or piloted simulation studies [6] and use the same initial cruise flight condition of 15,000 ft. altitude and 250 KIAS.

The three longitudinal configurations are identified as follows:

- Lon_2D – Borderline Level 1/2 pitch configuration that is highly PIO resistant even in the presence of significant rate limiting. Initial response may be considered too abrupt to consistently generate Level 1 ratings.
- Lon_2P – Level 2 pitch configuration that has the same bare airframe dynamics as 2D with a command path filter (τ = 0.25). This configuration is susceptible to PIO in the presence of rate limiting.
- Lon_2H – Borderline Level 2/3 pitch configuration that has the same bare airframe dynamics as 2D with a command path filter (τ = 0.5). This configuration is susceptible to PIO when performing high gain tasks and when performing any task in the presence of rate limiting.

A key proof of concept "success criterion" was to demonstrate that a pilot could distinguish variations in handling qualities as configurations were changed. Having worked through technical issues on the first two flights, the evaluation pilot was able to assess handling qualities between configurations on the third flight. To highlight this capability, the evaluation results of configuration Lon_2D and Lon_2H are considered. Lon_2D was the baseline configuration, while Lon_2H was the same as the baseline with the addition of a significant command path lag. Comments from the pilot are included below. Note that chronologically, the Lon_2H configuration was flown first.

- Lon_2D comments: “HQR 5 and PIOR 3. The simulation was more stable, but the evaluation was rushed. More stable laterally and in pitch. Less overshoots. More predictable.”

- Lon_2H comments: “Little bit of a pitch PIO there as I was trying to correct. Pitch is much more sensitive. Big time overshoots on every attempt to capture. It may be a time delay in there… it’s causing a PIO. I have to completely quit. Entering the control loop, divergent oscillations do develop and I have to just quit. PIOR 5. Could not get adequate performance. Considerable pilot compensation required for control. HQR 8.”

Ultimately, the feasibility of the Fused Reality® Flight system was successfully demonstrated using the Learjet in-flight simulator that was flown by three test pilots. Helmet/head tracking in the Learjet cockpit using IR cameras and reflective markers allowed a virtual scene that was driven by actual aircraft motion to be presented to the pilot at the controls, while a safety pilot monitored the flight. The out-the-window scene was sensed and replaced in real time, framed by the near cockpit environment that was left intact. Thus, the evaluation pilots were able to approach a virtual tanker and track an aerial refueling drogue that was extended from a Buddy Store on the wing of the tanker. The pilots were able to monitor key aircraft parameters from a virtual head-up display or by gazing at the actual cockpit instruments.

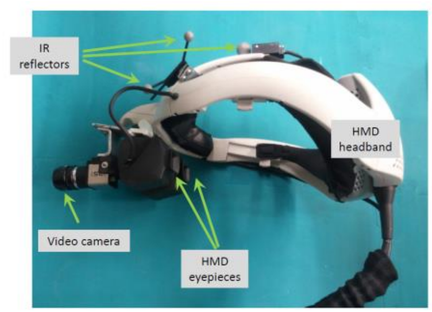
C. National Test Pilot School GippsAero GA-8 Airvan System Demonstration

This section features material summarized from Reference 2.

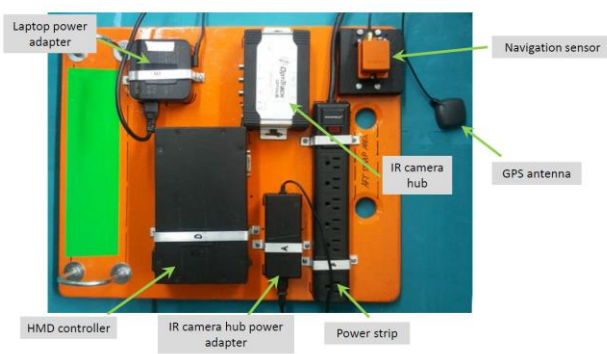
1. System Integration with the Test Aircraft

The hardware elements as integrated in the NTPS Airvan are shown in Fig. 8. The Optitrak IR cameras, Fig. 8a, are attached via suction cup camera mounts to the cockpit windscreen. The cameras with 640 x 480 resolution are used to track the pilots head in 6 degrees of freedom. The heart of the Fused Reality® system is the HMD shown in Fig. 8b. The Intevac IP40 HMD features 1024x768 resolution and a 42 degree diagonal field-of-view. The custom HMD has an integrated Imaging Development Systems USB 3.0 camera. Finally, the HMD includes a constellation of IR reflectors that are used for the head tracking.

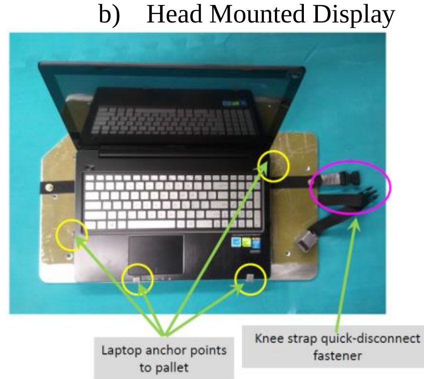
a) Head Tracker IR Cameras



b) Head Mounted Display



c) Component Pallet



d) Laptop Computer Pallet

Fig. 8 Fused Reality® system components as integrated with the NTPS Airvan [2].

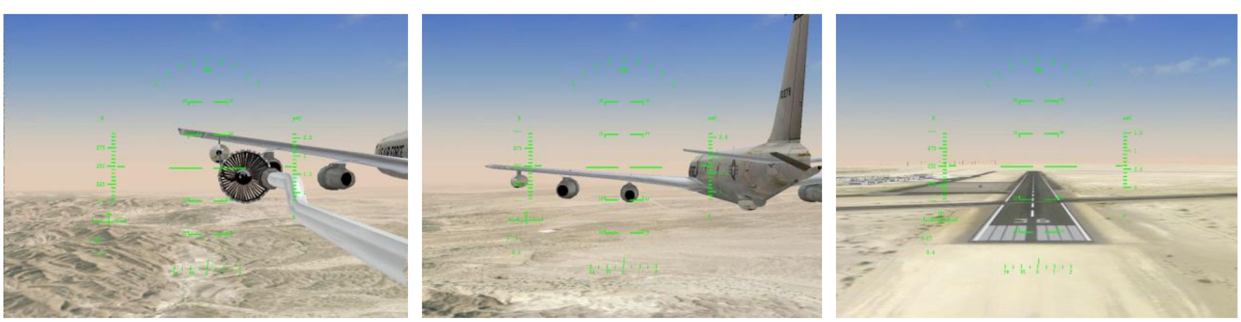
Two pallets complete the FR system integration, a component pallet (Fig. 8c) and a laptop computer pallet (Fig. 8d). The component pallet was secured to the floor using the row two seat attachment points. The Laptop pallet was secured to the FTE console installed in the NTPS Airvan. A key element of the component pallet is the Xsens MTi-G-700 GPS/INS sensor and GPS antenna that allows FR to be operated as a stand-alone system, thus allowing integration with virtually any aircraft. The ASUS laptop is a commercial-off-the-shelf system.

The GippsAero GA-8 Airvan (N215AV), shown in Fig. 9, is a strut braced, high wing, eight seat, Federal Aviation Administration (FAA) type certified aircraft. The test aircraft has 2,140 total hours and a single Lycoming IO-540-K1A5 piston engine with 480 hours SMOH. The engine is capable of producing 300 HP at 2,700 RPM (maximum takeoff power) and 275 HP at 2500 RPM (maximum continuous power). The engine is fitted with a two bladed 84 inch Hartzell HC-C2YR-1BF/F8475R metal constant speed propeller. The GA8 has single slotted manually actuated flaps which extend 14° in take-off configuration and 38° in landing configuration. The aircraft is equipped with fixed tricycle landing gear with nose wheel steering and hydraulic disk brakes lacking an antiskid system. The wings have integrated fuel tanks inboard of the strut junction capable of carrying 88 gallons of usable fuel. A pitot/static probe is installed in the leading edge at the outboard end of the left wing. A single electrical stall warning vane switch is located in the leading edge of the left wing at approximately mid span. The fuselage is designed as a lifting body which produces a significant percentage of the lift at high angles of attack and low airspeeds. The aircraft configuration under test has an empty weight of 2,601 pounds and a maximum gross weight of 4,000 pounds.

Fig. 9 NTPS Airvan.

2. Evaluation Tasks

Fused Reality® as evaluated as part of the NASA-sponsored flight test program featured three handling qualities evaluation tasks; 1) Drogue Tracking, 2) Formation Flying, and 3) Precision Landing at altitude, straight in and with 200 ft lateral offsets. These tasks were based on the Reference 7 demonstration maneuver catalog. The system allows the tasks shown in Fig. 10 to be performed in a consistent and repeatable manner. Each task featured elements to aid in the handling qualities assessments. For the drogue tracking task, the drogue would appear as shown in Fig. 10a. As the aircraft approaches the drogue, the drogue color turns green for desired tracking position and gray for adequate position. When the probe is outside of adequate, drogue color changes to red. For the formation flying task, markers can be added to the target aircraft that indicate how tightly the aircraft is being tracked. Finally, desired and adequate performance boxes can be added and sized as desired to the runway scene. It was also essential to indicate touchdown through visual cueing on the HUD, due to the lack of proprioceptive feedback at the touchdown point.



a) Drogue Tracking b) Formation Flying c) Precision Landing

Fig. 10 Evaluation tasks.

was on the Fused Reality® Flight system's ability to expose the aircraft's handling qualities and not the actual handling qualities of the Airvan.

a) Virtual Mode b) Stencil Mode

Fig. 12 Formation flying task Fused Reality® modes.

As a result of these flight tests, the issues uncovered in the initial flight test campaign using the Calspan Learjet and during the initial GA-8 checkout flights were corrected and tested in flight. The team that includes evaluation pilots, safety pilot, and flight test engineers, all felt that the handling qualities ratings obtained were representative of the actual aircraft and were not due to influences of the Fused Reality® Flight system. The key take away with regards to the utility of the Fused Reality® Flight system was the noted lack of latency issues. System lag was not identified as a factor by any of the evaluation pilots. There were several comments about how new elements could be added to the virtual HUD, particularly for the landing task. The virtual HUD could either be fixed or set to track pilot head movement depending on pilot preference. There were also for/aft cueing issues noted because of the limited field-of-view of the HMD.

IV. Integration of Commercial Off-the-Shelf Hardware

To create the new Fused-Reality® Flight system, the enabling Fused Reality® technology went through major updates to improve both the hardware and software elements as summarized herein.

A. Software Migration

The original Fused Reality® graphics were built using the Open Source 3D Graphics Engine. Support for this package has been discontinued. Furthermore, the algorithms for the keying effects that enable real-time video compositing of real-world and virtual elements were written in a low-level graphics processor code. To modernize the graphics, Fused Reality® was migrated to the Unreal Engine that is actively being developed and supported for the gaming development community. The keying algorithms were reproduced both in code and using Unreal Engine's block-based programming tool, Blueprints. Additionally, within the Unreal Engine, virtual object classes were created that enable users to rapidly initialize custom scenarios (e.g., the offset landing virtual environment). The new graphics also feature a custom head-up display interface so that the end users can develop symbology suited to their task and then seamlessly integrate the new virtual display within the graphics environment with little effort.

Another major overhaul to the Fused Reality® Flight system was rearchitecting the software to make it modular. This modularity allows the end user to develop and add new features without having to change core software components. This differs from the original code in that the kinematics, simulation, and head-up display software were all integrated with the graphics, making modifications difficult. With the new modular architecture, rapid development and testing of new software components is easily accomplished.

B. Hardware Enhancements

Another core element to Fused Reality® Flight that has been improved is the hardware. The original hardware was custom designed and integrated. Furthermore, the HMD was cumbersome to wear, had a limited field-of-view, used outside-in head tracking that required external cameras, and featured only one camera for capturing the real world. The new hardware features fully commercial-of-the-shelf components that were specifically designed to interface with each other. The Zed-mini cameras used for the real-world visuals not only are bifocal, adding depth to the visuals, but also include inside-out head tracking, eliminating the need for dash mounted cameras. The new HMD features higher resolution displays and greater field-of-view than the original hardware. It is also lightweight compared to its predecessor and is designed to fit comfortably on the user. Finally, because the new hardware is COTS, it is less expensive and easier to replace. The original and new hardware are illustrated in Fig. 13.

a) Original Fused Reality® Flight Hardware

b) Current Fused Reality® Flight Demonstration Hardware

Fig. 13 Comparison of original Fused Reality® Flight hardware and new demonstration hardware.

C. Technology Demonstration

A demonstration version of the new Fused Reality® Flight system was created using the software and hardware components described above. Three important keying technologies were included in the demonstration: 1) chromakey, the real-time video editing technique based on color; 2) lumakey, a real-time video editing technique based on light intensity; and 3) depth/geometry keying, a real-time video editing technique based on a three-dimensional map. These techniques can be used individually or in-combination to enhance overall system performance. A dynamic simulation environment was demonstrated using STI's research flight simulator components and a green screen technique as shown in Fig. 14. All desired features were successfully demonstrated with improved performance over the enabling Fused Reality® technology.

On the left a completely virtual scene as observed in the HMD is shown, while on the right a stenciled virtual aircraft is shown in an otherwise real-world environment. This panel also illustrates the proper occlusion of both real and virtual elements as the pilot's hand enters the camera field-of-view. That is, the pilot's hand is clearly seen in front of both the real-world out-of-the-window environment and the virtual aircraft that resides within this environment.

a) Full virtual image as seen in HMD

b) Stencil mode with occlusion of combined image

Fig. 14 Fused Reality® Flight demonstration.

D. Initial Hardware Assessment

For the new Fused Reality® Flight system, the current hardware for capturing and displaying the near space cabin environment to the pilot user is the ZED Mini Stereo Camera combined with the Oculus Rift HMD (Fig. 15). As shown in Table 1, the available image settings for the ZED camera vary in resolution, field-of-view (FOV), and trade-offs in framerates. Lower framerates at 30 fps were found to increase image jittering and lags, significantly affecting the usability of the HMD for pilot training purposes. A framerate of 60 frames per second using the HD720 image setting was found to provide the most optimal image relative to FOV and image quality.

To assess the visual acuity degradations and image quality trade-offs of the ZED camera at HD720, a preliminary evaluation was conducted using a sample of STI employees, $N = 5$. Far and near visual acuity tests were conducted while wearing the HMD at four camera image settings: HD2K, HD1080, HD720, and WVGA. A degradation category rating (DCR) test was designed to collect subjective image quality ratings of the four image settings using a series of screengrab images varying in object complexity (e.g., shape, textures, text). Findings may direct resources and effort towards: (i) mitigating current camera issues, (ii) improving imaging processing capabilities to allow for higher resolution settings, and/or (iii) considering alternative camera hardware options.

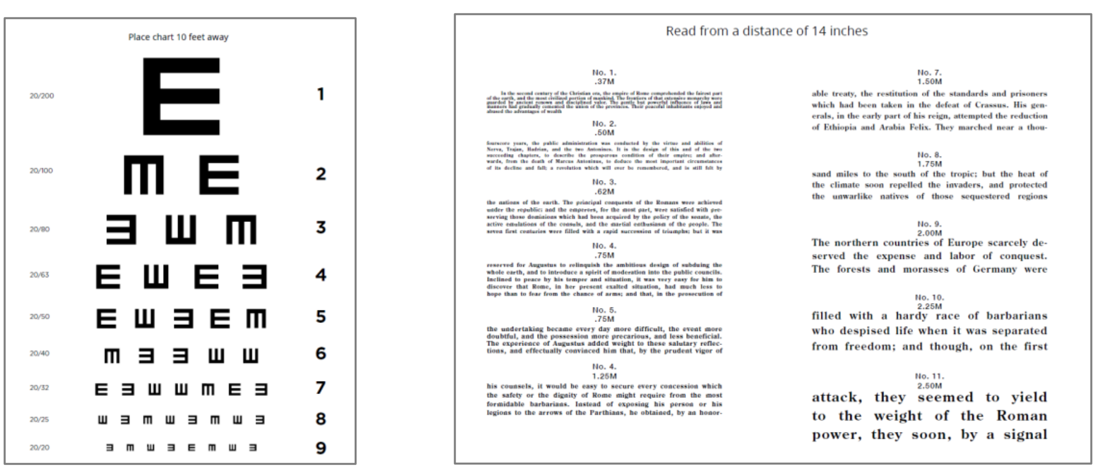
Fig. 15 Fused Reality® Flight system with ZED Mini Stereo Camera mounted on an Oculus Rift HMD.

Table 1: ZED Mini Stereo Camera Available Image Settings

Image Setting	Resolution (width x height)	Field-of-View (vert. x horiz.)	Framerate Max (fps)
HD2K	2208 x 1242	47° x 76°	15
HD1080	1920 x 1080	42° x 69°	30
HD720	1280 x 720	54° x 85°	60
WVGA	672 x 376	56° x 87°	100

A preliminary evaluation was conducted using a sample of five (males, aged: 27 to 43 years, normal health, 20/20 vision). Far and near visual acuity tests (Tumbling E and Jaeger eye charts) were conducted while wearing the HMD at four camera image settings: HD2K, HD1080, HD720, and WVGA.

Far visual acuity was measured using a 11 x 8.5-inch printout of the Tumbling E eye chart set at a viewing distance of 10 ft. Near visual acuity was measured using a 11 x 8.5-inch printout of the Jaeger eye chart set at a viewing distance of 14 inches (Fig. 16). Both charts were sourced from www.allaboutvision.com. To prevent memorization of eye chart items, the presentation order of the HMD image settings started with the lowest resolution (WVGA) and finished with the highest resolution (HD2K). Acuity tests were finished using the naked-eye (i.e., no HMD) to confirm a minimum of corrected 20/20 far vision and J1 near vision.



a) Tumbling E eye chart

b) Jaeger eye chart

Fig. 16 Visual acuity tests for far vision.

A degradation category rating (DCR) test was performed using a double-stimulus impairment scale method with still image screen grabs using the HD2K setting as the source reference. A total of 12 different still images types, composed of objects of varying image complexity (e.g., textures, presence of text) were used. For every still image type, four image setting pairs were used: HD2K vs. HD2K (rater reliability check), HD2K vs. HD1080, HD2K vs. HD720, and HD2K vs. WVGA. A total of 48 image pairs were randomly presented to participants using a slideshow format presented on a 31inch high definition (HD) monitor. First and second stimulus pairs were presented for 3 seconds each, followed by 8 seconds, asking participants to rate the impairment of image 2 compared to image 1. Ratings involved a 5-pt scale: 5=imperceptible, 4=perceptible but not annoying, 3=slightly annoying, 2=annoying, 1=very annoying.

Results of the visual acuity and subjective image quality tests of the HD720 image settings suggest that reading text via the ZED camera may be the most problematic issue for HMD users. Visual acuity was relatively poor for the HD720 setting (Table 1) suggesting readability of at best 13-14 point-type. Mean opinion values (MOV) for the DCR test suggest image quality under HD720 is poorest for objects ranking highest in complex imagery (Fig. 17). Unlike lower complexity objects (e.g., football, paper towel roll, salt shaker), these objects included texts, dials, and instrumentation that could explain participants' increased annoyance for any image quality degradations. However, objects that do not require the reading of texts may provide an image quality experience not too far from those experienced in HD1080. This suggests that the Fused Reality® Flight system using the ZED camera system may provide an effective HMD interface if text reading issues can be mitigated by either graphically displaying relevant flight information within the HMD or improving imaging processing capabilities to allow for use in the HD1080 image setting.

Future evaluations of the HMD cameras and Fused Reality® Flight system as whole may involve assessments not explored here. This includes: (1) action capabilities of users when wearing HMD cameras, i.e., near space object reaching accuracy and adaptation rates, (2) image quality assessments under more realistic pilot-user environments, (3) usability issues of displaying relevant flight display information within the HMD to compensate for visual acuity deficits from the HMD cameras.

Table 2: Mean (Standard Deviation) Far and Near Visual Acuity by Image Setting, *N* = 5

Image Setting	Visual Acuity Mean (*SD*)	
	Far	Near
Naked-Eye	20/20 (0)	J1 (0)
HD2K	20/81 (13)	J9 (.5)
HD1080	20/92 (11)	J10 (.5)
HD720	20/160 (55)	J11+
WVGA	20/200+	Out of range

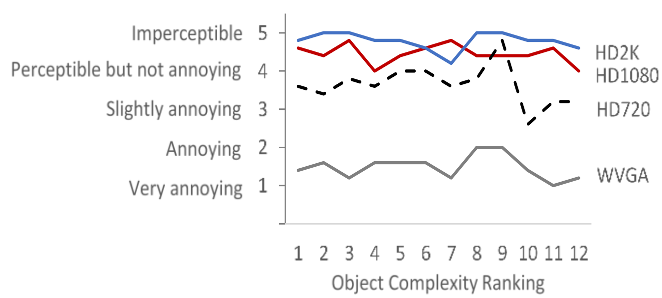


Fig. 17 Mean opinion values for the DCR test by image settings across object complexity rankings (1=Lowest, 12=Highest), n = 5.

V. Conclusions

Building on the promise of virtual, mixed, and augmented reality-based simulation solutions, Systems Technology, Inc. developed and patented Fused Reality®, a simulation tool that allows for the blending of real and virtual elements in a real-time environment. Using customized hardware, an in-flight simulation version known as Fused Reality® Flight was developed that features novel cueing techniques that allows for full virtual out-of-the cockpit window scenes or the placement of dynamic virtual objects within the real-world out-of-the cockpit window environment.

Under NASA sponsorship, the system was twice demonstrated in flight. In the first application, the system was integrated with the Calspan Learjet in-flight simulator, where a drogue tracking task was used to demonstrate the effectiveness of the system in exposing differences in aircraft handling qualities. Here the system made use of the Learjet instrumentation. In the second application, three handling qualities evaluation tasks were successfully demonstrated using a stand-alone version of the system as integrated in a National Test Pilot School GA8 Airvan. In its latest incarnation, low cost commercial-off-the-shelf hardware is now used with improved software and image generation capability to provide enhanced system performance.

Acknowledgments

The authors wish to acknowledge the technical talent of Systems Technology, Inc., past and present, that created and advanced the patented Fused Reality® system and its in-flight derivatives. The original concept was developed by Dr. Edward Bachelder. Technical and programmatic support for the Fused Reality®-based applications was provided by R. Wade Allen, Dr. Sophia Apreleva, Noah Brickman, Wagner de Abreu, John Grant, David Landon, Dr. Dongchan Lee, Dr. Chi-Ying Liang, Gabriel Lu, Thomas Myers, Cecy Pelz, Theodore Rosenthal, Peter Salvador, and Peijie Yang. A complete rewrite of the software code was made by Justin Gray for the latest Fused Reality® Flight iteration with support from Dr. Liang and Peijie Yang. Gabriel Lu provided the graphics imagery.

References

1. Bachelder, E. N., D. H. Klyde, N. Brickman, S. Apreleva, and B. Cogan, "Fused Reality for Enhanced Flight Test Capabilities," AIAA Paper No. 2013-5162 presented at the *Atmospheric Flight Mechanics Conference*, Boston, MA, 19-22 Aug. 2013.
2. Olson, R., D. H. Klyde, and B. Cogan, "Flight Testing of Fused Reality Visual Simulation System," *46th Society of Flight Test Engineers International Symposium*, Lancaster, CA, 14-17 Sept. 2015.
3. Bachelder, E. N., Ph.D. and G. D. Park, "Simulation Training Using Fused Reality," in PSI Handbook of Virtual Environments for Training and Education, D. Schmorrow, J. Cohn, and D. Nicholson, Eds., 2007.
4. Latimer, Kelly J., *An Investigation of Three Probe-and-Drogue Air Refueling Tasks to Investigate Longitudinal Closed-Loop Handling Qualities (HAVE GAS II)*, AFFTC-TR-97-13, June 1997.
5. Klyde, D. H., A. K. Lampton, P. C. Schulze, D. J. Alvarez, R. Johnson, and L. Rowe, "The Real Flight Approach to Assess Simulator Force Cueing Fidelity," AIAA Paper No. 2013-5161 presented at the *Atmospheric Flight Mechanics Conference*, Boston, MA, 19-22 Aug. 2013.
6. Mitchell, D. G., R. H. Hoh, *Development of Methods and Devices to Predict and Prevent Pilot-Induced Oscillations*, AFRL-VA-WP-TR-2000-3046, Dec. 2000.
7. Klyde, D. H., and D. G. Mitchell, *Handling Qualities Demonstration Maneuvers for Fixed Wing Aircraft Vol. II: Maneuver Catalog*, WL-TR-97-3100, Oct. 1997.
8. Cooper, George E., and Robert P. Harper, Jr., *The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities*, NASA TN D-5153, April 1969.