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Pocket-size Augmented Reality System for Flight Control

Andrey L. Gorbunov[1], Alessandro Terenzi[2] and Graziano Terenzi[2]

[1] Moscow State Technical University of Civil Aviation, Russia
[2]Inglobe Technologies S.r.l., Italy

Abstract

Head-up displays (HUDs) have become common equipment in aircraft cockpits. One of the uses of HUDs is to provide a specific visual interface for pilots in the form of what is called a "tunnel-in-the-sky" (i.e. 3D geometry for the navigation path displayed on a flat screen). According to recent studies the "tunnel-in-the-sky" approach does not provide crucial advantages in comparison with more traditional methods of presenting navigation information to pilots. This paper considers a stereoscopic version of the 3D "tunnel-in-the-sky" realized as an augmented reality (AR) pocket-size system with see-through light-weight AR glasses. The system consists of low-cost items and does not suffer from the drawbacks tied with existing synthetic/enhanced vision systems for pilots. The design of experiments with desktop simulators of different AR pilot's interfaces (2D, 3D and stereo 3D conditions) and their results are described. The results of the experiments prove the effectiveness of the proposed stereo AR solution. Flight test of the prototype of the proposed AR system carried out on Cessna 172 aircraft is also described.

Categories and Subject Descriptors (according to ACM CCS): I.4.8 [Image Processing and Computer Vision]: Scene Analysis — Tracking; J.2 [Physical Sciences and Engineering]: Aerospace; H.5.1. [Information Interfaces]: Multimedia Information Systems – Artificial, augmented and virtual realities.

1. Introduction

Pilot visual interface called "tunnel-in-the-sky" (TS) has been known for about 20 years. The first successful tests of aircraft control systems with TS on real aircrafts were carried out back in the 90s [BAJP99]. Despite its advantages, the synthetic vision systems (SVS) associated with TS are not a widespread tool, although they continue to be within the research scope [NKK*12] and are available for pilots on some modern Head-Up Displays (HUD).

The reasons why standard TS systems are not so widespread appear to reside on the following circumstances: 1) the progress of automatic systems for flight control has made TS not a high priority topic for big commercial aircrafts; specifically, existing HUD TS solutions are not compact and cost-effective enough to be easily adopted for civil aviation purposes; 2) the 3D version of TS working on standard SVS flat screens or even on HUDs endowed with enhanced vision system (EVS) does not provide any crucial advantages in comparison with conventional Primary-Flight-Displays (PFD) [AGB*11].

This paper describes the prototype of a stereoscopic TS system. The prototype is realized as an augmented reality (AR) system and it does not suffer from the aforementioned drawbacks because: 1) only low-cost components are used, i.e. light (<150 gm), optical see-through AR glasses with in-built tracking sensors and camera, and a mobile computer as a glasses controller; this makes the prototype autonomous and literally pocket-size; 2) the TS is presented in the form of stereo 3D frames with a depth dimension; such a presentation replaces all the navigation indicators of standard PFDs, and also has an extremely simple visual structure which is natural for humans

The 3D Stereoscopic Augmented Reality Tunnel in Sky system (3DS-ARTS) can be employed as an aid for commercial aircrafts during emergency situations, like, for example, when there are problems with standard equipment (e.g. the incident with American Airlines A-320 in Newark in 2008, the crash of Air France A-330 in the Atlantic in 2009) or while landing in low visibility conditions (e.g. the crash of Polish president Tu-154 in 2010). In the future 3DS-ARTS may become the main way of presenting navigation information to pilots of general aviation aircraft.

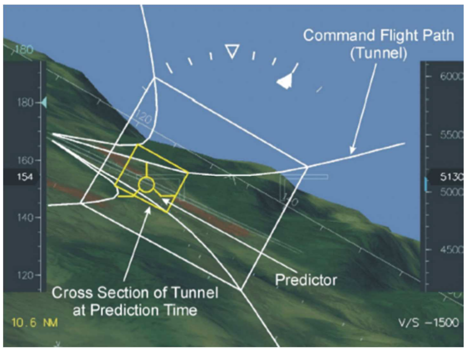

Figure 1. *SVS display with TS [SSS06].*

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2. Related work

Many studies have investigated the efficacy of synthetic vision systems (SVS) through "tunnel in the sky" (TS). In 1998 landing tests using SVS with TS on real aircrafts (Piper Dakota and Beechcraft Queen Air, 9 pilots) were conducted by researchers from Stanford University in 3 airports in Alaska where high levels of pilots' appraisals was reported [BAJP99]. The same system was used in the WAAS landing experiments carried out at the San Francisco International Airport in order to compare it with the traditional Instrument Landing System (ILS) [HBP*99]. Twenty-seven landings of Beechcraft Queen Air were made during these experiments. Two visual interfaces were analyzed: SVS with TS and the traditional course deviation indicator with needles. The results proved the advantage of SVS with TS (considerably less deviation from the landing trajectory) over the traditional system. Successful landing trials took place in Bandung (Indonesia) using Cessna-172 and SVS with TS, the pilots managed to maintain the aircraft inside the tunnel 45x27 m with the mean deviation 9 m [IJM04]. The landing along the curved and steep approach trajectory is described in [SSS06]. The goal of the experiment was to clarify whether it is possible to use SVS with TS (40x30 m frames) to execute such a maneuver. The vertical and lateral deviations from the command trajectory were monitored. The result: the aircraft was kept inside TS. The detailed description of the used SVS with TS is reported in [SH08].

A study of several TS types in low visibility conditions is described in [AGB*11]. The experiments were performed on a Boeing-747 simulator with 10 experienced pilots. The display type was an independent variable: a conventional PFD, used in conjunction with a degraded, but still available, outside-vision presentation in the simulator and four types of SVS with TS without outside visibility. The dependent variables included the pilot control activity, pilot workload, path-following performance and landing performance. The results showed that all SVS with TS helped to perform the landing procedure but no improvement of effectiveness was observed when compared to PFD. The authors suppose that this is caused by an intrinsic difficulty with the perception of information from a display, as the difference between the natural field of view and field of view of the display (not to mention the small size of the display) influence the pilot control strategy.

AR technology is strictly related with TS systems. In pilot applications, usually TS is an attribute of the enhanced vision systems (EVS) where the image of the real world is augmented (via HUD [KGI12] or the AR display with tracking of the pilot head [ZDLB11]) by the images from an infrared camera or a 3D model of the terrain. HUDs can be considered as a kind of AR display, even in the case when just conventional PFD symbolism is demonstrated on its screen (in this case we are talking about the augmentation of the real world by 2D symbols, 2DAR). A number of papers have been also dedicated to AR applications for the surface operations in airports [BAPK07, FAH05, MBT02]. In the context of this paper these studies are relevant because they contain the results of comparing different AR representations of information.

The specifications of visual AR interfaces per se have not been deeply investigated so far. The subject of the research described in [BTOF06] was "funnel-in-the-air". It consisted of frames very similar to TS. The test was to find one of 48 objects. The dependent variable was the type of the search instruction: 1) virtual funnel in the air, 2) green light highlighting and 3) audio instruction. It was discovered that the virtual funnel provides 50% increase of the search speed and 18% decrease of the workload (NASA TLX scale was used). [ABG*11] is dedicated to the study of an AR system that follows user's attention to objects in his field of view as well as searches the relevant text information and superimposes it onto the real world image. The tests was related with the comparison of two solutions for the visual AR interface: AR helmet and mobile computer.

The analysis of the research output on topics related to TS, SVS, EVS and AR allows us to draw the following conclusions:

1) SVS with TS as a navigation interface does not only provide any crucial advantages but also causes some specific problems; and

2) The use of AR technology is promising, especially when using 3D information, but today's HUDs do not provide support for stereoscopy and the impact of stereoscopic 3D information on pilot's performance is not well understood.

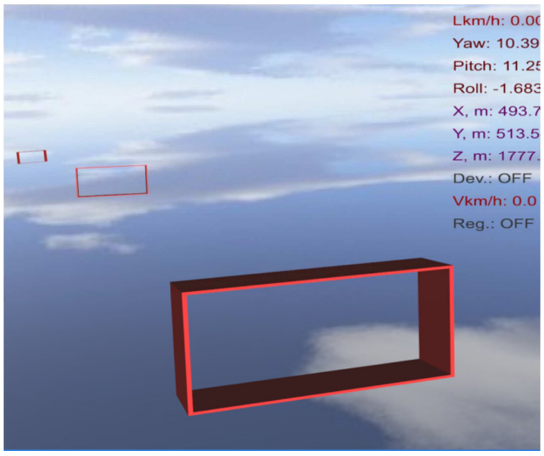

Figure 2. *3DSAR TS.*

3 Stereoscopic AR for tunnel in the sky systems

3DSAR is close to the natural human perception of visual information and possesses some significant advantages over the standard 2DAR and 3DAR:

- Being realized by means of see-through AR glasses, it excludes additional workload since it does not require the coordination of fields of view and zooms for the real world and the display image as it happens in the case of SVS [AGB*11];

- The frames forming TS gain a depth dimension and are oriented along the horizon (fig. 2). In stereo mode it allows visual evaluation for the aircraft yaw, pitch and roll in a way which is normal and highly accurate for humans. Also, it excludes the workload related with the transformation of symbology to the estimations of these angles as it is with PFD [FHWJ02];

- Stereoscopic vision provides pilots with the possibility to estimate the distance through the 3DSAR frames, i.e. space coordinates of the aircraft; and

- 3DSAR removes the problem of attention capture [Pri04] which is typical of HUDs, since the navigation indicators become a part of the real world.

3.1 Overview on the System

The components and the structure of 3DS-ARTS prototype is shown in fig. 3. TS is displayed to the user via see-through Vuzix STAR 1200XL stereo glasses with 1280x720 resolution, 75-inch virtual screen as viewed from ten feet and adjustable eye-separation. The positioning of virtual objects (3D shapes marking the flight trajectory) requires space and angle coordinates for the pilot’s head. Certified for landing procedures GPS/SBAS receiver Garmin GTN 625 is used as a source for the space coordinates. The angle coordinates in a global reference system are obtained from the microelectromechanical sensors (MEMS) built into the Vuzix glasses (accelerometers, gyroscopes, magnetometers), the yaw coordinate in local reference system related to the cockpit is received from the infrared tracker TrackIR 5

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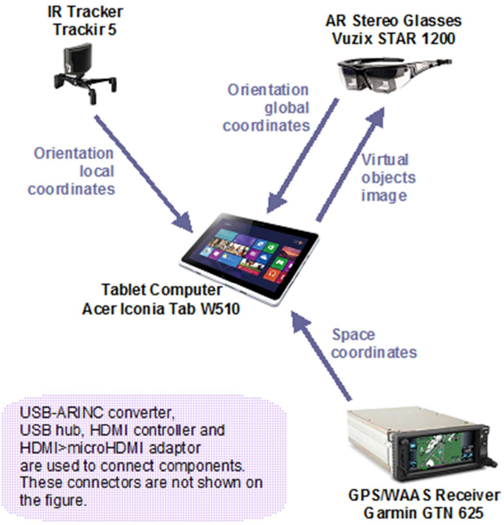

USB-ARINC converter, USB hub, HDMI controller and HDMI>microHDMI adaptor are used to connect components. These connectors are not shown on the figure.

Figure 3. *System architecture.*

A considerable drift of the gyroscopes causes a problem with the orientation coordinates obtained using MEMS only. It especially concerns the yaw drift (pitch and roll drifts are successfully compensated by the filtration with the use of the accelerometer data). The original patent protected technology [Gor11] (RU patent received [GKZ13], PCT patent filed) is used to correct the yaw drift. This technology implies a) the use of an aircraft movement vector (computed on the basis of the linear regression or the moving average for the GPS data) in conjunction with the infrared tracker data with the purpose to generate the yaw while moving and b) the use of an estimate of the yaw drift calculated a priori to generate the yaw when the aircraft is in state of no motion.

4 Method and results

Two main experiment series were designed with the purpose to get comparative evaluations for 2DAR, 3DAR and 3DSAR interfaces: 1) using the interfaces simulators on a desktop displays; 2) using 3DS-ARTS and PFD on board of a light aircraft.

4.1 Experimental study of the interfaces

The goal of the first series of experiments is to reveal general differences between the investigated interfaces. Subjects without pilot experience were recruited for the tests. Professional pilots were intentionally not included in the subject groups, since their flight experience would be a distorting factor for the comparative experiments for the technology.

Three groups of subjects took part in the experiments. Each group consisted of 12 university students. Groups were homogeneous by gender, age and education level. All subjects had an experience of playing flight simulators with joysticks. Being the participants students at an aviation university, all of them had basic knowledge of aircraft guidance systems. Three computer flight simulator programs have been developed using the Vizard VR Toolkit to simulate the flight along the same landing path: the flight simulator using 2DAR interface (imitating HUDs); the flight simulator using 3DAR interface (imitating SVS); the flight simulator using 3DSAR interface where the 3D shapes marking the flight trajectory had the depth dimension and were oriented horizontally. The virtual plane was controlled by means of a joystick.

2DAR and 3DAR simulators worked with a common display, and the 3DSAR simulator worked with a stereo display ViewSonic vx2268vm 3D Ready (22”, 120 Hz, 1680x1050 resolution) and NVIDIA 3D Vision active stereo LCD glasses. The first group of subjects “landed” the virtual plane using the 2DAR interface, the 2nd group of subjects used the 3DAR interface and the 3rd group of subjects used the 3DSAR interface. The simulators were run on a Intel Core i7/920 computer, RAM DDR-III 1Gbx3 and NVIDIA Quadro FX 3800 graphic processor. The independent variable was the type of the visual interface. The dependent variables were the mean deviation R of the virtual plane trajectory from the ideal landing path (was registered each 50 m) and the mean time K spent by a subject to correct deviations from the ideal landing path arising from the modelled external actions. The experiment results were processed to test: 1) anomalous values using the maximal relative deviation criterion, 2) the normal statistical law for a sample using Kolmogorov-Smirnov criterion, 3) the homogeneity for samples using Wilcoxin-Mann-Whitney criterion, and 4) the independence for sample elements using Abbe criterion. All of the subjects took part in a short learning session before the trial.

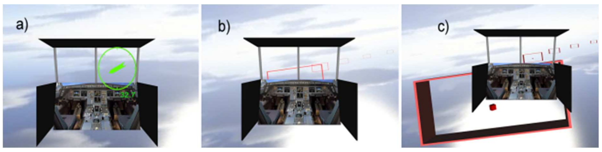

Figure 4. *Simulation interfaces; a) standard 2DAR / HUD b) 3DAR c) 3DSAR.*

The schema of the simulated interfaces 2DAR, 3DAR and 3DSAR is shown in fig. 4. The subject sees a part of the cockpit through the interfaces. 2DAR interface imitates HUDs. The arrow on the virtual HUD points to the direction of the required correction, and its length is proportional to the value of the correction. 3DAR interface has “flat” frames (40x20 m) as markers of the flight trajectory; 3DSAR interface watched via stereo glasses has the frames of the same size with depth dimension and with small cubes in the center of the frames. All the frames are aligned along the horizon.

Table 1. Experiment Results for R, m

Interface	Mean	Standard Deviation	Standard Error
2DAR	91.07	31.88	9.20
3DAR	10.12	4.14	1.19
3DSAR	7.19	1.39	0.40

Table 2. Experiment Results for K, s

Interface	Mean	Standard Deviation	Standard Error
2DAR	52.85	36.33	10.49
3DAR	5.87	2.85	0.82
3DSAR	4.8	1.24	0.36

The following hypothesis has been checked in the experiments: the stereoscopic interface 3DSAR provides better efficiency of the flight control by the criteria of the path following the accuracy and the speed of return to the path after deviations than flat 3D interface 3DAR and symbol interface 2DAR.

Tables 1, 2 represent experiment results as the statistical estimates of the mean deviation R and mean time K. Errors are shown as the standard errors in figures 5 and 6.

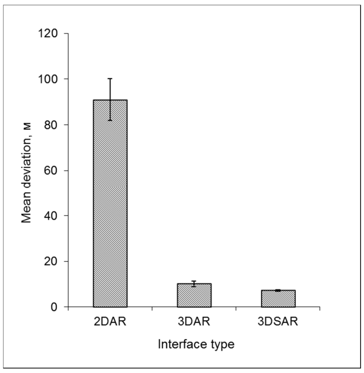

Figure 5. *Experiment results for R, m.*

All the tests of the experiment data were performed with p=0.05. The tests for the normal law and independence were positive for all samples. The test for the homogeneity was positive while comparing 3DAR a 3DSAR samples and negative for 2DAR and 3DAR samples. Such results are well explained by the significant difference between the symbol character of 2DAR and the nature of the visualization in 3DAR, where virtual objects are used.

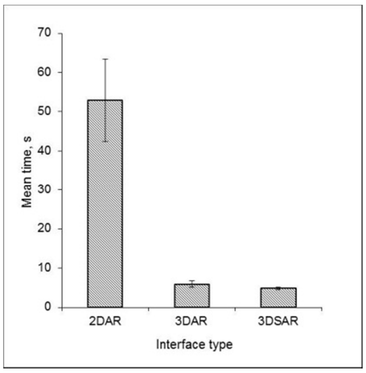

Figure 6. *Experiment results for K, s.*

The statistical significance of the obtained results is proved by one-way ANOVA test for all but one combination of data samples. The significant main effect has been shown for:

- mean deviations for 2DAR, 3DAR, 3DSAR – F(2,33)=78.79, p=2.71E-13;
- mean deviation for 3DAR, 3DSAR – F(1,22)=5.41, p=0.029;
- mean times for 2DAR, 3DAR, 3DSAR – F(2,33)=20.38 p=1.72E-06;
- it has not been shown for mean times for 3DAR, 3DSAR – F(1,22)=1.42, p=0.246.

4.2 Flight test

The flight test on the Cessna-172 aircraft has been carried out to check the ability of 3DS-ARTS to correctly position the virtual TS. A video reconstruction of the flight test is available at https://www.youtube.com/watch?v=zhu81jvVdKM. The video demonstrates the functioning of the system.

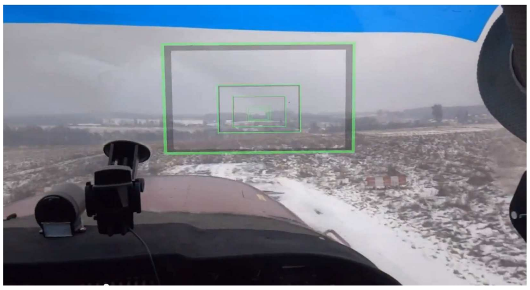

Figure 7. *Flight test on the Cessna-172 aircraft.*

As expected, the infrared tracker was found to be instable in sunny conditions. This instable behavior was improved by means of a semi-transparent metalized film used as a sun filter. We feel that the implementation of a SLAM method [SSC86] [LD91] using built-in Vuzix STAR 1200 camera for estimating position and head orientation in the local reference system might prove to be more effective in these circumstances.

The brightness of the virtual objects provided by STAR 1200 is unsatisfactory but still acceptable for the prototype since the field of the view in the real cockpit has the dark background of the dash. In the next versions glasses with improved brightness in outdoor environments (like Vuzix M2000AR) will be used.

5 Discussion and conclusion

The results of the experiments prove that 3DSAR is more efficient than more standard 2DAR and 3DAR interfaces supporting pilot navigation and landing procedures. The greatest difference (about a degree for both criteria) has been found between 2D and 3D interfaces. This is caused by the highest level of naturalness for the graphic interfaces with virtual objects “embedded” in the real environment using AR. However the comparison of 3DAR and 3DSAR shows considerably less mean deviation (significant difference, about 30%) and mean times (not significant difference, about 20%) for 3DSAR. Also standard deviations and errors were less in the case of 3DSAR.

The results from the desktop simulator tests cannot be directly translated into actual flight behaviors. This is the reason why NASA TLX workload test was not realized: the conditions of the desktop experiment differ from the cockpit experience, so it does not make sense to use it in a different context.

Notwithstanding the benefits this system has with respect to more traditional interfaces and systems, important improvement directions have emerged as a consequence of the flight test, like for example the opportunity to evaluate a different approach to estimate the pilot pose in the aircraft local reference system.

On one hand, the developed stereoscopic TS provides the pilot with everything necessary for spatial navigation to be able to follow the safe flight path (for example in low visibility conditions). On the other hand, it minimizes the amount of required information and makes the interface extremely simple and natural for human perception. Such an approach makes 3D terrain models for the landing area not obligatory and it decreases the requirements for hardware performance. Which, by-turn, leads to low cost, pocket size and wider accessibility.

References

[ABG*11] A. Ajanki, M. Billinghurst, H. Gamper, T. Järvenpää, S. Kaski, M. Koskela, M. Kurimo, J. Laaksonen, K. Puolamäki, T. Ruokolainen, and T. Tossavainen. An augmented reality interface to contextual information. *Journal Virtual Reality - Special Issue on Augmented Reality*, 15: 2-3, pp. 161-173, June 2011.

[AGB*11] R. Arents, J. Groeneweg, C. Borst, M. Van Paassen, and M. Mulder. Predictive Landing Guidance in Synthetic Vision Displays. *In The Open Aerospace Engineering Journal*, volume 4, pages 11-25, 2011.

[BAJP99] A. Barrows, K. Alter, C. Jennings, and J. Powell, “Alaskan flight trials of a synthetic vision system for instrument landings of a piston twin aircraft,” *Proc. SPIE Vol. 3691 Enhanced and Synthetic Vision*, pp. 98-106, 1999.

[BAPK07] R. Bailey, J. Arthur, L. Prinzel, and L. Kramer, “Evaluation of Head-Worn Display Concepts for Commercial Aircraft Taxi Operations,” NASA Langley Research Center, Hampton, VA, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070018770_2007018399.pdf 2007.

[BTOF06] F. Biocca, A. Tang, C. Owen, and X. Fan, “The Ominidirectional Attention Funnel: A Dynamic 3D Cursor for Mobile Augmented Reality Systems,” *Proceedings of the 39th Hawaii International Conference on System Sciences*, p 22c, 2006.

[FAH05] D. Foyle, A. Andre, and B. Hooey, “Situation Awareness in an Augmented Reality Cockpit: Design, Viewpoints and Cognitive Glue,” *Proceedings of the 11th International Conference on Human Computer Interaction*, Las Vegas, NV, USA, available at http://hsi.arc.nasa.gov/groups/HCSL/publications/Foyle_HCI2005.pdf 2005.

[FHWJ02] D. Foyle, B. Hooey, J. Wilson, and W. Johnson. HUD symbology for surface operations: Command-guidance vs. situation-guidance formats. *In SAE* Transactions*: Journal of Aerospace*, volume 111, pp. 647-658, 2002.

[GKZ13] A. Gorbunov, A. Kaurov, and A. Zelinsky, “System to correct the drift of MEMS gyroscope which is used in the augmented reality system on the moving object,” RU Patent 131151, 2013.

[Gor11] A. Gorbunov, “Modern Visual Interfaces for Aircraft Control,” *MSTUCA Research Bulletin*, volume 171, pp. 166-173, 2011.

[HBP*99] S. Houck, A. Barrows, B. Parkinson, P. Enge, and J. Powell, “Flight Test of WAAS for Use in Closely Spaced Parallel Approaches”, *Proc. of 1999 ION GPS conference*, Nashville, TN, USA, available at http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.167.4964&rep=rep1&type=pdf 1999.

[IJM04] A. Indriyatmoko, S. Jenie, I. Madani, and A. Budiyono, “Design and Implementation of Landing Guidance Program With Tunnel in the Sky based on GPS,” Department of Aeronautics and Astronautics Engineering Institute of Technology Bandung, http://www.ae.itb.ac.id/aves/paper/Tunnel-in-the-sky-Navigation-RC-ASTI-2004.pdf 2004.

[KGI12] E. Koyuncu, E. Garcia, and G. Inalhan, “Flight deck automation support with dynamic 4D trajectory management for ACAS: AUTOFLY-Aid,” *Proceedings of Integrated Communications,* *Navigation and Surveillance Conference (ICNS)*, Herndon, VA, USA, pp. C4-1 - C4-9, 2012.

[LD91] J.J. Leonard, H.F. Durrant-whyte: "Simultaneous map building and localization for an autonomous mobile robot", Intelligent Robots and Systems'91.'Intelligence for Mechanical Systems, *Proceedings IROS'91*. IEEE/RSJ International Workshop on, pp 1442-1447, 1991

[MBT02]J. Molineros, R. Behringer, and C. Tam, "Vision-Based Augmented Reality for Pilot Guidance in Airport Runways and Taxiways," *Proceedings of the 3rd IEEE/ACM International Symposium on Mixed and Augmented Reality ISMAR'2004*, pp. 302-303, 2004.

[NKK*12] J. Naylor, J. Kaber, S. Kim, G. Gil and C. Pankok, "Aviation display dynamics and flight domain in pilot perceptions of display clutter," *Advances in Human Aspects of Aviation*, S. J. Landry ed., CRC Press, pp. 43-53, 2012.

[Pri04] L. Prinzel, "Head-Up Displays and Attention Capture," Technical Report TR-213000, *NASA Technical Memorandum*, 2004.

[SH08] G. Sachs, and F. Holzapfel, "Predictor-Tunnel Display and Direct Force Control for Improving Flight Path Control," *Proceedings of the AIAA Guidance, Navigation and Control Conference*, Honolulu, Hawaii, USA, pp. 2179-2192, 2008.

[SSC86] R.C Smith, M. Self, and P. Cheeseman, "Estimating Uncertain Spatial Relationships in Robotics," *Proceedings of the Second Annual Conference on Uncertainty in Artificial Intelligence*. UAI '86. University of Pennsylvania, Philadelphia, PA, USA, Elsevier. pp. 435-461, 1986.

[SSS06] G. Sachs, R. Sperl, and I. Sturhan, "Curved and steep approach flight tests of a low cost 3D-display for general aviation aircraft", *Proc. of 25th Intern. Congress of the Aeronautical Sciences*, Hamburg, Germany, (available at http://www.icas.org/ICAS_ARCHIVE/ICAS2006/PAPERS/688.PDF) 2006.

[ZDLB11] S. Zou, Z. Dong, H. Lin, and H. Bao, "MRStudio: A mixed reality display system for aircraft cockpit," *Proceedings of IEEE International Symposium on VR Innovation (ISVRI)*, Singapore, pp. 129-135, 2011.