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Steering a simulated Unmanned Aerial Vehicle using a head-slaved camera and HMD

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ABSTRACT

Military use of Unmanned Aerial Vehicles (UAVs) is gaining importance. Video cameras in these devices are often operated with joysticks and their image is displayed on a CRT. In this experiment, the simulated camera of a simulated UAV was slaved to the operator's head movements and displayed using a Helmet Mounted Display (HMD). The task involved manoeuvring a UAV along a winding course marked by trees. The influence of several parameters of the set-up (HMD optics, Field of View (FOV), image lag, monocular vs. stereoscopic presentation) on a set of flight handling characteristics was assessed. To enable variation of FOV and to study the effect of the HMD optics, a simulated HMD consisting of a head slaved window (with variable FOV), was projected on a screen. One of the FOVs, generated in this way, corresponded with the FOV of the real HMD, enabling a comparison. The results show that the simulated HMD yields a significantly better performance than the real HMD. Performance with a FOV of 17 degrees is significantly lower than with 34 or 57 degrees. An image lag of 50 ms, typical of pan-and-tilt servo motor systems, has a small but significant influence on steering accuracy. Monocular and stereoscopic presentation did not result in significant performance differences.

Keywords: Head mounted displays, head tracked camera, Field of View (FOV), image lag, monocular vs. stereoscopic HMDs.

1. INTRODUCTION

In flying an Unmanned Aerial Vehicle (UAV), the remote operator's view of the ambient world is provided by one or more cameras on the vehicle and one or more monitors at the control station. In order to provide a large visual field, while restricting the required transmission capacity from vehicle to operator, a head tracked pan-and-tilt camera combined with a Head Mounted Display (HMD) is an potentially attractive solution. More attractive than joystick control of the camera's direction because, firstly, the operator's hands remain free and, secondly, the operator presumably knows intuitively and precisely in what direction with respect to himself and the UAV the viewed information is situated. In the Apache and Cobra helicopters, in flying at night or in low visibility, a HMD combined with a head tracked pan-and-tilt infrared camera were proved to be effective[2].

The present report is aimed to the question of the required instantaneous visual field size for a HMD-camera system, for adequately performing a nap-of-the-earth (NOE) flight on a winding course. In the same experiment we studied the performance effects of stereoscopic vs. monoscopic image presentation, and of the introduction of an image lag due to delays in camera aiming. To our knowledge no earlier published study addressed these matters in UAV operation. The experiments were done in a flight simulator.

The instantaneous field size is a technically important parameter in the design of a HMD-camera system, because it is related to parameters such as spatial resolution, magnification, and required transmission capacity. Operationally it is important because with larger instantaneous field sizes less head motion is required to anticipate the course of the path to be flown, and generally there is a more accurate perception of the vehicle's motion[6, 13].

In principle, a stereo image requires two cameras, which doubles the required transmission capacity. But it enables better depth perception than a monocular image, albeit that its advantage is generally negligible compared with monocular depth cues at distances above 15 m [5, 6].

An image lag due to delays in camera motion in response to head motion is theoretically unavoidable. In practice it can be restricted to 50 ms, with a sophisticated, powerful, tracking system[10]. It was reported that slaving system imperfections (time constant 0.5 s) in a helicopter simulation seriously constrain the pilot from making fast head movements and increased the time to estimate a location of a point on the flying path[2]. In an object handling task for subjects wearing a HMD, Kawara, Ohmi & Yoshizawa[3] found that version eye movements and accommodative response speed were delayed in the course of 40 minute sessions with image lags of 0.3 and 0.5 s, which was interpreted as increased visual fatigue. This is another indication for the load introduced by large image lags. It is of interest to which extent performance and load are influenced by a realistic image lag.

2. METHODS

2.1 Simulator and image presentation

The simulator consists of an Evans and Sutherland ESIG 2000® image generator with three channels, with as a display system either a HMD (Virtual IO i-glasses®) or a projection system (Seos HiView S-600®). A simple dynamic model was used for the UAV. It had a constant cruising speed of 25 km/h, and its yaw angle speed (-24 to +24 °/s) and vertical speed (-1 to +1 m/s) were controlled by a joystick (Logitech Wingman®). The joystick's signals were fed to the dynamic model with a time constant of 2 s. The subject was seated in the centre of a spherical screen, on which the scene could be presented. He wore a helmet on which the sensor of a Polhelmus Fastrack® magnetic head tracking system was mounted. Yaw and pitch of the head motion were fed into the image generator.

We tested the effects of eight different viewing conditions on flying performance, head motion and subjective task difficulty (see Figure 1). Among these conditions were two with a real HMD; in one HMD condition the outside world scene was presented stereoscopically, and in the other the image was monoscopic, but presented dichoptically to both eyes (diagonal field 28°). The additional viewing conditions were designed as HMD simulations, set up to manipulate optical presentation of the head slaved area of interest, field size and image lag. In one of those simulations the HMD was replaced by tubes mounted on the head, in which an aperture limited the instantaneous field to about the same size as the HMD. Through the tubes the subject could scan through head motion the outside world scene projected on a screen, with dimensions 151° H × 45° V (a similar available field was applied in the HMD conditions. In three conditions the subject looked directly to the screen. On the screen the instantaneous field was restricted by a window which slaved the subject's head motion. Diagonal field sizes were 17°, 34°, and 57°, respectively. The (estimated) delay of the window motion compared to the head motion (70 ms) was determined by the head tracker's update rate and the image generator's image delay. The conditions with field size 17° and 57° were also presented with an additional lag on the image content of 50 ms.

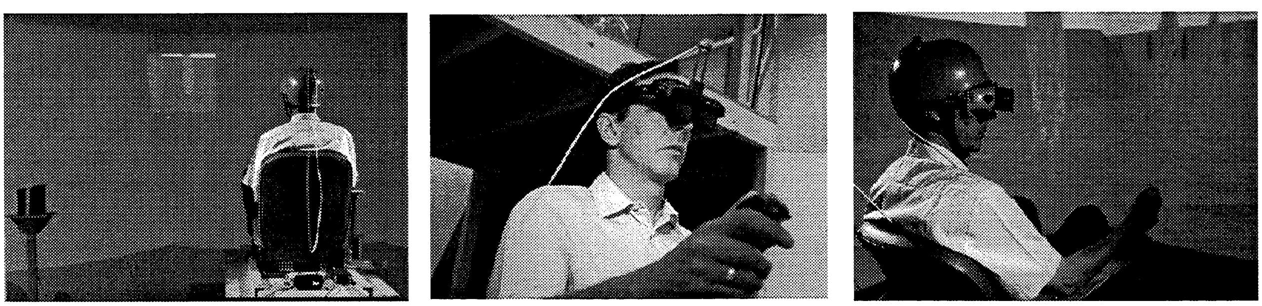

Figure 1. Examples of viewing conditions. From left to right: window 17° with head turned left-up; Head Mounted Display; tubes with apertures.

2.2 Database

32 different routes were used. The routes consisted of successive curved segments, with right and left curves, marked with trees of height 8.5 m, maximal diameter 2 m, and a inter-tree distance of 12 m. The trees were alternately grouped in red and green rows. Red trees on the right side of the route, green trees on the left side. The terrain was textured, and sloping. The route was in the middle of a canyon, limited on both sides by a dike, at 20 m from the centre of the course.

The shape of the path, including the slopes, was constructed by means of a path generator, consisting of the UAV dynamic model steered by time-varying signals corresponding to yaw angle speed and vertical speed. The signals had a block shape which had passed a integrating filter with a time constant of 2 s. The heights of the signal blocks were drawn randomly from evenly distributed populations, with maxima equal to 80% of maximum UAV's yaw angle speed and vertical speed, respectively. This procedure guaranteed that it was physically possible to fly the route, whilst it was necessary to make head movements to determine the path curvature, even with the largest instantaneous field size. The signal block lengths were drawn randomly from an evenly distributed population, with as a boundary condition that the path's direction should not cross itself. Each route started with a straight horizontal part of 75 m. The length of each route was 1.7 km.

2.3 Subjects, task, and training

Eight paid subjects, male university students of age 18-25, participated. They had normal visual acuity, stereo acuity and colour vision. Subjects received a general instruction on aim and design of the experiment, followed by three training sessions. The subjects' task was to follow routes marked with trees, trying to keep a lateral distance of 3 m to the trees, and a height of 3 m above the ground. The red trees were to be kept on their right side, the green trees on their left side. The flying time of each route was about 4 minutes.

In the training session subjects followed three different consecutive routes while they received both sound feedback and verbal feedback on their performance. The continuous sound feedback consisted of tones provided by speakers to the left and the right of the subject, indicating horizontal and vertical errors to the target path, in steps of 0.5 m. Apart from the sounds, subjects received verbal feedback on performance and looking and steering strategy from the instructor/supervisor of the experiment.

2.4 Dependent variables

The dependent variables consisted of flying performance measures, head motion attributes, and subjective difficulty scores.

Flying performance. The following measures were derived from comparison of the UAV's position (sampled with 10 Hz) with the target route (horizontal and vertical):

DISTH, DISTV	the lateral orthogonal error and the height error, relative to the target route (m)
MDISTH, MDISTV	the mean over one run of DISTH and DISTV (m)
SDH, SDV	the standard deviation over one run of DISTH and DISTV (m)
SDSPEEDH, SDSPEEDV	the standard deviation over one run of lateral and vertical error speed (m/s)

Head motion attributes. From the head yaw and pitch (sampled with 10 Hz) the following measures were derived:

MYAW, MPITCH	the means over one run of yaw and. pitch (°)
SDYAW, SDPITCH	the standard deviation over one run of yaw and pitch (°)
STDYSP, STDPSP	the standard deviation over one run of yaw speed and pitch speed (°/s)
TOTKOPMO, STDKOPMO	mean, resp. standard deviation over one run of the total speed vector magnitude (°/s)

Subjective difficulty scores. After each viewing condition, the subject was asked to rate the subjective difficulty MOEI on a scale ranging from 1 - "(almost) no problem" to 5 - (almost) unworkable.

2.5 Procedure

Each day two subjects participated. They successively received, after the general training session (sect. 2.3), all eight viewing conditions, and performed four different runs (one route per run) per viewing condition, of which the first run was a training run with feedback tones (sect. 2.3) and verbal feedback. Each subject performed a total of 32 runs, in which all 32 different routes were presented. When one subject was flying a set of four runs, the other subject rested. The order in which viewing conditions were presented, as well as the order of routes was balanced across subjects; the 32 different routes were equally distributed over all eight viewing conditions (according to a Greek-Latin square design).

2.6 Statistical design

Analyses of variance were run with the package STATISTICA 5.0® ANOVA/MANOVA, with the following sub-designs from the eight viewing conditions (sect. 2.1):

FOV	(windows 17° - 34° - 57°) × replica(3) × subject(8)
DISPLAY TYPE:	(window 34° - tubes - HMD mono) × replica(3) × subject(8)
STEREO:	(HMD mono - HMD stereo) × replica(3) × subject(8)
LAG	(no lag - lag) × (windows 17° - 57°) × replica(3) × subject(8)

Significance of main effects and interactions was tested against interactions with the factor subject. For significant effects and interactions involving more than two conditions (except for the factor replica) Tukey tests were applied in order to assess significant differences between conditions.

3. RESULTS

3.1 Steering bias

One may question whether the feedback during the training runs suffices to learn to stay on a more or less invisible track. The results show that the average deviation from the perfect course was rather small, 0.11 m horizontally and 0.42 m vertically. There was no significant effect of condition on this bias.

3.2 Effects of the factors FOV and of Display Type

Figures 1a,b show results for some of the performance indicators for various FOV sizes and display types, Figures 1 c-e show some of the head motion data and Figure 1e shows the subjective difficulty ratings made by the subjects. All data are for the monocular viewing and no-lag conditions.

Performance

Generally, the data showed a significant increase in performance with increasing FOV (see Table 1). The subjective difficulty ratings agreed very well with the objective performance indicators.

Table 1: Statistics for the effects of the factor **FOV** on steering performance.

Performance indicator	$F(2,14)$	p-level
standard deviation of the lateral error (SDH)	29.2	****
standard deviation of the lateral error speed (SDSPEEDH)	35.2	****
standard deviation of the vertical error (SDV)	15.7	**
standard deviation of the vertical error speed (SDSPEEDV)	11.3	**
**** $p \leq .0001$; *** $p \leq .001$; ** $p \leq .01$; * $p \leq .05$; ns $p > .05$		

Post-hoc Tukey tests showed results for all FOV values to differ significantly from each other except in two cases, SDV for field sizes 17 and 34 degrees and SDSPEEDV for field sizes 34 and 57 degrees.
The data also showed a remarkable large and significant (see Table 2) difference between the performance with the simulated HMD (using the window or the tube method) and the real HMD, with the simulated HMDs scoring better than the real HMD..

Table 2: Statistics for the effects of the factor **display type** on steering performance.

Performance indicator	$F(2,14)$	p-level
standard deviation of the lateral error	10.4	**
standard deviation of the lateral error speed	18.5	***
standard deviation of the vertical error	22.5	****
standard deviation of the vertical error speed	10.3	**
**** $p \leq .0001$; *** $p \leq .001$; ** $p \leq .01$; * $p \leq .05$; ns $p > .05$		

Post-hoc Tukey tests showed the real HMD to differ from both simulated HMDs for all performance indicators. The "tube HMD" and the "window HMD" did not differ significantly for any indicator.

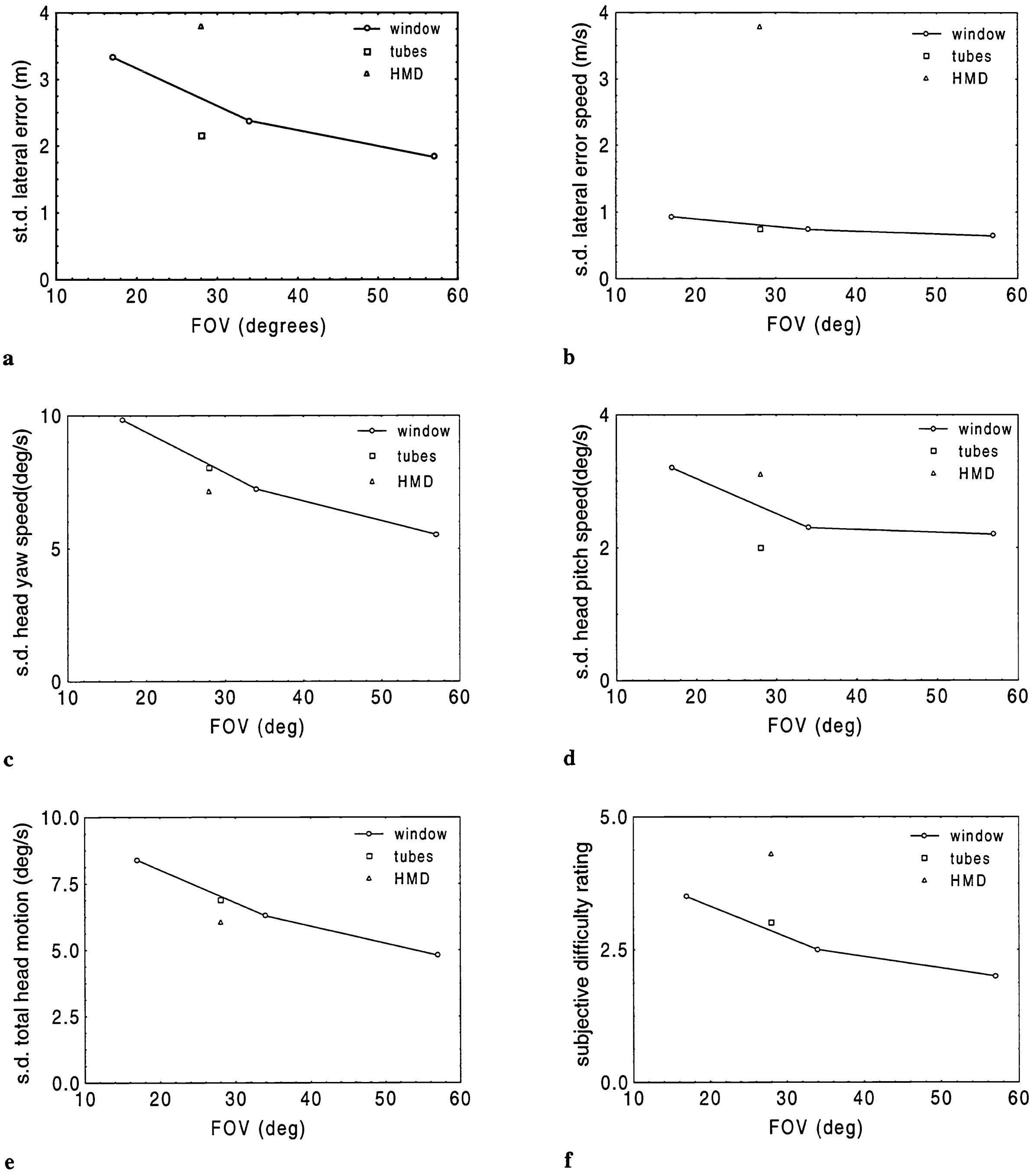

Figure 1: Performance indicators (a,b), head movement data (c-e) and subjective difficulty ranking (f) as a function of FOV and display type. All results are for monocular viewing and no additional lag.

Head movements
The FOV had a significant effect on most head movement descriptors (see Table 3). Clearly, the subjects made less and slower movements when the FOV is large.

Table 3: Statistics for the effects of the factor **FOV** on head movements.

Head movement descriptor	F(2,14)	p-level
standard deviation of the yaw	22.1	****
standard deviation of the yaw speed	40.0	****
standard deviation of the pitch	0.22	ns
standard deviation of the pitch speed	8.99	**
mean total head speed	39.7	****
standard deviation of total head speed	32.2	****
**** $p \leq .0001$; *** $p \leq .001$; ** $p \leq .01$; * $p \leq .05$; ns $p > .05$		

Generally, the HMD-type did not make a significant difference. Table 4 presents the results of ANOVAs which show that this factor has a significant effect on the standard deviation of the vertical head velocity. Post-hoc Tukey tests revealed the differences between the real HMD and the simulated HMDs for this descriptor to be significant. The simulated HMDs did not differ significantly.

Table 4: Statistics for the effects of the factor **Display Type** on head movements.

Head movement descriptor	F(2,14)	p-level
standard deviation of the yaw	0.24	ns
standard deviation of the yaw speed	0.86	ns
standard deviation of the pitch	0.93	ns
standard deviation of the pitch speed	14.3	***
mean total head speed	1.43	ns
standard deviation of total head speed	0.71	ns
**** $p \leq .0001$; *** $p \leq .001$; ** $p \leq .01$; * $p \leq .05$; ns $p > .05$		

Subjective difficulty
The subjective difficulty rankings supported the results on performance, in the sense that worse performance was coupled with higher difficulty.

3.3 Lag

Performance

The two extreme FOV values (17 and 57 degrees) were used with and without an additional lag of 50 ms. Figure 2 shows the resulting performance for the standard deviation of the lateral error and the standard deviation of the lateral error speed. In both graphs the influence is clear. An ANOVA shows that the effect of lag was statistically significant for three of the four performance indicators (see Table 5). Lag did not result in significant subjective difficulty rating differences.

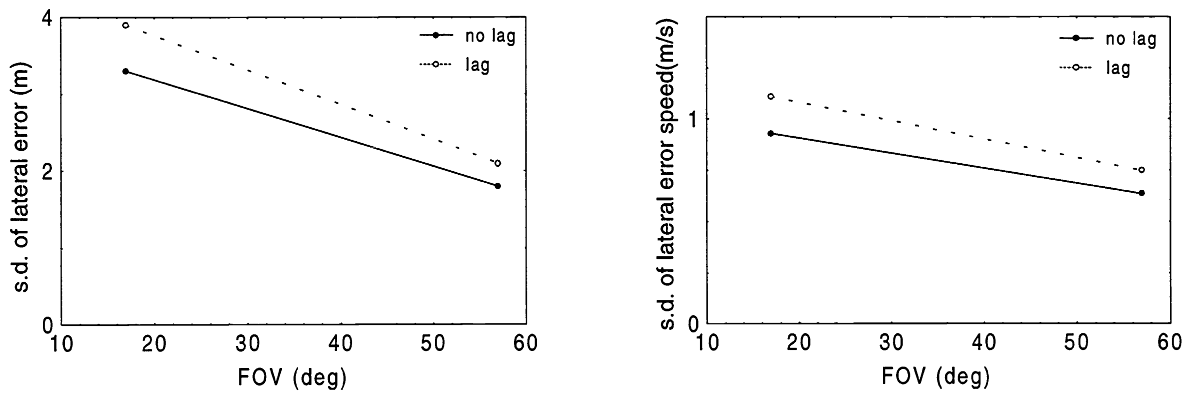

Figure 2: Influence of lag on steering performance.

Table 5: Statistics for the effects of the factor **Lag** on steering performance.

Performance indicator	F(1,7)	p-level
standard deviation of the lateral error (SDH)	6.4	*
standard deviation of the lateral error speed (SDSPEEDH)	37.4	***
standard deviation of the vertical error (SDV)	25.4	**
standard deviation of the vertical error speed (SDSPEEDV)	2.8	ns
**** p ≤ .0001; *** p ≤ .001; ** p ≤ .01; * p ≤ .05; ns p >.05		

Head movements

The lag did not influence head movements as indicated by most of the head movement indicators, except for the s.d. of the pitch and the s.d. of the pitch speed (F(1,7)=12.8, p= .009 and F(1,7)=6.1, p=.04, respectively). In the former case a significant interaction between FOV and lag was present (F(1,7)=6.2, p=.04); a post-hoc Tukey test indicated that only for a FOV of 57° there is a significant effect (p=.0005) of lag. In this case the standard deviation of the pitch was lower (2.1°) when lag is present than when no lag was added (2.8°). The s.d. of the pitch speed decreased from 2.7 °/s to 2.0 °/s when a lag was added; there was no significant interaction of FOV and lag in this case.

Subjective difficulty

Lag did not significantly influence subjective difficulty ratings.

3.4 Stereoscopic vs. monocular HMD presentation

None of the performance indicators indicated a difference between monocular and stereoscopic HMD presentation. As far as head movements are concerned, only in one case did the data show a significant effect: The average pitch in the stereo condition was 1.5° higher than in the monocular viewing condition (F(1,7) =20.5, p = .003). This was probably a spurious result. The subjective difficulty ranking did not indicate a preference for either monocular or stereoscopic presentation.

4. CONCLUSIONS AND DISCUSSION

We have measured the influence of Field Of View, image lag, monocular and stereoscopic presentation, and display type on several performance indicators, head movement descriptors and subjective difficulty ratings. Of these factors, FOV has a profound effect on the measurements, with less steering errors and less head movements with higher FOVs. The same clear results are found for the display types, with the simulated HMDs scoring noticeably better than the real HMD. The effect of lag is somewhat smaller, and is found mostly as a lower performance with added lag and less with changes in head movements. There is no apparent effect of monocular or stereoscopic presentation.

Field Of View

The effects of the FOV on head movements are easily explained. For a particular FOV the movement behaviour is dictated by the course ahead (see Figure 3). The lower the FOV the less the amount of information about the approaching course features can be acquired instantaneously and therefore more and faster movements are necessary to collect the required information in time.

The effects of the FOV on the steering accuracy are less easily explained. In principle, all the information present in the case of a large FOV can be gathered by increasing the amount of head movements if the FOV is small. Four possible explanations for a lower performance at small FOVs are:

1. Initiating and controlling the increased amount of head movements increases the workload which interferes with the steering task. Normally, head movements are both controlled by attention (foveal selection) and by events in the outer periphery of the retina. With HMDs the FOV is too small to cover the periphery and therefore head movements need to be initiated more consciously. Furthermore, some subjects reported interference of head motion with joystick motion.
2. The increased amount of head movements does not fully compensate for the loss of information content due to a smaller FOV. This hypothesis is supported by the data: the horizontal viewing angle range (here loosely defined as the range in which 95% of the head movements can be found plus the instantaneous FOV) is 59.7°, 64.6° and 76.4° for the small, mid-size and large FOV respectively. Even if we examine the full range of head movements (extreme values) is the horizontal viewing range about 10° larger for the large FOV than for the small FOV. This is much clearer in the pitch data. The s.d. of the pitch showed no effect of FOV, which means that the subjects did not compensate for decreased vertical FOV. Compensation of decreasing vertical FOV was probably less necessary since the largest changes in the course were in horizontal direction and not in the vertical direction.
3. The increased amplitude and velocity of the head movements decreases the accuracy with which visual data is acquired and used. It is known that head movements may lead to considerable retinal slip. However, it seems that this retinal slip does not diminish visual acuity considerably.[11, 12]
4. Increased head motions may lead to (subconscious) symptoms of simulator sickness. One of the subjects got sick during the experiments while using a small FOV. He was replaced by another subject who, as all the others, did not show similar symptoms. Nevertheless, a slight discomfort may play a role.

Image lag

Although our head slaving lag was rather small at 50 ms, it resulted in noticeable performance loss (about 20% higher error scores) and a small reduction in head movements (25 % less pitch standard deviation with lag, but only in the 57° case, no significant influence for head yaw movements). Grunwald et al.[2], using a lag of 500 ms, found a small influence on performance (4% higher error scores) but a large impact on head movements (a 53% lower head yaw rate). The differences in head movements may be explained by the lower lag value we used. The higher steering error rates we obtained may be due to the higher importance for steering accuracy of the head movements in our set up.

Monocular vs. stereoscopic presentation

Stereoscopic presentation did not improve the steering performance. This can not be explained by the fact that the subjects made head movements. Although Steinman and Collewijn[12] show that head rotations lead to retinal slip and that vergence is not kept stable during the movements, their results and those of Patterson and Fox[7] and others[8] indicate that stereo-acuity is not impaired by head movements.

Calculations of optimal just noticeable depth differences (jnd) for the Virtual IO HMD, based on its addressable resolution, show that at a distance of 3 m a depth jnd of about 9 cm could be achieved. The s.d. of the lateral error is 3-4 m, so the resolution may not seem to restrict the utility of the stereoscopic presentation. However, in course planning pilots and drivers look forward in time. Values of about 2-5 s are quite common, which in our case means looking ahead approximately 15–40 m.

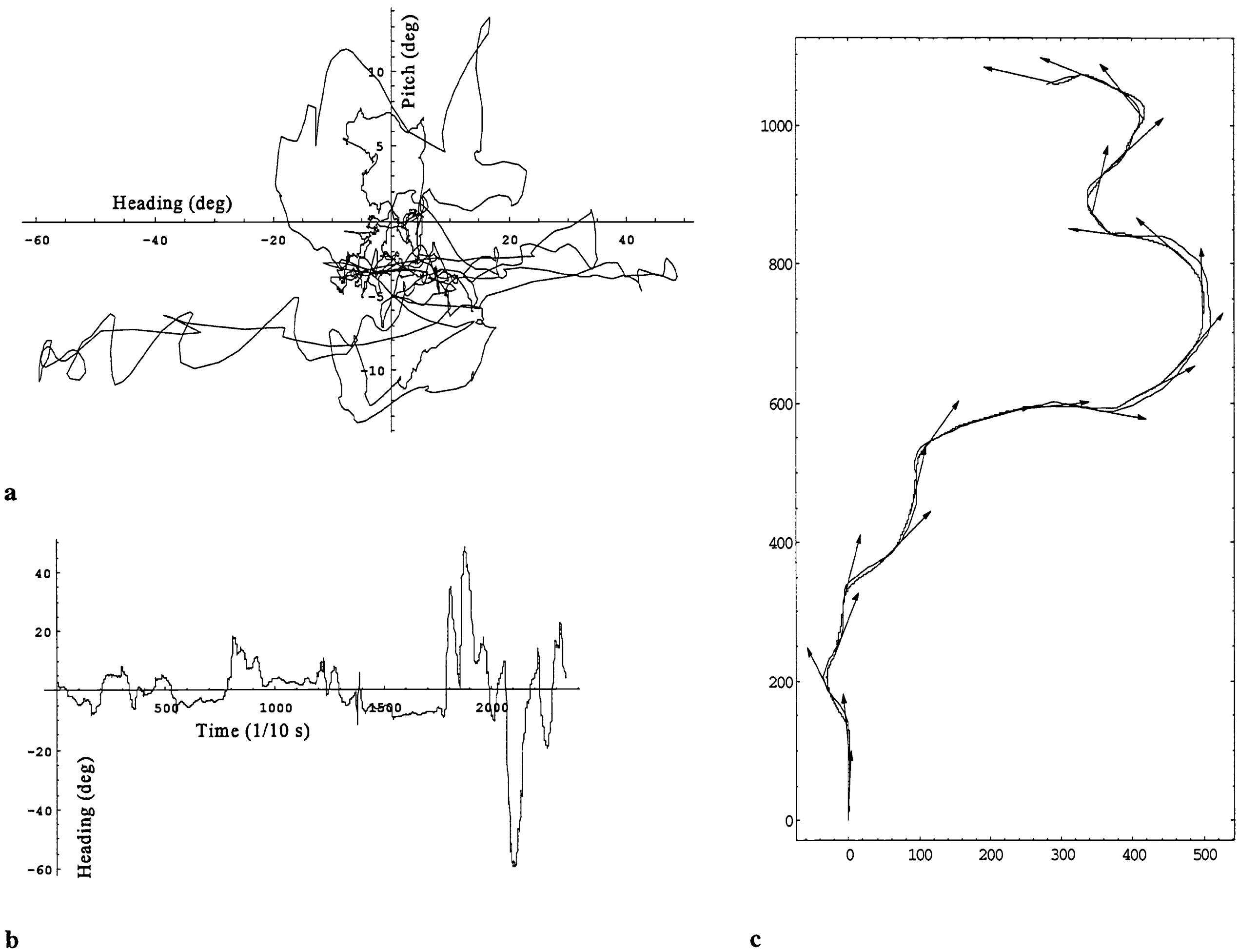

Figure 3: A closer analysis of the observatory head movements of a subject during a particular run using a simulated HMD with FOV of 17 degrees. Please note that the plot only indicates the head direction and not the direction of the eyes. (a) A plot of heading and pitch directions showing a tendency to fixate in the forward direction and some extreme movements in either pitch and heading directions. (b) A heading vs. time plot reveals that the heading is close to zero for most of the time except for some rapid movements at the end of the run. (c) A plot of the actual flown track (starting point of the arrows), the ideal track and the general viewing direction (indicated by the arrows). This plot explains the sharp movements at the end of the heading-time plot. High heading values are necessary when the route is changing sharply.

The jnd at these distance is 3–24 m, so it follows that stereo given the resolution of the Virtual IO HMD is probably of not much use at this distance. Furthermore, the monocular cues in the scene were quite strong; all trees were of the same size so that their size in projection corresponded directly with distance. The effect of a stereo cue may have been drowned in the effects of this monocular cue.

Display type

The performance using a real HMD (the Virtual IO HMD) is considerably *lower* than with using the simulated HMD's whereas the addressable vertical resolution is *higher* by a factor of almost 2 compared to the simulated HMDs. Furthermore, Van Erp[1] showed that for manoeuvring tasks drivers tolerate a reduction of the resolution by a factor of 2 without loss of performance. To explain the results in terms of resolution would therefore imply that the VGA to NTSC conversion needed to drive the Virtual IO HMD lowers the resolution by at least a factor of 4, which would have been clearly noticeable. Since this was not the case, and because all objects in the database were rather large and visible distances short, we can probably exclude resolution as an explanation.

With the simulated HMDs, vergence and accommodation of the eyes match. Both are at a distance of about 3 m. For the Virtual IO HMD[4], convergence is at 2.5 m and accommodation at 4 m. Accommodation is a weak cue which does not have much influence at distances more than 1-2 m. Effects of convergence have a slightly larger range, but the effects of and the differences between convergence of real and simulated HMDs are too small to account for the difference in performance.
We conjecture that the simulated HMDs work better because they give the subjects the possibility to orient themselves in space: the projection screen is dimly visible and its centre corresponds with the heading direction of the UAV. When using the HMD, no such visual orientation marks are present. Since the optic flow is a combination of head motion and vehicle motion and the head motion may not be accurately represented internally, calculation of the heading direction will be more difficult for a real HMD than for a simulated HMD. This suggests that users of immersive HMDs should be provided with reference marks.

REFERENCES

1. J.B.F. van Erp, "Effects of update rate and spatial resolution on operator performance in a simulated unmanned ground vehicle". TNO-report TM-96-B008, TNO Human Factors Research Institute, Soesterberg, The Netherlands, 1996.
2. A.J. Grunwald, S. Kohn and S.J. Merhav, "Visual field information in nap-of-the-earth flight by teleoperated helmet-mounted displays", *Proc. of the SPIE, Large-Screen-Projection, Avionic, and Helmet-Mounted Displays,* **1456,** 132–153, 1991.
3. Kawara, T., Ohmi, M. & Yoshizawa, T. "Effects on visual functions during tasks of object handling in virtual environments with a head mounted display", *Ergonomics,* **39**, 1370-1380, 1996.
4. F. Kooi, "Visual strain: a comparison of monitors and head-mounted displays". *Proc. of the SPIE, Imaging Sciences and Display Technologies,* J. Bares, C.T. Bartlett, P.A. Encarnação, N.V. Tabiryan, P. Trahanias, A.R. Weeks (Eds.), **2949**, pp 162–171, 1996.
5. Padmos, P. "Quality criteria for simulator images: a literature review", *Human factors,* **36**, 727-748, 1992.
6. Padmos, P. "Ambient view for operators of Unmanned Ground Vehicles; a literature survey". TNO-Report TM 1995 B-6, TNO Human Factors Research Institute, Soesterberg, The Netherlands:, 1995.
7. R. Patterson and R. Fox, "Stereopsis during continuous head motion", *Vision Research*, **24**, pp 2001–2003, 1984.
8 D. Regan, J.P. Frisby, G.P. Poggio, C.M. Schor and C.W. Tyler, "The perception of stereodepth and stereomotion", In *Visual Perception, the neurophysiological foundations*, L. Spillman and J.S. Werner (Eds.), pp. 317–347. Academic Press, San Diego, 1990.
9. G.L. Ricard, Manual control with delays: a bibliography, *Computer Graphics*, **28**, 149–154, 1994.
10. Sharkey, P.M. & Murray, D.W. "Coping with delays for real-time gaze control (The fall & rise of the Smith "predictor")", *Proceedings of SPIE, Sensor Fusion VI*, Boston, 1993.
11. G. Sperling, "Comparison of perception in the moving and stationary eye", In *Eye movements an their role in visual and cognitive processes,* E. Kowler (Ed.), Elsevier Press, Amsterdam, 1990.
12. R.M. Steinman and H. Collewein, "Binocular retinal image motion during active head rotation", *Vision Research*, **20**, pp. 415–429, 1980.
13. W.H. Warren, Jr., A.W. Blackwell, K.J. Kurtz, N.G. Hatsopoulos, and M.L. Kalisk, "On the sufficiency of the velocity field for the perception of heading", Biological Cybernetics, 65, 311–320, 1991.