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Effects of Grid Cell Size in Altitude Control in an Augmented Reality Terrain Display

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Helicopter pilot performance in degraded visual conditions may be improved through sensor fusion and an augmented reality display. A simulator experiment with 12 participants was done to test the effect of synthetic terrain grid cell size and helicopter heave dynamics on task performance and control behaviour in a terrain-following hill-climb task. An increase in grid cell size lowered task performance and increased control activity due to reduced optical information. Slower heave dynamics decreased task performance and led to a more prospective control strategy. It was concluded that an effective AR terrain display for altitude control can be designed independently from the vehicle dynamics.

I. Introduction

Low-level helicopter flight in a degraded visual environment (DVE) often leads to spatial disorientation (SD) and results in a significant amount of controlled flight into terrain (CFIT) incidents [1–4]. The out-of-the-window view of the surrounding terrain and obstacles can be degraded by unfavorable lighting conditions, as well as by dust particles (brown-out) or precipitation (white-out). As pilots rely on the visual cues present in the optical flow of the outside visual field, their degradation has adverse effects on situation awareness (SA) and workload, and eventually on flight safety.

An analysis of U.S. Army helicopter accidents between 2002 and 2011 identified 100 cases linked to SD and concluded SD to be linked to significantly more fatalities [4]. Similarly, research on European helicopter accidents from 2000 through 2008 by the NLR, the Dutch National Aerospace Laboratory, found that more than half of the crashes was related to DVE or CFIT [3]. Both studies emphasise the necessity of effective visual aid technologies to increase situation awareness and reduce pilot workload in DVE conditions for safer helicopter flight.

To mitigate the risks of low-level helicopter flight in DVE, the information from board-mounted sensors and databases can be fused to reconstruct a virtual image of the surroundings. A virtual terrain grid can then be used to restore part of the degraded optic cues by means of an augmented reality (AR) display with semi-transparent visors and head-tracking capability, so the pilot can perceive the grid while preserving the out-of-the-window gaze [5–9]. This superimposing of symbology on the outside scene elements, to which sensory information is added, is known as conformal symbology [10].

However, designing safe and effective AR terrain symbology requires understanding how pilots use the optic flow in flight control, how they react to visual degradation and how a see-through display can help

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restore the essential optic cues. Extensive human factors studies on conformal symbology in optical see-through displays in DVE confirm benefits in divided attention and task performance but also pointed out the risks of clutter and attentional tunneling [11, 12]. Effective AR terrain symbology will need to mitigate these undesired side-effects.

Clark investigated the effect of various levels of visually degraded conditions on prospective guidance in low-level helicopter flight by analysing the time-to-contact in a terrain-following hill climb manoeuvre [13]. His analysis revealed that decreasing levels of visibility cause pilots to start their avoidance manoeuvre closer to the slope, and provided more evidence to suggest pilots use an implicit motion guide as a guidance strategy for the manoeuvre. A study by Flach et al. (2011) tasked participants to drive from an idle position to a stopped position just in front of an obstacle as quickly as possible while avoiding collision [14]. The method used by participants to determine the moment at which to release the accelerator to start braking corresponded to a constant time to contact strategy, that was being tuned ever more closely towards the optimal solution as the task was repeated. This led to the hypothesis that the optical time to contact variable expressed how participants were developing their internal model of the dynamical limits of the vehicle.

An AR terrain grid could partly replace the degraded visual cues in the optic flow by providing splay and depression angle cues. Flach et al. (1997) studied the relative effects of these optic cues on altitude control across various forward speeds [15]. They found that the visual system is not differentially tuned to either splay angle or depression angle for perceiving altitude change, but that splay angle provides a higher quality cue due to its increased visible range in the forward view, its insensitivity to forward motion and its symmetry properties.

Yet, the effects of AR terrain displays on altitude perception and control in DVE remain unclear. Clark's work on the hill climb begs the question whether visual augmentation would counteract the consequences of degraded optic cues on a pilot's control strategy [13]. Likewise, as the experiments of Flach et al. featured flat terrain, their work invites inquiry into the effects of relatively minor and major changes in terrain height on the optic cues of an AR terrain grid [15]. How do pilots react to the superimposing of an AR terrain grid on irregular, nonflat terrain? Does the terrain grid size change a pilot's perception of the terrain elevation profile? How does the AR terrain grid size affect the control strategy and is there an interaction effect with the vehicle dynamics?

This paper aims to investigate the effects of synthetic terrain grid size in head-worn displays on task performance and control behaviour in a realistic hill climb task throughout varying vehicle heave damping settings in DVE. The results are presented of an experiment conducted with 6 novices and 6 pilots in the generic cockpit (GECO) simulator of the DLR Institute of Flight Guidance in Braunschweig, Germany. The hill climb task in Clark's work is essentially modified into an altitude control task by adding terrain irregularity, reducing vehicle control complexity and adding a simulated AR terrain grid. The effects of terrain grid size, helicopter heave dynamics and experience on various measures for task performance are examined. Control behaviour is studied using a time to contact analysis.

The paper is structured as follows. First, Section II introduces useful background concepts for time to contact analysis. Section III describes the experimental setup and methods. Experimental results are presented in Section IV, followed by a discussion in Section V. The paper ends with a conclusion.

II. Background

A. Optic cues of a terrain grid

A nap-of-the-Earth flight course closely follows the terrain curvature, requiring accurate perception of the terrain geometry as well as the aircraft height and speed. Locomotion research has shown that pilots use the angles between the lines defining the textural gradients to determine their position and motion with respect to the terrain [16]. One of these angles is the optical splay angle S , defined as the angle at the vanishing point between an edge parallel to the direction of motion and a line on the ground along the direction of motion, perpendicular to the horizon line. It is calculated through:

$$S = \tan^{-1} \left(\frac{Y_g}{z} \right), \quad (1)$$

where S is the splay angle, Y_g is the lateral displacement from the ground track and z the altitude. This is illustrated in Figure 1.

Figure 1. Effect of altitude change on splay angle. As the altitude decreases from z_1 to z_2 , the texture lines rotate away from the direction of motion toward the horizon, increasing the splay angle.

The rate of change in splay angle with changing observer position can be calculated as :

$$\dot{S} = -\left(\frac{\dot{z}}{z}\right) \cos(S) \sin(S) + \left(\frac{\dot{Y}_g}{z}\right) \cos^2(S) \quad (2)$$

In the case of symmetric forward flight, the rate of change in lateral position is zero and the second term in Equation (2) cancels out. We are left with the first term, which shows that changes in splay angle depend on the initial altitude since they are scaled by z . Moreover, increasing altitude leads to a decrease in splay angle and vice versa.

Another optical angle used to detect changes in altitude is optical depression. Any edge perpendicular to the direction of motion has an angular position with respect to the horizon as viewed by the observer, the optical depression angle [15]. By convention, this angle is calculated with respect to the observer taking the distance on the ground to the edge feature in the forward visual field and by scaling this distance by the height of the observer, as in Equation (3):

$$\delta = \tan^{-1} \left(\frac{x_g}{z} \right), \quad (3)$$

with δ the depression angle, x_g the longitudinal distance on the ground to the texture element and z the altitude. Figure 2 illustrates the angular depression.

For rectilinear forward motion the rate of change in depression can be calculated as:

$$\dot{\delta} = -\left(\frac{\dot{z}}{z}\right) \cos(\delta) \sin(\delta) + \left(\frac{\dot{x}_g}{z}\right) \cos^2(\delta) \quad (4)$$

Similar to splay, the rate of change in depression angle depends on the eye-height scaled altitude and on the initial optical position of a texture element. Texture elements that are low in the field of view will have a greater depression angle rate for constant forward speed.

Equations (2) and (4) show that altitude and forward speed have different effects on the splay and depression rate. Splay rate is a visual cue of higher quality for change in altitude as changes in speed do not affect edges parallel to the direction of motion. Depression angle rate, however, depends both on forward speed and on change in altitude. Through a series of experiments Flach et al. have demonstrated that both cues are used in altitude control [15]. The authors noted that splay angle is the preferred optical cue for altitude perception as a greater angular range is generally visible in the field of view, since it is decoupled of the natural forward motion and because it is symmetrically affected by altitude change as opposed to density angle.

Even if optical splay is preferred for altitude control, it may be infeasible to exclude the optical density angle from an AR terrain display for NOE flight. Such a display needs to support perception of irregular terrain elevations as well as speed, both of which benefit from the density angle cue. Adding optical density to optical splay naturally results in a grid texture, that may allow the geometry of rugged terrain to be perceived more easily. Corwin et al. had 12 military pilots compare different types of synthetic terrain

Figure 2. Effect of altitude change on depression angle. As altitude decreases from z_1 to z_2 , the depression angle increases, moving the texture lines perpendicular to the forward direction of motion upwards toward the horizon.

imagery against a terrain background on a helmet-mounted display (HMD) in a full flight mission [17]. Among a variety of display formats, the one with an orthogonal mesh and the display with points and ridge lines were preferred.

Variations in terrain elevation change the geometry of a synthetic grid similarly to change in altitude, although the variations appear locally in the field of view. A square, synthetic grid orthogonally displayed to the direction of flight essentially replaces the optic cues of the splay and density angles, provided the terrain is flat. With flat terrain, texture lines parallel to the direction of motion run straight into the vanishing point at the horizon and the spacing between each horizontal texture line further ahead decreases, tending towards zero at the horizon line. When terrain elevation increases in the forward direction, the direction of the splay lines and the spacing between the density lines become distorted: the section of increasing elevation has a smaller splay angle than the flat area and the spacing between horizontal lines locally increases, as shown in Figure 3. On the contrary, a descending section leads to a larger local splay angle than the flat area and the spacing between horizontal lines locally decreases, as shown in Figure 4.

Figure 3. Effect of forward increase in terrain elevation on synthetic terrain grid.

Figure 4. Effect of forward decrease in terrain elevation on synthetic terrain grid.

The grid cell size of a synthetic terrain grid determines the amount of grid lines in the field of view. This controls the magnitude of the optic flow used to perceive egomotion and the resolution of the terrain elevation available to the observer, consequently affecting flight control. The grid cell size of an AR terrain display should provide sufficient terrain detail while avoiding clutter. Let's consider an orthogonal terrain grid obtained by linear interpolation of perfectly accurate terrain elevation data. The accuracy of the terrain grid depends on the grid cell size. A smaller terrain grid leads to a more accurate terrain grid that's able to show finer variations in terrain elevation. Figure 5 illustrates the effect of doubling the cell size on the accuracy of a terrain grid.

Figure 5. A grid cell size twice as small shows more detail of a 2D terrain elevation profile. This effect is magnified in 3D.

Grid cell size in AR terrain displays turns out to be a key factor influencing the perception of altitude, speed and terrain geometry that can potentially cause human performance issues such as display clutter and attentional tunneling [11]. It affects the extent to which synthetic terrain imagery can show variations in terrain elevation, which in turn impact optic splay and density angles picked up as optic cues for altitude and speed. Yet, the direct effects of grid cell size remain largely undocumented. Their examination could benefit from an understanding of the coupling of perceptual information with the control strategy that pilots tend to use.

B. Optic Flow and Tau

Lee introduced an analytical form of Gibson's ecological optic flow theory that describes the fundamental relation between perceptual information and control coordination [18,19]. This general tau theory hypothesises that targeted motion is not guided through the observation of its spatial form of displacement rate and remaining distance, but is rather directly perceived and controlled in its temporal form: the time-to-contact, tau (τ). The motion gap between a current and target state is effectively closed by keeping constant the rate of change of tau. Evidence for Lee's tau theory was found in a wide range of controlled motions including human and non-human animals, underpinning temporal motion control as a fundamental product of evolution [20–22].

Tau theory provides a unifying framework that encompasses a multitude of optic cues identified in studies of the perception of egomotion. As the invariants in the optic flow can be expressed as angles and angular rates, pilots infer tau to close gaps when moving from a current hovering position to an adjacent, desired one or when coupling an obstacle-bound trajectory onto one that safely evades the obstacle. For a given motion gap, the instantaneous time to contact τ is the ratio of the negative distance to the target $x(t)$ and the closure rate $\dot{x}(t)$, Equation (5).

$$\tau_x(t) = \frac{x(t)}{\dot{x}(t)} \quad (5)$$

τ is used to coordinate when to apply motion controls, but when combined with its derivative $\dot{\tau}$ there is sufficient perceptive information to tune the motion control. Differentiating and rearranging Equation (5) yields Equation (6):

$$1 - \dot{\tau}_x = \frac{x\ddot{x}}{\dot{x}^2} = \frac{\tau_x}{\tau_{\dot{x}}} \quad (6)$$

Tau theory hypothesises that τ and $\dot{\tau}$ are the fundamental inputs to the natural motion control system. If $\dot{\tau}$ is kept constant, the taus of the motion gap and of its closure rate remain in a fixed ratio while they are brought to zero. Equation (7) defines the coupling constant $k = 1 - \dot{\tau}$ for $0 \leq k \leq 1$:

$$\tau_x = k\tau_{\dot{x}} \quad (7)$$

The value of k in two tau-coupled motion gaps describes how one motion gap is closed in relation to the other. Using one tau motion to guide another is considered a natural control strategy. If the guiding tau motion is a mental model of the controller, it is referred to as an *intrinsic* motion guide. Evidence suggests that one such commonly used intrinsic tau-guide is the constant acceleration tau guide τ_g , presumably because the gravitational acceleration is ubiquitous. Figure 6 shows a distance and time-normalised, τ_g -guided motion gap, its closure rate and its tau for different values of k .

Figure 6. Effect of coupling constant on motion gap, gap closure rate and tau for a normalised, constant acceleration motion.

Figure 6 illustrates motions that follow a constant acceleration guide for different values of k :

- The motion directly starts with an acceleration, of which the intensity is higher for lower values of k . The point of maximum closure rate is therefore increasingly delayed for higher values of k .
- Increasing k from zero changes the deceleration at the end of the motion from gentle to aggressive. For $k = 0.5$ a finite deceleration can close the gap, higher k -values require infinite deceleration, e.g. a collision.
- For $k = 1$ the motion follows the guide exactly and constantly accelerates into the goal.

C. Tau guidance in hill-climb

Initiating a helicopter climb from steady horizontal flight requires raising the collective control θ_0 to move the flight path angle γ to the final flight path angle γ_f . The negative flight path gap γ_a is the difference between these angles ($\gamma_a = \gamma - \gamma_f$). The manoeuvre starts with θ_0 input and ends when the flight path rate goes from positive to negative ($\dot{\gamma}_a = 0$), defining the manoeuvre duration T .

The flight path gap tau τ_γ is calculated by applying Equation (5):

$$\tau_\gamma(t) = \frac{\gamma_a(t)}{\dot{\gamma}_a(t)} \quad (8)$$

Clark applied this method of analysis in an experiment with a single experienced pilot flying a hill-climb mission task element (MTE) across various levels of visibility in a UH60A Black Hawk simulator [13]. Starting from the initial hover point, the terrain had a flat run-in of 750 m, a 5 deg slope of 60 m high and a flat run-out of 2000 m to test the restabilization of the rotorcraft after the slope. Flight speed and altitude could be freely selected by the pilot. Visual conditions varied across usable cue environment UCE 1-3 [23], by blurring textures and decreasing the visible range. Instruments were disabled and trees were included for height reference. To relate the observed τ_γ to the constant acceleration tau-guide τ_g a least-squares fit was done, moving backwards from the end of the manoeuvre until the correlation coefficient R^2 went under a set threshold. The fit was then made using the resulting k . The tau analysis showed that decreasing visibility led to higher overshoots of the flight path angle and that the minimum time-to-contact τ_{min} decreased, both indicating an increased difficulty to perceive the slope angle. Significant correlations of the flight path gap tau τ_γ with the constant acceleration tau-guide τ_g were found. It appeared there was no link between the level of visibility and k .

One outcome of Clark's study was that the minimum tau decreased as the visibility deteriorated, so a setback in visual perception of the hill delayed the pull-up manoeuvre [13]. However, there was apparently no conflict yet with the pilot's mental model of the rotorcraft dynamics, which tolerated safely awaiting visual perception of the terrain before initiating the climb became necessary to avoid CFIT. Flach et al. (2011) showed that test subjects used a constant time-to-contact strategy to manoeuvre a car into standstill right before an obstacle while internalizing a mental model of the vehicle's dynamical limits [14].

This study attempts to start establishing the design trade-off for the appropriate grid cell size of an AR terrain for NOE flight. This flight task incorporates the interaction of pilots' visual perception of the environment and their awareness of the dynamical limits of the rotorcraft. As such, the influence of the vehicle dynamics on the control strategy will be investigated in combination with the variation of the grid cell size. Regarding the minimum distance to the slope, no effect of the grid cell size is expected as any synthetic terrain should provide sufficient information about the start of the slope regardless of its cell size. Pertaining to the vehicle dynamics, a slower flight-mechanical response of the controlled element should not lead to an effect on performance but instead to a more anticipating control strategy, e.g., higher minimum time-to-contact and a longer manoeuvre time.

III. Experiment Design

To investigate how an augmented reality terrain grid affects task performance and control behaviour in DVE Nap-of-the-Earth (NOE) flight, a simulator-based experiment was conducted with a modified hill-climb Mission Task Element. Twelve participants were instructed to maintain constant altitude above ground level (AGL) in degraded visual conditions, the view out the window being their only source of visual information. A semi-transparent synthetic grid was overlaid on the outside visual to simulate an augmented reality terrain display. The experiment aimed to study the effect of *varying cell sizes in an augmented terrain grid* on altitude perception and control, and whether this phenomenon is affected by the *heave dynamics of the controlled rotorcraft*.

A. Participants & Instructions

A total of 12 right-handed men took part in the experiment, all with normal or corrected-to-normal vision. Participants were recruited within the DLR Institute of Flight Guidance. Two groups of equal size were formed. Six were non-pilots, six were licensed general aviation fixed-wing pilots with ratings ranging from glider pilot through to flight instructor. One held a commercial multi-engine pilot license with instrument rating. Half of the pilots had about 50 h of helicopter practice in simulators. Flight experience ranged from approximately 60 h to over 2000 h.

Average age of participants was 35.8 yrs ($\sigma = \pm 10.5$ yrs). A pre-experiment briefing was provided before the experiment to explain its purpose and the piloting task. Furthermore, the briefing explained the purpose and functioning of the peripheral display symbology used during training. The same briefing was repeated

at the start of the experiment, to ensure the instructions were clear to all participants.

B. Control Variables

1. Apparatus

The experiment was conducted in the Generic Cockpit (GECO) simulator, shown in Figure 7. It has a wooden A320 cockpit shell and a collimated visual system, providing depth perception of infinity, using three high resolution projectors (2160×1440 pixels) displaying an area of $180^\circ \times 40^\circ$. A spring-loaded, passive side-stick was used as manipulator, of which only the longitudinal axis was activated. Participants were seated in the same longitudinal position in the right seat. They were instructed to keep their gaze fixed forward to limit the slight advantage of looking at the edges of the display to infer altitude above terrain.

Figure 7. The Generic Cockpit simulator of the DLR Institute of Flight Guidance in Braunschweig, Germany

2. Control Task

Participants controlled the rotorcraft in the heave axis by manipulating the simulator sidestick using rate command. The dynamic model in the simulator had first-order linear dynamics in the heave axis as described by Equation (9), with w the vertical velocity (m/s), Z_{θ_0} the dimensionless collective control derivative in the Z-axis, and Z_w the heave damping coefficient (s^{-1}). A rotorcraft with relatively higher heave damping coefficient in absolute terms exhibits faster dynamical response in the heave axis.

$$\dot{w} = Z_{\theta_0}\theta_0 + Z_w w \quad (9)$$

Helicopter collective control θ_0 was replicated through the longitudinal axis of the manipulator, e.g., backward stick deflection increased altitude whereas forward stick deflection decreased it. Attitude remained constant at all times, so the simulated vehicle behaved more like a flying elevator than a helicopter, in order to control the amount of visible ground texture. The objective was to maintain a constant altitude of 70 ft above ground level (AGL) with varying terrain elevation, thus the terrain effectively acted as a disturbance signal.

3. Scene

Total terrain dimensions were 4000×4000 m, subdivided into a flat run-in length of 850 m, followed by a slope of 60 m height at an angle of 30° , which transitioned into a flat run-out section, as depicted in Figure 8. All runs started at the same initial condition of 70 ft AGL with an initial forward speed of 30 kts, corresponding to about 0.7 eye-heights/s. In order to reduce predictability, three starting positions introduced variation in longitudinal and lateral directions. One run was done from each starting position for every experimental condition.

Figure 8. Schematic representation of terrain geometry including starting positions and without Perlin noise

The terrain simulation aimed to achieve a relatively high level of visual fidelity as to give participants some sense of realism. The simulation was built and rendered through the Unity3D gaming engine. Perlin noise was added to the three straight terrain sections to obtain an irregular ground surface. The generated terrain noise was configured such to keep the hill climb intact while providing enough visible relief. Its average was corrected to zero and its standard deviation was set at 0.85 m. The ground was rendered using multiple high-resolution textures to prevent artefacts, and covered with grass. Trees of 40-70 ft high were sparingly added along the flight trajectories which helped to estimate altitude. Unity's built-in wind simulation was used to animate the grass and trees. Linear density fog was simulated with a visible distance of 80 m, corresponding to UCE 3. Helicopter sound was played aloud during runtime.

The augmented reality terrain grid was displayed on the dome projection. A colour augmented reality headset with 90° field of view was originally planned to be used, but was unfortunately unavailable at the time of the experiment. The synthetic terrain display was rendered by vertically projecting an orthogonal grid on the ground and by connecting the adjacent intersection points with green, transparent lines, as shown in Figure 9.

Figure 9. Simulation scene overview including the augmented reality grid.

Figure 10. The terrain display tested in the experiment for three different grid cell sizes. The terrain grid is superposed over the outside scene to simulate the augmented reality display.

C. Independent Variables

A $3 \times 2 \times 2$ mixed design was used with terrain grid cell size at 100, 150 and 200 m (S, M and L, see Figure 10.) and helicopter dynamics with a heave damping coefficient Z_w of -0.56 s^{-1} (HD1) and -0.14 s^{-1} (HD2), both manipulated within-subjects. Piloting experience was a between-subjects factor (half the participants were novices, half were pilots). The within-subjects factors formed six experimental conditions, which were counterbalanced using the same Latin square design for both participant groups, as shown in Table 1.

Table 1. Experimental conditions with grid cell size (S, M and L) and heave dynamics (HD1 and HD2) for pilots and novices.

Subjects	1	2	3	4	5	6
N1 P1	S HD1	M HD1	L HD2	L HD1	M HD2	S HD2
N2 P2	M HD1	L HD1	S HD1	S HD2	L HD2	M HD2
N3 P3	L HD1	S HD2	M HD1	M HD2	S HD1	L HD2
N4 P4	S HD2	M HD2	L HD1	L HD2	M HD1	S HD1
N5 P5	M HD2	L HD2	S HD2	S HD1	L HD1	M HD1
N6 P6	L HD2	S HD1	M HD2	M HD1	S HD2	L HD1

D. Dependent Variables

Task performance was measured by the root-mean-square height error (RMSE) and fraction of runtime spent within performance boundaries around the desired flight path, e.g., desired and adequate within 25% and 50% of nominal height, respectively, or inadequate if over 50% of nominal height. Pilot control behaviour was measured by control activity (control signal variance), minimum time-to-contact to the slope and tau motion guide following (flight path angle gap γ_a , manoeuvre duration T and coupling constant k).

E. Procedures

The experiment consisted of two phases, training and measurement, combined taking a maximum of 3 h. During training participants got accustomed to the controls of both vehicle dynamics, the visual scene and the target altitude through three progressive training levels. The first level presented participants with maximum visual range and relatively simple ground height variation in the flight direction only. The second level additionally introduced ground height variation in the lateral direction and the same visual degradation as used in the measurement phase. During these first two levels, visual cues on the outermost edges of the visual field indicated whether participants were flying either within a 10% margin of the intended altitude, or above or below it. The peripheral cues provided the necessary information without obstructing the forward view. The third training level presented a more challenging terrain geometry and removed the peripheral height cues. This level pushed the participants' performance beyond the difficulty of the measurement runs, to ensure they were ready for the experiment. The synthetic terrain grid augmentation was not introduced during training to prevent pre-measurement adaptation to the terrain grid cell size factor. During training, the root mean square of the altitude error was tracked and reported to participants after each run to spur motivation. Each training level was practised until scores were approximately stable and with the same amount of runs for both vehicle dynamics.

During the measurement phase three runs were taken for each of the six experimental conditions to average out terrain geometry effects and to introduce some task variation. Throughout the three runs the starting position varied by 50 m longitudinally (obtaining effective run-in lengths of 850, 800 and 750 m, respectively) and laterally by 500 m (lateral starting positions of 1500, 2000 and 2500 m, respectively). Run order was unchanged between conditions and (groups of) participants. Runs ended once the longitudinal 1500 m mark was touched, between 90 and 100 s. 10-minute breaks were given after the training phase and after each pair of experimental conditions and micro-breaks could be taken between runs. Participants were informed of a new experimental condition being tested and of its vehicle dynamics (1 or 2), but not of the variations between runs of the same experimental condition.

F. Hypotheses

A smaller grid cell size enables perceiving a higher terrain resolution, it is therefore hypothesised that task performance will decrease with grid cell size, leading to a higher RMSE of the altitude error as well as higher fractions of runtime spent within the inadequate performance boundary. Clark's work has shown that minimum tau decreased as the visibility deteriorated and suggested that manoeuvre duration increases as well [13]. As an increasing grid cell size may lead to overestimation of the distance to the slope, the minimum time-to-contact is expected to decrease. Manoeuvre duration is not expected to be affected by grid cell size. As less terrain detail is displayed, control activity is hypothesised to decrease and flight path angle gap is expected to increase with higher grid cell size. The coupling constant is expected to be unaffected by grid cell size in extension of the results of Clark's experiment, which showed no apparent effect of forward visibility on coupling constant [13].

A lower heave damping coefficient is analogous to having faster heave dynamics, e.g., a helicopter with a lower coefficient reacts quicker to collective control inputs along its heave axis. It is expected that slower heave dynamics leads to worse task performance, shown by an increase in mean RMS of the altitude error and an increased fraction of runtime spent outside of adequate performance boundary. Control activity is expected to decrease with rising heave damping in response to the filtering of higher frequency control inputs. The minimum time-to-contact is hypothesised to increase for HD2 compared to HD1 as pilots adapt to the slower vehicle response. The expectation is that slower heave dynamics with HD2 will lead to longer manoeuvre duration but will not impact flight path angle gap. The coupling constant is hypothesised not to be affected by the helicopter dynamics.

Piloting experience was assumed not to influence any of the dependent measures because of the simple dynamics and control task. Instead, this independent variable was included to verify that other results were not confounded by piloting skills.

IV. Results

A. Tau analysis

For the tau analysis the start and end of the manoeuvre within the full run are selected by using the plots of control input, vertical position, flight path angle and flight path angle rate against time, as shown in Figures 11 to 14 respectively. The control input and vertical position signals indicate the approximate instant of climb initiation.

The start of the manoeuvre is the instant at which the pilot starts applying positive collective control input that sets the aircraft into a climb. At that moment the flight path angle rate crosses zero from negative to positive. The manoeuvre start is selected by means of the following criteria:

- Vertical flight position starts increasing with the intention of flying over the hill, as shown in Figure 12.
- Collective control input is positive and increasing, see Figure 11.
- Flight path angle is positive, as is the case in Figure 13.
- Flight path angle rate is positive after a zero-crossing, as in Figure 14.

The manoeuvre ends when the pilot has reached the target flight path angle. The moment of the last positive flight angle rate is automatically selected as the manoeuvre end. The manoeuvre time vector t_m is then calculated through Equation (10).

$$t_m = \{t_0 \leq t \leq t_f\} \quad (10)$$

with the starting instant of the tau manoeuvre t_0 and its end t_f , which are both used to calculate the manoeuvre duration T through:

$$T = t_f - t_0, \quad (11)$$

The instantaneous flight path error γ_a , also called gamma to go, is defined as the deviation from the goal flight path angle γ_f as:

Figure 11. Control input vs. time with selected manoeuvre

Figure 12. Vertical position vs. time with selected manoeuvre

Figure 13. Flight angle vs. time with selected manoeuvre

Figure 14. Flight angle rate vs. time with selected manoeuvre

$$\gamma_a = \gamma - \gamma_f \quad (12)$$

The angular motion gap γ_{gap} is calculated as the difference in flight path angle between the manoeuvre start and end:

$$\gamma_{\text{gap}} = \gamma_f - \gamma_0 \quad (13)$$

Everything is now set up for the actual tau analysis, which consists of finding a least-squares fit of the constant acceleration tau guide τ_g , linearly coupled by the coupling constant k , to the tau motion:

$$\tau_\gamma = k \tau_g, \quad 0 < k < 1 \quad (14)$$

From Equation (12) it is inferred that the instantaneous flight path error rate $\dot{\gamma}_a$ equals the flight path angle rate because γ_f is constant. The tau of the flight path angle error is calculated by:

$$\tau_\gamma = \frac{\gamma_a}{\dot{\gamma}_a} \quad (15)$$

The manoeuvre-scaled time vector $\bar{t}$ is set up by normalising the manoeuvre time vector t_m by means of the manoeuvre start t_0 and duration T as follows:

$$\bar{t} = \frac{t_m - t_0}{T} \quad (16)$$

The constant acceleration tau guide for the manoeuvre τ_g is calculated by:

$$\tau_g = -\frac{T}{2} \left(\frac{1}{\bar{t}} - \bar{t} \right) \quad (17)$$

Fitting the constant acceleration tau guide to the motion consists of selecting values of the linear coupling constant k and the number of data points used in the fit N_f for which the linear least-squares fit yields a sufficiently high coefficient of determination R^2 . Figure 15 presents the flight path angle and its rate as functions of normalised manoeuvre time. As the flight path angle rate quantifies the variation of the motion variable the higher frequency content of the motion signal becomes more visible.

Figure 15. Flight path angle and its rate vs. manoeuvre time

Applying Equation (15) yields tau, displayed as a function of normalised manoeuvre time in Figure 16 and as a function of the guide time-to-contact in Figure 17. The tau curve features the same high-variation signal content as the gamma rate. A decreasing tau differential is seen between adjacent data points on the graph towards the start of the manoeuvre, further extending to lower values of tau. This is due to the gamma rate tending to zero while the gamma gap is stable at its starting value.

Figure 18 displays the evolutions of R^2 and k as a function of N_f . This is the main plot used to determine the length of the recorded run the tau guide is fitted to. The coupling constant k and resulting R^2 are calculated for each fraction of the manoeuvre, moving back from the last two to all data points. Minimum satisfactory R^2 is set at 0.97 and k must be positive and inferior to 1.

Picking the manoeuvre length used in the fit is not as straightforward as selecting the maximum value of N_f that yields sufficient R^2 . As data points with higher tau values at the start of the manoeuvre have

Figure 16. time-to-contact and fitted guide vs. manoeuvre time

Figure 17. time-to-contact vs. guide time-to-contact

Figure 18. Coefficient of determination and tau constant vs. number of points used in fit

a larger impact on R^2 than those at the end, R^2 meets the 0.97 threshold if (almost) all data points are included, i.e. $N_f = 314$ for the run shown in Figure 18. To summarise, the following criteria are used:

- Coupling constant k from least-squares regression, not exceeding unity: $0 < k < 1$.
- Coefficient of determination $R^2 > 0.97$.
- Moving backwards from the end of the manoeuvre, N_f is selected as the last value before R^2 drops below its threshold.
- N_f values close to the maximum value that yield satisfactory R^2 are disregarded.

For the gamma gap, the manoeuvre duration and the coupling constant, the statistical analysis is applied to subsets of the data based on minimum subjective ratings. The results presented hereafter include all runs with minimum rating of 1. The ratings qualify the extent to which the fitted tau guide describes the last half of the manoeuvre on a scale of 0 to 5 with the following rating descriptions:

0. Does not meet fitting conditions
1. Barely describes last half of manoeuvre
2. Slightly good
3. Moderately good
4. Good
5. Very good

B. Statistical analysis

Results were visually inspected by representing the run-averaged data in box plots. The sphericity assumption was tested using Mauchly's test for the grid cell size (Grid), as vehicle heave dynamics (Dynamics) had only two levels. Homogeneity of variance was tested using Levene's test and normality was graphically checked using Q-Q plots and numerically verified using a Shapiro-Wilk test.

A three-way repeated measures mixed-design Analysis of Variance (ANOVA) was performed with two within-subjects factors (Grid, Dynamics) and one within-subjects variable (Experience) to study whether Experience had an effect. If no significant effect of Experience was found, a two-way repeated measures ANOVA was done with the within-subjects factors Grid and Dynamics, thus increasing the sample size for each dataset.

The results show that Experience was not a significant factor for any tested variable. As hypothesised, mixed ANOVA did not reject the null hypothesis that Experience did not significantly affect any of the dependent variables, therefore a two-way repeated measures ANOVA was performed on the Experience-lumped data.

1. RMS of altitude error

An increase in grid cell size from S to L lead to higher RMSE, meaning worse task performance and confirming the hypothesis. Moreover, slower heave dynamics also decreased task performance in RMSE, opposing the hypothesis that pilots would adapt to the change in controlled element dynamics. The box plot for the Experience-lumped RMSE, shown in Figure 19, suggests that RMSE increases as Grid changes from small to medium and then to large. It also conveys that HD2 leads to higher RMSE than HD1. ANOVA showed main effects of Grid $F(2, 22) = 5.64, p = .011$ and of Dynamics $F(1, 11) = 12.22, p = .005$. Pairwise comparisons using the Bonferroni correction revealed that an increase in grid cell size from small to medium elicited an insignificant increase in mean RMSE from 8.05(0.47) to 9.07(0.74) and an increase from medium to large increased mean RMSE to 9.34(0.62), also not statistically significant. However, a change from small to large Grid evoked a statistically significant increase in mean RMSE ($p = 0.011$). Switching Dynamics from HD1

to HD2 increased mean RMSE from 7.92(.59) to 9.73(.67). The Grid $\times$ Dynamics interaction turned out to have no significant effect on RMSE.

Figure 19. Box plot of terrain error RMS

Positive and negative error contributions to the RMSE were determined to assess to which extent participants flew above or below the target signal. Figure 20 displays the mean and standard deviation (SD) of positive and negative error RMS for each condition. Mean and SD of the negative error RMS were significantly smaller than those of the positive error RMS across all conditions. Figure 21 shows the mean time fractions of the positive and negative error signals. Mean fraction of time spent below the target altitude varies between 3.3 – 7.6%.

Figure 20. Mean and standard deviation of the root mean square of positive and negative error.

2. Time fraction per performance boundary

Grid cell size did not affect the time fraction spent within performance zones, invalidating the hypothesis that it would increase T_{ina} . However, slower heave dynamics did negatively affect task performance measured by an increase in T_{ina} , disproving the hypothesis that pilots would adapt to changing vehicle dynamics to maintain consistent performance. Box plots of the Experience-lumped time fractions spent within desired, adequate and inadequate performance zones, shown in Figures 22 to 24, show no effect of Grid and only suggest that slower heave dynamics increased the relative amount of time spent in the inadequate region. ANOVA showed no main effect of Grid on either T_{des} , T_{adq} or T_{ina} . Dynamics had a main effect on T_{ina}

Figure 21. Mean time fractions spent above and below target altitude.

only, $F(1, 11) = 6.665, p = .026$, with an increase in mean T_{ina} from .122(.012) to .173(.020) when switching from Dynamics 1 to 2. The Grid $\times$ Dynamics interaction effect was not statistically significant. The participant-averaged, Experience-lumped time fractions spent within performance boundaries are represented by a barchart in Figure 25, summarizing the aforementioned effects.

Figure 22. Box plot of time fraction within desired performance boundary

3. Control activity

Control activity was significantly increased by a larger grid size, contrary to the hypothesis, yet the effect was only present between the medium and large grid cell size. Dynamics significantly lowered control activity, against the hypothesis as well. The box plot of the Experience-lumped σ_u^2 , displayed in Figure 26, does not present a clear trend for the effect of Grid but does indicate that control activity increases with slower heave dynamics. ANOVA found a significant main effect of Grid on σ_u^2 , $F(2, 22) = 4.737, p = .019$, with an insignificant decrease in mean σ_u^2 from 7.98×10^{-3} (4.56×10^{-3}) for small to 7.11×10^{-3} (3.86×10^{-3}) for medium, and a significant increase to a mean of 9.11×10^{-3} (5.07×10^{-3}) for the large grid cell size ($p = .025$). A significant main effect of Dynamics on σ_u^2 , $F(1, 11) = 30.062, p < .01$ was found too, with a decrease from 9.564×10^{-3} (4.833×10^{-3}) for HD1 to 6.570×10^{-3} (4.161×10^{-3}) for HD2. No statistically significant interaction effect of Grid $\times$ Dynamics was found.

4. Minimum time-to-contact

Minimum time-to-contact was not affected by the grid cell size, though it had been hypothesised to decrease. As expected, an increase in heave damping raised the minimum time-to-contact. A box plot of the

Figure 23. Box plot of time fraction within adequate performance boundary

Figure 24. Box plot of time fraction outside of adequate performance boundary

Figure 25. Time fractions spent within performance boundaries.

Figure 26. Box plot of the control signal variance

Experience-lumped τ_{min} is displayed in Figure 27, showing no discernible trend for Grid and an increase in τ_{min} for HD2. ANOVA indicated only a significant main effect of Dynamics on τ_{min} $F(1, 11) = 7.584, p = .019$, with an increase of mean τ_{min} from 6.026(.491) to 6.924(.521) when switching from HD1 to HD2. No statistically significant interaction effect of Grid $\times$ Dynamics was found.

Figure 27. Box plot of the minimum time-to-contact

5. Manoeuvre duration

As hypothesised, there was no effect of Grid on the duration of the tau manoeuvre. Dynamics did not have an effect either, against the expectation that manoeuvre duration would increase. The box plot of the Experience-lumped T , displayed in Figure 28, shows a lack of any apparent effect. ANOVA indicated no significant main effect of Grid or Dynamics, nor of their interaction of Grid $\times$ Dynamics.

6. Flight path angle gap

The hypothesis that the flight path angle gap would increase with an increase in grid cell size was partially confirmed. The hypothesis that Dynamics would have no effect is invalidated as γ_{gap} increased with the slower dynamics. The box plot of the Experience-lumped γ_{gap} , displayed in Figure 29, indicates that γ_{gap} goes down and then rises again as the grid cell size increases from small to medium to large. It also suggests that γ_{gap} is consistently higher for HD2 compared to HD1. ANOVA indicated a significant main effect of both

Figure 28. Box plot of the manoeuvre duration

Grid and Dynamics on γ_{gap} . An increase in Grid from small to medium elicited a statistically insignificant decrease in mean value from 20.82(5.75) deg to 17.19(6.50), whereas further enlarging to large significantly increased mean γ_{gap} to 23.33(8.29) deg ($p = .012$). Switching Dynamics from HD1 to HD2 showed a main effect by increasing mean γ_{gap} from 18.50(6.23) deg to 22.40(7.47) deg, $p = .006$. No interaction effect was found for Grid $\times$ Dynamics.

Figure 29. Box plot of the gamma gap

7. Coupling constant

Neither Grid nor Dynamics had an effect on the coupling constant, confirming the hypotheses. A box plot of the Experience-lumped k is displayed in Figure 30, showing no clear trend. ANOVA indicated neither a significant main effect of Dynamics or Grid on k , nor a significant interaction effect of Grid $\times$ Dynamics.

The statistical analysis has been repeated out by taking each rating between 1 to 5 as a minimum, omitting runs with a lower rating. No additional effects have been found by applying the statistical analysis to subsets of the data based on minimum ratings.

Figure 30. Box plot of the coupling constant

C. Optical Analysis

An optical variable analysis has been applied to the experiment scene, focusing on the effects of the terrain grid geometry on the splay and density angles and their rates in the experiment. To exclude potential pilot influences, point-mass simulations are done for each of the three starting positions in the experiment scene. During these simulations the nominal height of 70 ft above terrain is constantly maintained.

1. Total depression angle rate

As the terrain height in the experiment scene varies in the direction perpendicular to the direction of flight, the depression lines are slightly slanted. The grid height is therefore averaged between two laterally adjacent grid points to calculate the depression angle in the forward line of sight. The depression angle can then be calculated for each grid line perpendicular to the direction of flight by applying Equation (3).

As the AR terrain display has multiple grid lines, each visible at a certain depression angle varying across time, the combined depression angle rate cannot directly be expressed as a single value at each instant. The depression angle rate of each edge varies from naught when the edge is at the horizon to a maximum value when the edge is passing underneath the observer. If the depression angle rate of each edge visible in the forward field of view is summed, we get a total depression angle rate Δ as defined by Equation (18):

$$\Delta = \Sigma \begin{cases} \dot{\delta}, & \text{if } x_g \geq 0 \\ 0 & \text{if } x_g < 0. \end{cases} \quad (18)$$

Total depression angle rate for the first starting position across the three grid cell sizes is plotted against time in Figure 31. The passing of the lateral grid lines is displayed in the signal by the negative spikes. When the upcoming edge is relatively far away, total depression rate is near zero. Once the edge is approaching, the total depression angle rate decreases to a maximum negative value with an increasing rate. It quickly returns to about zero once the pilot has moved over the edge.

As the total number of edges increases as the grid cell size decreases, the total depression angle shows more peaks since the grid cell size is smaller. A smaller grid cell size will therefore provide more visual feedback, as confirmed by the total depression angle rate. Grid size does not have an effect on the absolute maximum depression angle rate, as witnessed by the coinciding edges of the small and large grid cells.

2. Splay rate

To calculate the splay angle in the experiment scene for the nominal height data, the average splay angle of the splay lines directly next to the pilot is determined through Equation (1). The splay rate is then computed by differentiating the splay angle against time.

Figure 31. Depression angle rate for nominal height across grid cell sizes for starting position 1

Splay rate is plotted against time for starting position 1 for the different grid cell sizes in Figure 32. The time axis is broadly set around the moment of the climb. Comparing the effect of the different grid cell sizes, the splay rate appears to vary more when the grid size is smaller. In Figure 32 the small grid cell size shows the highest absolute splay ratios. To compare the magnitude of the splay rates between the grid cell sizes, splay rate ratios are shown in Figure 33. The plot does not seem to add additional insight.

Figure 32. Splay angle rate for nominal height across grid cell sizes for starting position 1

V. Discussion

The results provide some insight on the implications of an AR terrain grid and the experiment design.

A. Experience

Following expectations, Experience did not affect any of the dependent variables, confirming that acquired piloting skills affected neither performance nor control behaviour. This suggests that the simplifications to the altitude control task were adequate for inclusion of participants of a lower skill level. Further, the

Figure 33. Splay rate ratios comparing splay rates between the three grid cell sizes

pre-experiment training can be inferred to have provided sufficient familiarisation across varying experience levels. As Experience had no effect, the experiment could be reduced from a mixed design to a fully within-subjects design for Grid and Dynamics, doubling the group sample size for these factors. Based on this outcome it is recommended to assess the impact of Experience during preliminary testing for potential future experiments.

B. Grid cell size

The main outcome of this experiment is that an increase in grid cell size from small to large significantly decreased task performance measured in mean RMSE by 16%. This confirms the hypothesis that a larger grid cell size leads to a lower amount of perceivable detail in terrain geometry, in turn causing worse task performance in altitude control. Another outcome is the unexpected 28% increase in mean control activity for the large relative to the medium grid cell size. It suggests that pilots were controlling more actively because they had a higher degree of uncertainty due to less optical information. The large grid cell size also led to a 36% gain in mean flight path angle gap compared to the medium grid cell size, implying increasing the grid cell size incites pilots to close larger motion gaps.

The lack of significant differences in task performance and control behaviour between the small and medium grid cell sizes suggests that these sizes provided a similar perception of the terrain geometry. The decrease in task performance and the substantial increases in control activity and flight path angle gap for the larger grid cell size indicate adverse effects on terrain geometry perception. Each of the significant effects of Grid occurred between two levels: either between small and large or medium and large grid cell size. This suggests that the optic cues originating from the small and medium sizes grid cells were of similar quality for the pilots.

The absence of significant effects of Grid on the coupling constant is in agreement with previous findings [13, 24].

Point-mass simulations of the AR terrain grid in the experiment scene showed that a smaller grid cell size provides more visual feedback, but that grid cell size does not have an effect on the absolute maximum depression angle rate. Further, the splay rate has a higher amplitude when the grid size is smaller. The small grid cell size causes the highest absolute splay ratios.

C. Helicopter Dynamics

The performance effects of Dynamics were mostly in accordance with the expectations. Pilots had more difficulty controlling the altitude with slower heave dynamics in HD2 compared to HD1, as witnessed by a 23% increase in mean RMSE and a 42% rise in the mean relative time spent beyond the adequate performance boundary. The unexpected rise of 21% in mean γ_{gap} when switching from HD1 to HD2 reinforces that the slower heave dynamics were more difficult to control.

The results have substantiated the hypothesis that slower heave dynamics of the rotorcraft cause pilots to apply a more prospective control strategy. A 31% decrease in mean control activity was seen in HD2 compared to HD1 due to the damping of higher frequency inputs and a 15% increase in mean minimum time-to-contact to the slope to account for the slower pull-up.

D. Interaction of Grid with Dynamics

The results show that Grid and Dynamics have various effects on task performance and control behaviour, but that there is no interaction between the two factors. Not a single interaction effect of Grid $\times$ Dynamics was found, clearly answering the question whether grid cell size affects pilot behaviour differently for various heave dynamics: this is not the case. The lack of any interaction effect simplifies the design of an effective augmented reality terrain for altitude control since its grid cell size setting can be based on its main effects, independently from the rotorcraft heave dynamics.

E. Recommendations

The experiment setup was mainly built upon Clark's hill climb experiment, with the additions of a reduction in the complexity of the altitude control task, more realistic, irregular terrain and the simulated AR terrain display [13]. The simplification of the control task successfully prevented the potential influence of pilot experience on the results.

The tau analysis led to a few insights. Both the manoeuvre duration and coupling constant were not affected by Grid or Dynamics. The lack of an effect in these parameters underline the difficulty in applying the tau analysis to realistic flight scenarios. The methodology of the tau analysis on experimental data is likely to benefit from improvements. First, it seems that the analysis can more easily be applied in strictly controlled conditions. For instance, the combination of the run-in length with irregular terrain before contact with the hill led to different starting conditions. Moreover, the analysis was indeed influenced by the manual work required to apply it. Applying a subjective rating to select the best fits over a large amount of runs did not prove fruitful either.

The effect of an AR terrain display with irregular terrain with variation in local height versus a flat one remains unclear. This could be further investigated by using the terrain geometry itself as an independent variable, rather than the geometry of the AR display. As the results between the small and medium grid cell sizes were statistically insignificant, this may be improved by testing sizes with larger differences. Finally, this study would greatly benefit from the addition of a baseline condition without any visual augmentation to see through the fog.

VI. Conclusions

The aim of this study was to research the effects of the grid cell size in an AR terrain display on task performance and control behaviour in a helicopter altitude control task with degraded visibility, and the potential impact of the controlled vehicle dynamics. Following a simulator experiment, analysis and discussion of the results several conclusions can be made.

First, a larger grid cell size negatively affects task performance and increases control activity, likely due to a worsened perception of the terrain geometry with the decrease in optic cues. This was further confirmed by an increase in the flight path angle gap when pilots had to pull up to climb over a hill. However, varying the vehicle dynamics by means of the heave damping coefficient had no interaction effect with the variation in grid cell size, meaning that this factor can likely be disregarded when designing an effective AR terrain display for altitude control.

We recommend to investigate the effects of various terrain geometries, test larger differences in grid cell size and compare the effects of the AR terrain display with a baseline condition without visual aid.

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