An Integrated Three-Dimensional Terrain and Primary Flight Display for Terrain Awareness and Alerting*

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ABSTRACT

This report describes preliminary research into three-dimensional (3D) terrain displays for enhancing pilot terrain situational awareness and warning of potential ground collision.

Two- dimensional plan-view terrain displays, as employed by current advanced terrain avoidance warning systems, are reviewed and their characteristics discussed. Previous research into 2D and 3D terrain displays is then examined to elucidate the relative merits and demerits of each format.

A prototypical 3D terrain display integrated with a primary flight display, dubbed the Primary Flight and Terrain Display (PFTD), was developed to evaluate the technical and operational feasibility of using computer-generated 3D terrain images to enhance pilot terrain situational awareness. Various technical aspects of the implementation are discussed, in particular the selection of visual cues to enable the form of the terrain to be perceived with sufficient depth and trade-offs with computational load. The results of preliminary qualitative evaluation by a test pilot are also presented.

Finally, this report briefly examines potential technical and operational problems of three-dimensional computer-generated terrain renderings for aerospace applications, including the problems of navigation and database error and human factor problems.

Keywords : Ground Collision Avoidance, Terrain Avoidance Warning System (TAWS), Three- Dimensional Displays, Synthetic Vision, Cockpit Displays, Pilot-Vehicle Interface.

概　　要

本報告は主に、パイロットの地形に関する状況認識の向上、及び対地衝突警報のための３次元地形表示の試験的研究について報告するものである。

最新式の対地衝突警報システムで採用されている、地形の２次元平面表示について見直しを行いその特性について述べる。次にこれまでの２次元及び３次元地形表示について、それぞれの表示形式の持つ利点や欠点を明らかにするため検討を行う。

パイロットの状況認識能力を向上させるために計算機合成された３次元地形を用いることの技術的および操作上の有用性を評価するため、３次元地形表示をPrimary Flight Display (PFD) と統合したPrimary Flight Display and Terrain Display (PFTD) と呼ばれるシステムを試作した。実装上の各種技術的側面、特に十分な奥行き感をもって地表の形状が認識されるための視覚上の手がかりの選択とそのための計算機負荷とのトレードオフについて記述した。テストパイロットによる予備的定性的評価結果についても述べる。

最後に、航法やデータベースの誤りの問題、ヒューマンファクターの問題も含めて、航空宇宙分野への応用のための計算機合成３次元地形表示の潜在的な技術的及び操作上の問題について簡単に述べる。

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List of Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
ASI	Airspeed Indicator
ATC	Air Traffic Control
CFIT	Controlled Flight Into Terrain
CGI	Computer-Generated Imagery
CDU	Control/Display Unit
CPU	Central Processing Unit
DEM	Digital Elevation Model
EGPWS	Enhanced Ground Proximity Warning System
FMS	Flight Management System
GCAS	Ground Collision Avoidance System
GPWS	Ground Proximity Warning System
HUD	Head-Up Display
IMC	Instrument Meteorological Conditions
I/O	Input / Output
LOD	Level of Detail
MIT	Massachusetts Institute of Technology
MSL	Mean Sea Level
NAL	National Aerospace Laboratory
ND	Navigation Display
PCP	Proximity Compatibility Principle
PFD	Primary Flight Display
PFTD	Primary Flight and Terrain Display
PVD	Plan-View Display
SSI	Spatial Situation Indicator
TAWS	Terrain Avoidance Warning System
VE	Virtual Environment
VFR	Visual Flight Rules
VSI	Vertical Speed Indicator

List of Symbols

α	Angle of attack
β	Sideslip angle
γ	Flight path angle
θ	Pitch attitude angle

1 Introduction

1.1 Background and Motivation

1.1.1 The CFIT Problem and GPWS

Controlled Flight Into Terrain (CFIT) is one of the largest classes of fatal aviation accidents. A classic definition describes CFIT accidents as

> ...those in which an aircraft, under the control of the crew, is flown into terrain (or water) with no prior awareness on the part of the crew of the impending disaster[1].

Although many accidents have multiple causal factors, a common feature of all CFIT accidents is human error — CFIT accidents occur when the crew is unaware of the position of the aircraft with respect to the terrain.

A number of measures have been proposed to reduce the rate of CFIT accidents, including better crew training, improving safety management, abolishing step-down non-precision approaches, improving the design of approach charts and standardising altimeter settings. Another approach is technological — aircraft on-board terrain avoidance warning systems (TAWS). The most widespread TAWS currently in use is the AlliedSignal (formerly Sundstrand) Ground Proximity Warning System (GPWS).

GPWS is an innovation which has saved many lives since its introduction in the 1970s. The system uses radio altimetry to monitor the aircraft's height above the terrain and can issue a variety of warnings, including of excessive terrain closure rate, dangerous terrain clearance, and excessive deviation below the glide slope during approaches to runways having a glide slope signal. However, GPWS has three major deficiencies. The first of these results from the fact that it only senses terrain clearance directly below the aircraft and has no means of "looking ahead" along the aircraft's flight path. This complicates the design of the filter logic and leads to both false positive warnings, which can erode pilot confidence in the device, and false negative or inadequately short warnings. Although these problems particularly affected early GPWS versions, later versions have only reduced, rather than completely eliminated, them.

A second major deficiency is that GPWS does not adequately protect the aircraft during approaches to runways lacking a glide slope signal. To allow the aircraft to land without spurious warnings, certain GPWS functions are disabled when the aircraft is in a landing configuration but since GPWS cannot determine the position of the aircraft with respect to the runway threshold, it cannot issue an alert in cases where the aircraft executes an otherwise normal approach but touches down short of the runway.

A third major deficiency is that GPWS is a "last resort" device which attempts to break the last link in the chain of events leading to CFIT. To borrow a medical analogy from Corwin[2], GPWS may be viewed as treating the symptoms, namely unsafe terrain proximity or closure, instead of addressing the disease, namely the information deficit (i.e. lack of situational awareness) which allowed the hazardous situation to develop in the first place. Consequently, recommendations have been made to develop new concepts to provide better terrain awareness to flight crews[3,4].

1.1.2 Towards a Better GPWS

Since the development of the original GPWS, electronic and computer technology has advanced considerably and now allow its shortcomings to be addressed. With the high accuracy of modern aircraft navigation systems (particularly satellite navigation), the development of compact yet powerful computers and high density mass-storage devices, it is now possible to create a system which continuously compares aircraft position and predicted trajectory against a terrain elevation database, providing the lookahead capability lacking in GPWS and consequently enabling substantially increased warning times while reducing the probability of false warnings. Runway positions and orientations can also be stored, allowing protection against "land short" accidents even for non-precision approaches. With flexible "glass cockpit" displays and powerful graphics generators, it has also become possible to display directly to the pilot the relationship between the aircraft and the terrain, thus enhancing situational awareness and hopefully breaking the CFIT causal chain.

At least three such advanced ground collision warning devices are currently either under development or in production for civil applications: AlliedSignal's Enhanced Ground Proximity Warning System (EGPWS)[5,6,7] and Dassault Electronique's Ground Collision Avoidance System (GCAS)[8], which are designed to be "drop-in" replacements for GPWS for fixed-wing aircraft (although a version of EGPWS is now being developed for helicopters), and Kawasaki Heavy Industries' GPS/MAP display with terrain proximity warning function[9,10] for helicopters. These devices support pilot terrain situational awareness by showing the aircraft and its surrounding terrain on a two-dimensional (2D) plan-view display (PVD), usually the pilots' navigation displays (ND) or weather radar display, or in the case of GPS/MAP, on a dedicated control/display unit (CDU).

EGPWS is enjoying wide acceptance among the pilot community, with several major airlines throughout the world equipping their fleets or evaluating the device at the time of writing. EGPWS provides a substantial advance over GPWS, and should prove to be even more effective at saving lives and aircraft.

1.1.3 Two-Dimensional or Three-Dimensional Terrain Depictions

Whereas EGPWS and similar displays show the relationship between the aircraft and terrain in a two-dimensional plan format, an alternative method exists of presenting terrain information to the pilot, namely as a three-dimensional (3D) perspective picture. The major advantage of such a display is that it is "natural" — a 3D presentation is more compatible with the way in which we perceive the world than a plan view, and presenting spatial information in this form can reduce the workload required for a viewer to interpret it. This can potentially equate to further enhanced terrain situational awareness, particularly of the vertical dimension which by definition cannot be depicted pictorially by a 2D PVD.

Why, then, do EGPWS-type displays not use such a depiction? There are a number of possible reasons for this. One may be that to encourage rapid introduction and retrofitting of the device as widely as possible for it to have the greatest benefit to safety, it must be compatible with current generation avionics technology and must be relatively inexpensive to manufacture, acquire and maintain. Generating detailed 3D renderings at interactive frame rates (a minimum of approximately 25 frames/second being required for smooth animation) is beyond the power of current generation avionic graphics generators and electronic displays, particularly since airborne electronic devices tend to lag considerably behind the state of the art in the consumer electronics sector.

A second possible reason is that the characteristics of three-dimensional displays are not as well understood as those of 2D depictions, and so require a much greater research and development effort which outweighs any advantages which they may have over more conventional displays. In particular, 3D displays have many more design parameters than 2D displays, some of which interact with each other, and this can greatly complicate the achievement of an optimal design solution.

A third possible reason is that 3D displays may not be suitable for conveying terrain situational awareness to cockpit crews, or that 2D displays may be sufficient. Whether a 2D or 3D display is the more suitable for an application is somewhat application-dependent and can be non-intuitive: For example, in previous research in which the author looked at 2D and 3D displays for air traffic control (ATC), it was found that for the current air traffic controllers' tasks, the current 2D plan-view depiction was in many ways more suitable than a 3D depiction even though ATC involves controlling the trajectories of aircraft through 3D space, because the way in which the controllers' tasks are defined and have evolved tend to treat vertical and horizontal dimensions separately11,12).

A fourth possible reason is the fact that a 3D terrain display may require a much greater accuracy of terrain database information and navigation position than a 2D display, which makes guaranteeing the accuracy of the terrain and navigation data and certificating the display much more challenging. Since a pictorial image is far closer to the domain of the real world view through the cockpit windows than a rather more abstract plan view, it invites both direct comparison with the real world and even use in lieu of a real-world image by the crew in cases of, for example, flight in instrument meteorological conditions (IMC). Added to the fact that 3D displays tend to be more compelling than 2D displays, there is a danger of pilots placing greater faith in the 3D depiction than is warranted by its limitations.

These reasons notwithstanding, the large-scale commercial production of powerful graphics generators and computers is pushing the costs of interactive 3D graphics capability ever downwards, and it is almost certain that this technology will eventually be used for avionics applications. It is therefore probably wise that research be carried out into ways of exploiting such a capability when it becomes available. Bearing the above points in mind, this research is aimed at investigating the feasibility of using a 3D presentation of terrain for enhancing pilot terrain situational awareness and as a terrain collision warning device.

1.2 Research Objectives & Scope

1.2.1 Overview

The aim of this research is to explore the feasibility of using a 3D perspective terrain display to support pilot terrain awareness and to function as a terrain collision warning device, providing advance warning of possible dangerous proximity of the aircraft to terrain and supporting recovery from potentially hazardous situations.

This report is divided into three parts. In the first part, the characteristics and theoretical advantages and disadvantages of 2D and 3D displays are examined, and some previous research which has looked at advanced terrain depictions is reviewed. The author's intention in this part has been to help to clarify some of the benefits and drawbacks of each display type and to show how these relate to flight crew task requirements.

The second, main part of this report concentrates on the development and preliminary evaluation of a prototype 3D terrain display integrated with a primary flight display (PFD), dubbed the Primary Flight and Terrain Display (PFTD). A commercially-available digital elevation database was used to generate a perspective 3D terrain image onto which were overlaid primary flight instruments and symbology. An initial prototype display was evaluated informally by a test pilot and suggestions for improvements were incorporated into a second version, which was also evaluated.

The PFTD was developed to investigate technical issues in implementing a 3D cockpit terrain display and to determine its basic acceptability. Implementation issues received much attention, and the author hopes that the results achieved will be useful to others considering constructing such a display.

The third part of the report comments on issues such as database integrity and required navigation system accuracy which have not been addressed in detail by this research, but which merit further study.

1.2.2 Overlap with Other Research Areas

There is a high degree of overlap between 3D terrain awareness displays and so-called synthetic vision displays. Definitions of synthetic vision and enhanced vision vary, but in this report synthetic vision will be taken to refer to the use of computer-generated imagery (CGI) to augment or replace the external view through the cockpit transparencies for the purposes of flight guidance, irrespective of whether or not the CGI is fused with a sensor image. This is an altogether more ambitious aim than terrain situational awareness and proximity warning as it is flight critical and therefore requires a much higher level of accuracy and integrity of navigation, elevation and feature data.

Prototype synthetic vision displays tend to be visually rich, depicting not only the shape of the terrain surface but also airport features such as runways and taxiways for landing, takeoff and surface operations, and cultural and geographical features such as roads, railways, rivers and built-up areas. For this research, it is assumed that such features are unnecessary and irrelevant for the task of providing basic terrain awareness, for which adequately legible rendering of the shape of the terrain is assumed to suffice. Visual richness would enhance the level of realism of the display, but at considerable cost of increasing the complexity and size of the database, reducing frame rate, increasing hardware and software complexity, and possibly increasing clutter, and there are doubts as to whether such realism is necessary or even desirable in a warning device.

For this reason, this research will concentrate only on the graphical depiction of the shape of the terrain.

1.2.3 Some Limitations

A major problem with research into 3D terrain displays is the lack of readily available published empirical evidence, particularly comparing 2D and 3D depictions, with the exception of the work of Kuchar & Hansman described in §3.1. Although this research postulates the relative merits of 2D and 3D terrain display types, these hypotheses need to be investigated experimentally.

The emphasis of this research is on a practical terrain display implementation, and the resulting display has been evaluated by a test pilot. However, it should be stressed that the implementation of this research is just one of a number of possible implementations and that there remain a large number of design issues to be explored which were not investigated. Further, although the PFTD prototype displays were evaluated by a test pilot, these evaluations were qualitative and informal in nature, and were conducted with only a single subject.

1.3 Structure of this Report

The following section looks at design issues relating to two- and three-dimensional displays, focusing on their characteristics and suitability for the tasks of terrain awareness and collision warning. §3 then examines some previous research in the context of the theory and hypotheses developed in §2.

§4 gives an overview of the implementation of the PFTD display developed in this research. §5 describes a proof-of-concept display which was used to gain opinions as to the efficacy of the 3D terrain display concept. An evaluation of this display by a test pilot uncovered problems with the sense of depth afforded by the display, and §6 describes possible ways of enhancing the sense of depth and a subjective evaluation of displays incorporating different combinations of depth cues.

Issues relevant to this research which were not explored but which are nonetheless important are conjectured in §7. Finally, §8 presents the conclusions.

2 Display Design Considerations

2.1 Display Objectives

Three objectives are posited for a cockpit display for terrain awareness and collision alerting, which can be paraphrased as questions which the flight crew might want to ask of it:

1. To warn of immediate danger, and to allow determination of a suitable avoidance manoeuvre. (*"Are there any immediate threats, and if so, how can I avoid them?"*)
2. To convey to the flight crew the position of the aircraft with respect to local terrain and to allow rapid assessment of the level of possible hazard, with sufficient orientation references to allow rapid and accurate location of hazards in the real environment. (*"Where is the terrain? How hazardous is it?"*)
3. To allow the flight crew to anticipate possible future hazards along an intended flight path. (*"Are there any non-immediate threats?"*)

These objectives are intended to reflect pilot information requirements according to workload, and correspond broadly to three tasks: Terrain Avoidance, Terrain Situational Awareness and Strategic Planning.

Objective (1), a warning, addresses high workload situations where the flight crew's attentional resources may be too limited for effective monitoring, with the consequent degradation of situational awareness. A warning device serves actively to bring potential hazards to the attention of the crew in a timely manner such that the hazard can be avoided safely, preferably in such a way that enables the nature of the hazard to be determined and that assists escape from it.

Objective (2) addresses moderate workload situations: sufficient information should be conveyed in a "quick glance" for the crew to be able to confirm the aircraft's position with respect to local terrain and to check for hazards in the short term.

Objective (3) addresses lower workload situations, such as during cruise, where the crew can engage in strategic planning and monitoring of the progress of the flight.

Having defined these objectives and tasks, the problem is to create a suitable display design which satisfies them. Two types of display are considered in this report: A 2D PVD, as employed by current advanced ground collision warning devices, and a 3D perspective terrain view.

2.2 Design Considerations

The effectiveness of a display for a task depends partly on whether or not the characteristics of the depiction are suitable for the way in which the operator processes and uses the presented information in executing the task. Two-dimensional and three-dimensional displays have different characteristics, and these can be understood from display theory. The way in which these characteristics are suited to different tasks can be addressed by theories such as the Proximity Compatibility Principle (PCP)[13], which considers the organisation of sources of information (displays) given their relatedness (proximity) to other displays and the way in which the information is processed by an operator performing a task. For example, PCP suggests that more integrated, "object-like" representations tend to support more integrative cognitive tasks, whereas tasks which require the focus of attention on single dimensions or objects are likely better to be served by more separated displays[14].

2.2.1 Characteristics of 2D and 3D Displays

The main advantage of a pictorial 3D display is that it is a "natural" way of showing spatial relationships. Exploiting innate human perceptual capabilities, a single 3D display may integrate information which would otherwise require multiple planar displays or a mix of spatial and non-spatial codes on a single planar display, and can reduce the mental workload required to scan and integrate the information presented. According to PCP, 3D displays may be suited to tasks which require integrated judgements rather than focus of attention on parameters singly.

However, 3D displays have a number of drawbacks. For this application, two of the most critical are the existance of an ambiguity regarding the precise location of objects along the line of sight into the display, and reduced precision in reading values along any one particular axis[15,16]. For a perspective terrain display, this implies that there may be difficulties for tasks requiring the focus of attention along the display line of sight, for example determining distances to obstacles ahead of the aircraft.

Two-dimensional plan-views, such as those employed by EGPWS-like terrain displays, aircraft collision alerting systems and ATC radar displays, are able to pictorially show horizontal spatial relationships unambiguously, but require other codes (e.g. colour coding, contours or numeric height readouts) to represent information along the vertical axis. One would therefore expect them to be superior to 3D displays for tasks in which spatial judgements are mostly in the horizontal plane, but inferior to them for the perception of vertical relationships and for making spatial judgements involving both horizontal and vertical elements. As anecdotal evidence, one can consider the difficulties sometimes experienced by flight crews in the awareness and management of vertical flight path in flight management system (FMS) equipped aircraft. Part of the difficulty may be that, in contrast to lateral navigation functions which are supported by a graphical plan-view representation of the aircraft's horizontal flight path on the pilots' navigation displays (ND), there is no direct visualisation of vertical flight profile. Vertical profile displays[17,18] and "tunnel-in-the-sky" displays[19,20] have been proposed as means of addressing such problems.

Another advantage of 2D displays over 3D displays is that they are less complex and costly to implement and design, and are much better understood from a human factors viewpoint. Three-dimensional displays have many more design parameters and this can greatly complicate the optimisation of a design. Further, problems associated with some types of 3D display can have adverse effects on the viewer ; for example, stereoscopic immersive "virtual reality" displays have been known to induce feelings of nausea, perhaps related to the effects of time lags between motion and scene update and conflicts between stereopsis and muscular depth cues since the eyes no longer have to converge when fixating on objects even though they may appear to be close to the viewer.

There are a number of methods of addressing the perceptual problems relating to two-and three-dimensional displays, which include21):

- In the case of 3D displays, operator training or deliberately introduced distortions to compensate for perceptual biases in viewing resulting from choice of display parameters.
- Symbolic enhancements.
- Tools and other aids for elucidating or extracting information.

However, the use of these must be balanced against considerations such as clutter, the potential for operator error and increased workload.

2.2.2 Exocentric versus Egocentric Viewpoint

One taxonomy of displays pertains to the relationship between the viewer and the display; displays may be categorised as exocentric (outside-looking-in) or egocentric (inside-looking-out). A plan-view display is exocentric, whereas a 3D perspective display of the type proposed in this research is egocentric.

A further taxonomy, although more vague, classifies displays according to the degree of "association" of the viewer with the depicted environment. Conventional displays can be thought of as showing a computer-generated virtual environment (VE) "through the window" of a computer monitor, with the VE separate from the real environment (dissociated perspective)22). In associated displays, either the VE can be brought into the viewer's environment or the viewer can be "immersed" in the VE. Association is the definitive attribute of so-called "virtual reality" displays.

An advantage of the exocentric PVD is that the position of the viewpoint (i.e. the position of the centre of the display) is independent of that of the viewer and this allows for the display to be arbitrarily manipulated (offset, zoomed, scaled and rotated). This allows, for example, different sections of a flight plan to be viewed and is useful for tasks such as strategic planning. It also allows the pilot to view the terrain all around the aircraft. A drawback is that unless the display is closely orientated with the real environment (e.g. a "heading up" presentation) it may be difficult rapidly to reconcile features depicted on the display with the features they represent in the real world.

An advantage of the egocentric perspective display (i.e. generated from the viewpoint of the viewer) is that the location of real-world features from the depicted VE is potentially extremely rapid. However, perceptual distortions can occur when viewing 3D displays; for example, magnification or minification which can make objects appear further away or closer than they really are. Also, only the view straight ahead is shown, thus creating difficulty in showing any hazardous areas to either side of the aircraft which might be relevant in turning flight, and increasing the angle of view to compensate for this leads to minification.

An egocentric associated 3D display is also a possibility. A head-slaved VE projected onto, for example, a head-mounted display and presented conformally with the external environment would enable the pilot to see not just the terrain ahead but also around the aircraft simply by turning his or her head, and would allow the pilot to fly "eyes out" instead of "head down". While such displays are beyond the scope of this research, there may be advantages to other displays in which symbology is conformally displayed on the external environment.

2.2.3 Conformal Symbology

Displays such as Head-Up Displays (HUDs)23), synthetic vision systems24,25) and enhanced vision systems26,27) can superimpose symbology conformally onto (that is, in registration with) an external view, whether the external view is a natural one, a sensor image, a synthetic view or some combination of these.

Studies comparing head-up and head-down presentations have shown that information which must be integrated between the domains of the display and the external environment benefits most from the

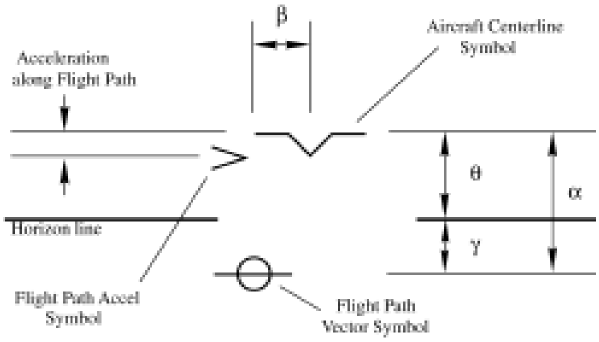


Figure 1 : Flight Symbology and Flight Parameters

closer proximity afforded by conformal presentation13). Pilot awareness of the state of the aircraft with respect to the terrain might therefore benefit from a conformal presentation of information such as attitude references and flight path cues with the terrain. Another benefit is that such an integrated device would eliminate the need for separate displays for the terrain and primary flight information.

Figure 1 shows the relationship between HUD-type flight symbology and basic flight parameters. It is hypothesised that showing this symbology overlaid onto the synthetic terrain image will convey awareness of the state of the aircraft with respect to the terrain; for example, if the flight path vector is shown superimposed on the terrain, there is a potential collision hazard. It is further hypothesised that the symbology can assist the pilot in assessing aircraft performance in a terrain escape manoeuvre. In such a manoeuvre, it is recommended that the pilot apply maximum thrust and pitch up to an appropriate pitch attitude for the aircraft, between 15 to 20 degrees nose up, and to maintain this until stick shaker activation (if fitted, representing optimum angle of attack) or until terrain clearance is assured28). If this is carried out but the flight path acceleration symbol indicates high deceleration or the flight path vector remains superimposed on the terrain, the pilot may be able to recognise that a pure vertical escape may be impossible. In such cases, the perspective terrain display can give guidance for lateral escape manoeuvres.

There are a number of potential disadvantages with displays of this type29,30). Clutter in a poorly-designed display can interfere with the pilot's ability to extract information from the display and so can increase workload. This problem can be addressed by careful design and by features such as pilot-selectable symbology, automatic declutter (for example, removal of non-pertinent symbology on flight phase transition) and so-called "smart" symbology which appears only when appropriate. Attentional aspects also need to be addressed — an integrated 3D / primary flight display may encourage inappropriate fixation on one aspect of the display to the neglect of others (so-called tunnel vision behaviour).

There will inevitably be discrepancies between the depicted scene and the real world, due to both errors in the data from the aircraft's navigation system and database errors. Accuracy issues relating to terrain database and navigation performance are considered in §7.1.

Finally, pictorial displays, and 3D displays in particular, are compelling and there is thus the danger of the crew treating the information as being of higher fidelity than it actually is. The reduced information access workload of an integrated 3D display might also lead to crews neglecting to cross-check with other sources of information, such as paper charts and "raw" navigation data, which have a higher access and interpretation workload.

2.2.4 Data Accuracy and Display Type

It is postulated that the realistic nature of a pictorial three-dimensional terrain display may itself impose a requirement for a higher level of accuracy of both aircraft state (position and attitude angles) and terrain elevation information than a plan-view schematic display of the EGPWS type. This accuracy requirement is notwithstanding the basic levels of accuracy required for reliable and efficacious terrain hazard computation and warning generation. The reason for this is that the 3D depiction is much closer to the domain of the environment and can easily be compared with it directly. Because of this domain proximity, any discrepency (for example in the location of features due to navigation error, or the shape of the terrain due to database error) might therefore easily be detectable and is likely to be less tolerable than for a plan-view display, which is more abstract and further from the real world domain.

If symbology are to be presented conformally with the synthetic terrain image (§2.2.3), the aircraft state vector and terrain data must be sufficiently accurate if such symbology is to be useful for terrain avoidance guidance and not misleading, especially in close terrain proximity situations, or else adequate margins must be built into the evasion guidance computation to account for errors.

2.3 Summary

From the preceeding discussions, it can be realised that each type of display, 2D and 3D, has both merits and drawbacks. It is postulated that no single display design is ideally suited to all the objectives in §2.1. although there are methods of addressing the drawbacks of each display type.

Advantages of a 2D plan view are that it shows the aircraft's position in relation to features all around the aircraft, and that it can be zoomed and offset to show terrain clearance around different segments of a flight plan. This gives it utility in tasks such as navigation and strategic planning. Other advantages are the relatively low complexity (and therefore cost) of such displays, and the familiarity of the user community with plan-view presentations. A drawback is that it may be difficult to make judgements involving the vertical dimension with such displays, especially if the aircraft is not in level flight.

The main advantage of a 3D pictorial display is that the depiction is more "natural" and so can potentially offer higher situational awareness of hazards immediately in front of the aircraft, as both vertical and lateral information are conveyed in a form which can be easily interpreted and related to the actual environment. With conformal flight symbology, situational awareness may be improved in near-terrain situations and better guidance can be given during terrain avoidance manœuvres. Disadvantages include the relatively high complexity of such displays, human factors issues such as the ambiguity of the location of objects along the display line of sight and the possibility of perceptual distortions in viewing, and the number of display variables which must be optimised in a design.

Accuracy of both navigation and terrain data are major concerns and it is postulated that more than any other factor, limitations in accuracy will determine the ways in which the displays can be used. In particular, a perspective terrain display cannot be used as a substitute for visual references for navigation or guidance without high fidelity.

3 Review of Previous Research

This section reviews two research projects which examined advanced terrain awareness displays: Preliminary research into advanced electronic terrain displays conducted at MIT by Kuchar & Hansman, and a 3D display for increasing pilot terrain awareness during approach by Williams & Mitchell.

3.1 Advanced Terrain Displays (Kuchar & Hansman)

3.1.1 Overview

Kuchar & Hansman conducted some preliminary research into advanced displays for depicting terrain hazards, using pilots as subjects in part-task flight simulation experiments. Two investigations focused on plan-view displays while a third compared plan, profile and perspective displays.

An initial study31) established the need for cockpit terrain displays by demonstrating the inadequacy of current paper charts for providing terrain awareness. It also found a plan-view smoothed-contour display to be superior to a spot-height display for terrain hazard recognition. Two modes of terrain information usage were identified: Terrain Situational Awareness involving large-scale depictions (>18 520m (10 n.mi.)) used for strategic planning purposes, and Terrain Alerting (<18 520 m) used when immediate manoeuvering is required to avoid a hazard.

A second investigation32) examined subject preferences for vertical and horizontal resolutions of the terrain depiction. Subjects were found to prefer 153 m (500 ft) or 305 m (1 000 ft) contour intervals and while the highest available horizontal resolution was generally preferred, display reading error rates were not found to be highly correlated with selected resolution level. Kuchar & Hansman therefore suggest that the horizontal resolution limits (in a PVD) will be driven by task requirements rather than by human factors issues. The investigation also compared two methods of shading contours: Relative to Mean Sea Level (MSL) and relative to ownship altitude. Subjects were asked to determine whether a (level flight) route was clear of hazardous terrain and to estimate minimum terrain clearance or distance to a hazardous region. Those using the ownship-relative display gave faster responses, suggesting that this type of display is more effective for conveying terrain hazards to pilots.

A final investigation[32] compared three types of display as shown in Figure 2: (a) a profile view showing vertical path of the aircraft relative to the terrain, (b) a plan view on a navigation display, and (c) a perspective 3D view on a primary flight display. Subjects flew a number of terrain alert scenarios with each display type, with four levels of terrain hazard severity crossed with three flight conditions (straight and level, turning and descent). Terrain hazards "popped up" on the display, whence subjects made an assessment of the terrain threat and flew an avoidance manœuvre. It was found that no display was entirely effective in conveying the true level of hazard when descending into flat terrain, and in 50% of trials involving plan or perspective views, the aircraft impacted the terrain before successful recovery. Profile and perspective displays were found to overemphasise the level of hazard when the aircraft was turning safely in front of a ridge. Unsurprisingly, the type of avoidance manœuvre was found to be correlated with display type, lateral manoeuvres being initiated 80% of the time with the PVD, 30% of the time with the perspective display and 5% of the time with the profile display. Subjects preferred the plan or perspective displays, citing the desirability of the increased lateral information which these afforded.

3.1.2 Discussion

This research provided experimental evidence which supports the need for an electronic cockpit display to enhance pilot terrain situational awareness, and empirically investigated different types of display. The comparison of plan-view, profile and perspective displays is particularly germane to the discussion in §2.

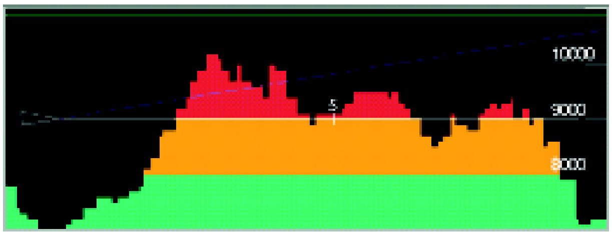
The findings of two modes of terrain information usage (strategic and for immediate terrain avoidance) are consistent with the display objectives outlined in § 2.1.

For the task of ensuring terrain clearance, the research suggests that the pilot is primarily interested in the relative height of the aircraft with respect to the terrain. A display in which heights of the terrain are colour-coded relative to that of the aircraft makes terrain clearance directly visible, instead of placing the burden of determining terrain clearance on the pilot (and hence increasing workload and error rate) as in an MSL-relative display.

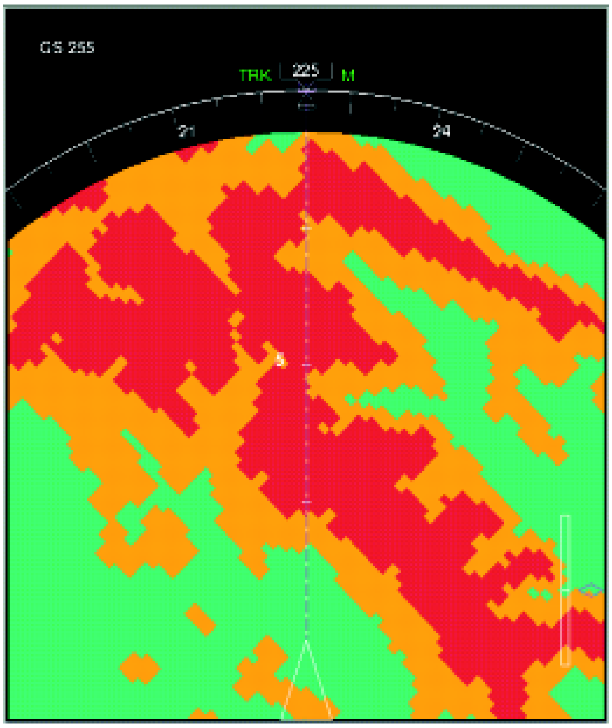
The lack of effectiveness of the plan-view and perspective displays in conveying the level of hazard when descending into flat terrain merits further examination, particularly since CFIT accidents do occur in areas absent of high terrain[3]. The PVD does not pictorially visualise the vertical dimension, making it difficult for the pilot to predict terrain clearance at points along the flight path, particularly if the aircraft is climbing or descending. This might account for some of the reported lack of effectiveness of this display in the cases of descent into flat terrain. Although Kuchar & Hansman suggest that the MSL-relative display may have uses in applications where prediction of terrain clearance along a non-level flight path is required, this still places the burden of determining terrain clearance on the crew ; a better alternative might be to assist the pilot with terrain clearance prediction aids.

In the case of the perspective 3D display, such displays are subject to ambiguity regarding the location of objects along the display line of sight, making it difficult to determine the distance to obstacles along the flight path and so possible contributing to the observation of sometimes unsuccessful recovery (late pull-out) and the overemphasing of the level of hazard of a ridge line. Further, judgements of absolute and relative distance are influenced by the number and type of depth cues which are incorporated into the display, and Figure 2(c) does not show a great sense of depth which might assist the pilot in making such judgements.

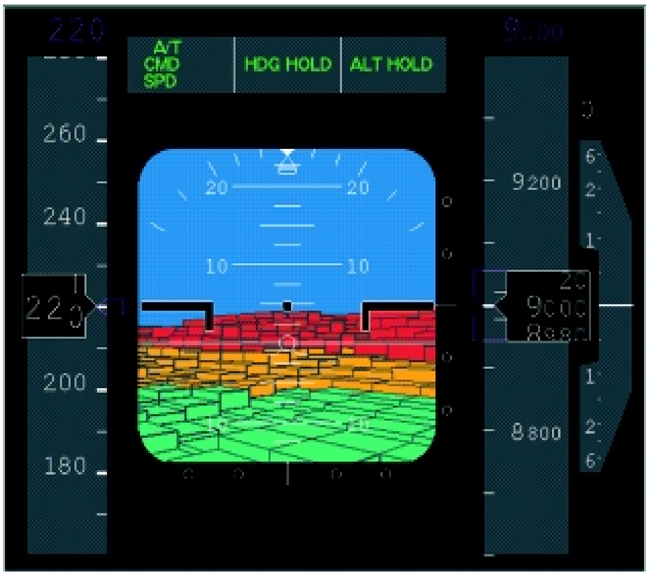
The profile display shows distances in the longitudinal horizontal and vertical planes unambiguously (thus clearly showing distance to impact to obstacles directly ahead of the aircraft or terrain clearances along the flight path in non-turning flight, whether the aircraft is ascending or descending) but cannot convey lateral information pictorially. This is consistent with the experimental observation that subjects initiated lateral escape manœuvres in only 5% of the trials involving the profile display. Conversely, that such manoeuvres were initiated in 80% of trials using the PVD might also be explained by the fact that although the PVD provides some lateral guidance, it may not provide sufficient vertical guidance for pilots to be able to execute vertical escape manœuvres with confi-



(a) Profile Display



(b) Plan-View Display on ND



(c) 3D Perspective Display on PFD

Figure 2 : MIT Advanced Electronic Terrain Displays
Reproduced with kind permission of J. Kuchar

dence of terrain clearance.

In summary, the results of the MIT research are consistent with the theoretical advantages and drawbacks of the different display types as regards perception and judgements of spatial relationships. No display is ideal, and simply presenting the raw terrain information may be insufficient; if the viewer is left to make judgements such as terrain clearance along the flight path or distance to obstacles unsupported, higher workload and error rates may result. In order to reduce these errors, assistance aids such as symbolic enhancements and prediction features may be necessary.

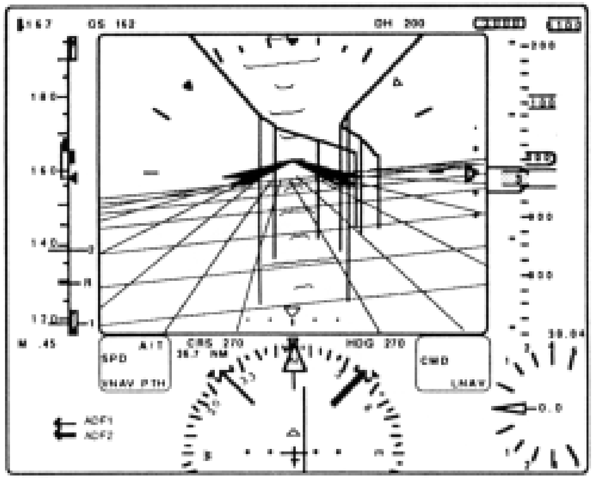
3.2 Spatial Situation Indicator (Williams& Mitchell)

3.2.1 Overview

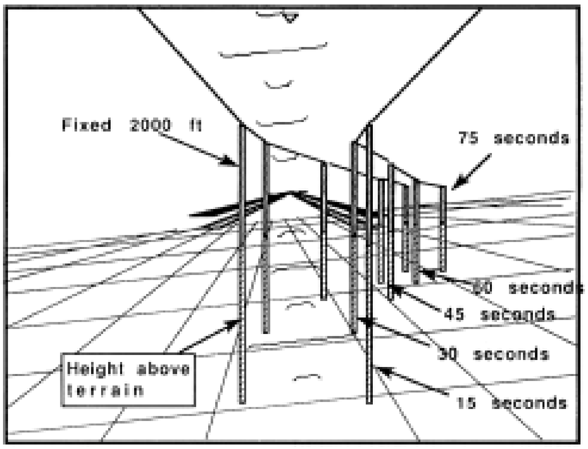
Williams & Mitchell carried out research aimed at developing a prototype integrated display for terrain avoidance in the terminal phase of flight[33]. The display, dubbed the Spatial Situation Indicator (SSI), shows a perspective view of a three-dimensional terrain grid map and flight path information on a PFD-type instrument, as show in Figure 3.

The terrain is rendered as a Gouraud smooth-shaded triangle mesh generated from spot elevations at 3 704 m (2 n.mi.) intervals. The mesh is dynamically colour-coded according to predicted terrain clearance, using dark green to indicate safe terrain clearance and dark red to indicate dangerous terrain clearance. Information on artificial obstructions is also incorporated into the database.

Predicted position and terrain clearance information are shown for up to 75 seconds ahead of the aircraft. Clearance information is provided by a pair of vertical lines, dubbed "whiskers", displayed at constant objective width and positioned at 15 s intervals along the predicted trajectory. These are colour-coded green and yellow; a green portion extends from the predicted aircraft altitude to the terrain below, its length thus representing the projected terrain clearance at that point in time. The upper, yellow whisker portions extend 610 m (2 000 ft) upwards from the predicted altitude. The tops of each whisker pair are connected to provide a visual flow which is reported to be useful in discerning flight path during moderate to steep turns.



(a) Spatial Situation Indicator



(b) Detail of Terrain Clearance Predictor "Whiskers"

Figure 3 : Spatial Situation Indicator
Reproduced with kind permission of C. Mitchell

Williams & Mitchell also examined autopilot mode and spatial awareness in CFIT incidents, and identified three representative types of error which can be introduced into a pilot-flown approach to result in near-CFIT situations for display evaluation, *viz* autopilot mode reversion, incorrect altitude selected on the autopilot control panel, and improper barometric altitude. However, it is uncertain as to whether an evaluation of the SSI was ever carried out.

3.2.2 Discussion

The SSI is an advance over the perspective display of Kuchar & Hansman in that it contains predictive features and symbolic enhancements which reduce the information extraction and interpretation workload. In particular, it addresses the problems of judgement of distance along the display line of sight and of judgement of terrain clearance along the predicted flight path.

A further enhancement might be to modify the colour-coding of the whiskers such that the portion of the whisker within 305 m (1 000 ft) of the terrain is highlighted in red, since in normal flight rules aircraft must fly at least 1 000 ft above the level of the highest obstacle in the area.

Unfortunately, this research did not produce any empirical results but it does serve as a useful design example.

4 PFTD Display Development

4.1 Introduction

Having reviewed theory and previous research, this report will now focus on the development of the Primary Flight and Terrain Display used as an exploratory vehicle for this research. This section describes the overall design and implementation of the PFTD.

As stated previously, although the avionic 3D graphics generators required to implement such a display are not extant at present, this capability is certain to become available and so research should be carried out into ways of exploiting it. The PFTD was constructed with the aim of investigating the feasibility of using a perspective terrain presentation for enhancing pilot situational awareness and as a TAWS, and to identify issues concerning its practical implementation and use. Implementation issues received much attention, and the author hopes that the results achieved will be useful to others considering constructing such a display.

The PFTD used a commercially-available digital elevation database to generate a perspective terrain image onto which primary flight instruments and symbology were overlaid. An initial proof-of-concept display shown in Figure 4 was developed and evaluated informally by a test pilot. This initial evaluation revealed problems concerning the perception of depth in the display, as well as yielding other suggestions for improvements. To investigate further the problem of providing an adequate impression of depth, a second prototype display was constructed, an example of which is shown in Figure 5, for which a variety of depth cues were investigated. Different versions of this display incorporating different cues were also evaluated by the test pilot, who selected the combination of depth cues which he judged to be the most effective.

4.2 Apparatus: Software & Hardware Overview

The software was implemented on a Silicon Graphics Indy workstation running the Silicon Graphics IRIX variant of the Unix operating system, and comprises three programs: A display program, which generates the display and provides terrain clearance computation and warning functions, a flight simulation program and a pilot control input program.

The display program is written in C++ and uses the OpenGL graphics library34). It comprises two lightweight processes (pthreads) which share a common address space: The display generation process and a terrain clearance and collision computation process. These two processes share a cache (stored in shared memory) of a terrain database file which resides on hard disk.

The display is driven by a flight simulation of a Dornier Do228 twin turboprop unpressurised commuter aeroplane, a program written in FORTRAN with a C "front end" and a graphical user interface using X11 windows. The flight simulation and display program communicate via shared memory.

Flight control inputs (elevator, ailerons, rudder and engine power) are through either of two separate programs, one of which allows input via the keyboard, the other of which allows input via a BG Systems Flybox joystick unit connected to a serial port. The control programs communicate with the flight simulation program via Internet domain BSD sockets, allowing them to run on a separate computer from the display and flight simulation programs.

Source and object codes are portable between different Silicon Graphics computers, which allowed the code to be developed on a workstation of relatively low performance but later run on more powerful computers, such as the Indigo 2 and Onyx. Required graphics hardware is two frame buffers, each of minimum 24-bit colour depth plus alpha channel, z-buffer and stencil buffer, with double buffering for smooth animation.

The terrain display, terrain database processing, terrain clearance computation, and input device interface software was developed by the National Aerospace Laboratory (NAL), and the simulation front-end

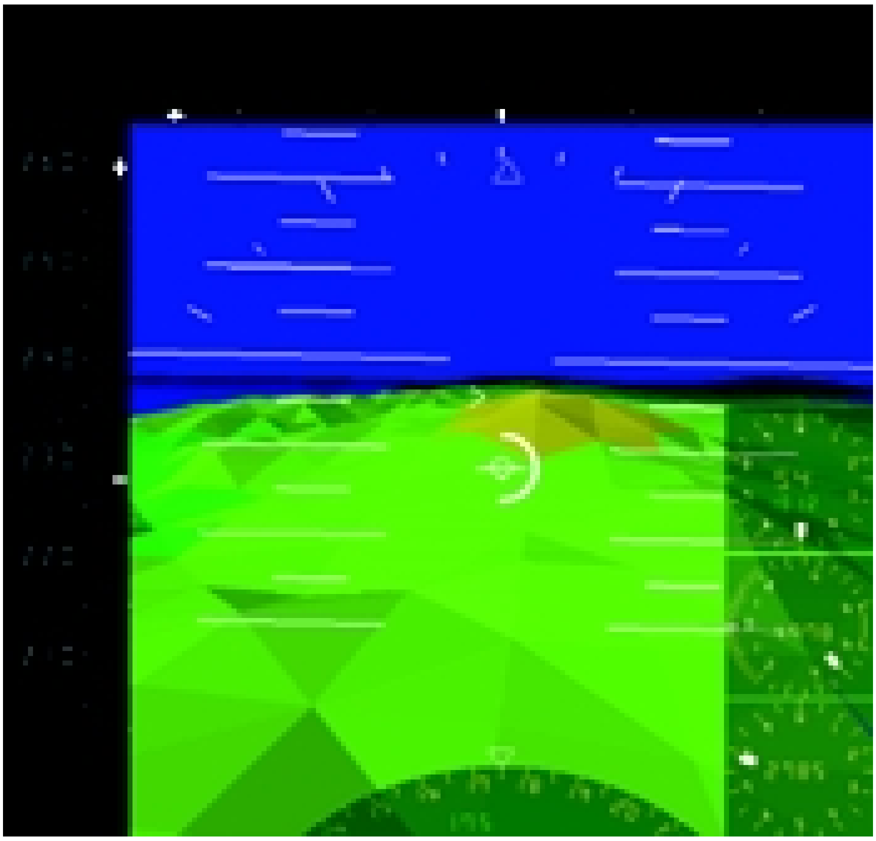


Figure 4 : Proof-of-Concept Display

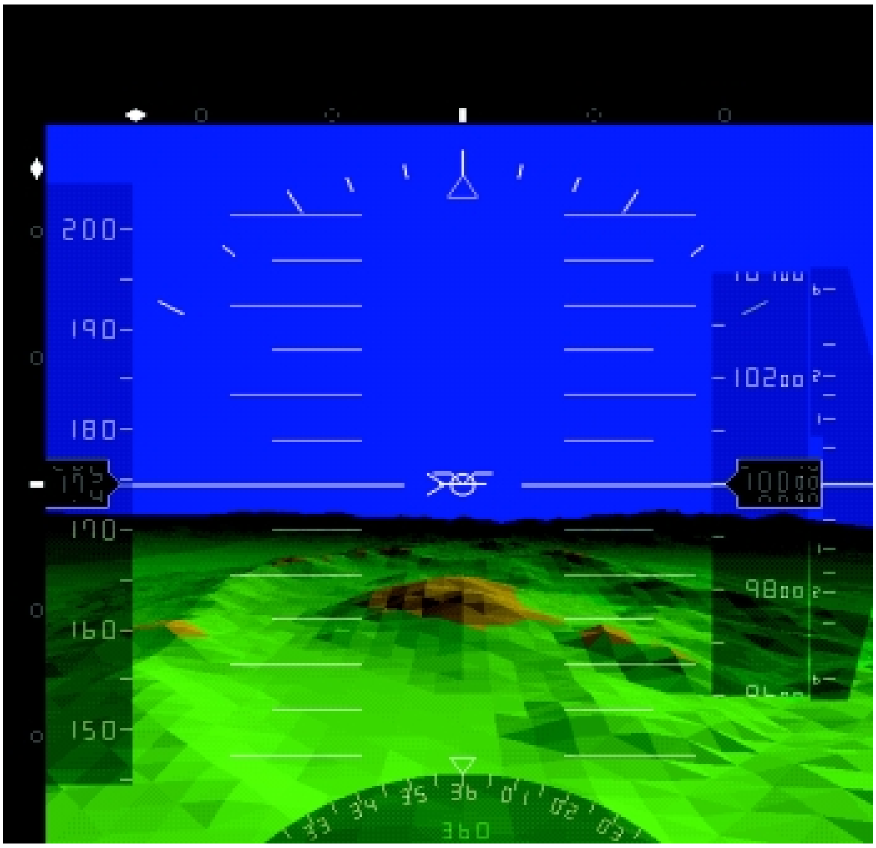


Figure 5 : Instrument and Symbology Layout for Second Prototype Display

code, graphical user interface and elements of the PFD code were contributed by K. Funabiki, another researcher at NAL.

4.3 Display Design and Implementation

This section describes the design and implementation of the PFTD.

4.3.1 Primary Flight Display

The three-dimensional perspective terrain image is integrated with a PFD. Some flight instruments are overlaid semi-transparently onto the terrain image in order to maximise the area available to the terrain display.

The PFD elements should be in the visual "foreground", subordinating the "background" terrain view. They should therefore have strong contrast with the terrain and be easily legible against it. To this end, a concept of visual "layers" is used to separate foreground and background : Strong, saturated colours have connotations of being in the foreground and so are used for symbology and instruments whereas weaker, desaturated hues have connotations of being in the background and so are used for the terrain image.

Instruments

For the initial proof-of-concept display (Figure 4), round dial instruments were largely adopted but these were mostly replaced by strip instruments following the initial evaluation with the exception of the heading indicator and radio altimeter (Figure 5). This instruments are:

- Altimeter
- Vertical Speed Indicator (VSI)
- Air Speed Indicator (ASI)
- Heading Indicator
- Radio Altimeter

The heading indicator is a "rose" type, with current magnetic heading being indicated by green numerals as well as against an index mark. Initially, labelled ticks on the horizon line were used to indicate heading, but this was later rejected as it made the display too cluttered.

The radio altimeter is a round-dial type instrument with a digital readout of height in its centre. This instrument is not permanently visible but pops up at or below 915 m (3 000 ft) radio altitude as an extra cue of close proximity to the terrain.

Attitude Indicator

This comprises three parts:

- Pitch ladder, with the centre knocked out to make space for flight path vector and acceleration symbols. Ticks at 5° intervals, with the minor ticks (at odd integer multiples of 5°) shorter than the major ticks (at even integer multiples of 5°). The horizon line is thicker than the other pitch ladder lines.
- Roll markers : Roll scale with ticks at 0°, ± 10°, ± 20°, ± 30°, ± 45° and ± 60°. The ticks at 0°, ± 30°, ± 45°, ± 60° are longer than the others to increase their prominence.
- Aircraft centreline symbol: Otherwise known as the waterline symbol. An inverted wing symbol, provided for pitch reference.

HUD-type Symbology

The following symbols are borrowed from HUDs in order to increase situational awareness (see Figure 1 and the discussion in §2.2.3).

- Flight path vector. This is in the shape of a ring with a horizontal line through its centre.
- Flight path acceleration symbol. In the shape of a chevron. Moves vertically with respect to the flight path symbol to indicate acceleration along the flight path.

Terrain "Time to Impact" Indicator

Because of the potential difficulty in determining distances to obstacles with a 3D display, it was considered that an additional cue of proximity to terrain would be required. To this end, a "time to impact" symbol was incorporated into the display symbology. This is in the form of an arc which appears around the flight path vector, the angle filled in clockwise from 12 o'clock depending on the computed time to impact the terrain along the instantaneous flight path vector. The time-to-impact symbol is automatically displayed where computed time to impact is 60 seconds or less;

a full circle corresponds to one minute to impact, a half circle corresponds to 30 seconds.

Although it is recognised that this implementation is rather unrefined, it was included to test pilot reactions to the concept. A fuller implementation might take into account distance to impact over an area around the flight path vector, and consider turning flight.

4.3.2 Terrain Database and Surface Generation Data Source

The terrain image was generated from commercial digital elevation model (DEM) data obtained from the Japan Map Center [‡]. DEM data are supplied as elevation points sampled on a regular grid with mesh sizes of 50 m, 250 m or 1 000 m, with elevation values given to a resolution of 0.1 m. Stated maximum error is 5 m. Data sampled on a 250 m mesh were used in this research.

The DEM data are supplied as Shift-JIS encoded files [§] on floppy disk or CD-ROM, each file covering 320 × 320 data points (an area of 80 × 80 km for a 250m mesh), or approximately 1° of arc east / west by 40 minutes of arc north / south. Strictly speaking, attention should be paid to conversion between the coordinate systems of aircraft's navigation system, the terrain database and the rectilinear Cartesian system used for the graphics, but such considerations were neglected for this prototype.

Terrain Database Generation

This Shift-JIS DEM files are converted into a single binary terrain database file for use by the display program. It is infeasible to hold the entire database in memory, so the file is formatted so that sections can be loaded and cached in main memory as required. The terrain data are split into blocks called *gridblocks* covering 65 × 65 elevation points. To be able to load and render gridblocks independently of each other, each gridblock has its edge points common with its neighbours.

The terrain database file is generated by a preprocessor program. This first scans all available DEM files and computes out their adjacency relationships and the size and population of the (possible sparse) two-dimensional gridblock array. This information is used to build a dictionary data structure which is stored at the head of the database file. The preprocessor then reads in the DEM data into the gridblock array, copies the edge vertices between adjacent gridblocks and writes each gridblock to the binary database file, back-patching its offset from the start of the file into the dictionary to enable it to located quickly at runtime.

Tessellation and Level of Detail

For rendering, the elevation spot height data must be converted into a mesh of polygons. Groups of 3 × 3 spot heights are tessellated into groups of eight triangles sharing a common central vertex, as shown in Figure 6. Each group of triangles is then rendered as a triangle fan in OpenGL. Triangles were chosen for tessellation since they eliminate any problems with polygon non-planarity. This approach generates a lot of polygons, and it may be possible to coalesce nearly coplanar triangles or take other measures to reduce the complexity of the scene without greatly affecting image fidelity, although such optimisations were not investigated in this research. Alternative methods of tessellation are available; for example, instead of regarding each elevation data point as a vertex in a triangle mesh, each spot elevation could be regarded as the height of a column of square cross-section centered on that point, and each data point then rendered as a cuboid as in Figure 2(c).

Different *levels of detail* (LODs) are obtained by resampling the data at larger grid intervals. Downsampling was carried out simply by selecting every second, fourth or eighth data point from the original grid (i.e. resampling at 500, 1 000 and 2 000 m grid intervals) to give progressively lower levels of detail. However, downsampling by simply skipping data points and them linearly interpolating between them carries the hazard that the actual terrain may protrude above the resulting surface. Depending on the degree of protrusion, this may or may not be significant depending on how steeply the terrain changes with respect to the sampling interval. For this application, it may be better to devise a sampling scheme which results in a "convex hull", i. e. a surface which

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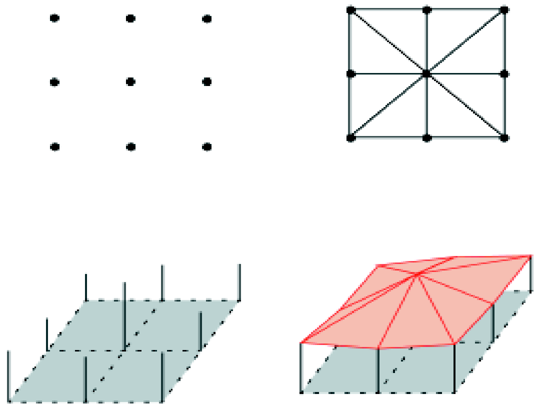
[‡] Japan Map Center, 4-6-9 Aobadai, Meguro-ku, Tokyo 153.

[§] The Shift-JIS encoding scheme is a superset of ASCII used for encoding Japanese characters. For the purposes of this research, it can be treated as an ASCII file.



(a) Gridpost (b) Tessellated

Figure 6 : Tessellation of Elevation Data

entirely encloses all the underlying data points to give a conservative approximation to the terrain surface.

Dynamic Level of Detail

Rendering all visible gridblocks at the highest level of detail imposes a large penalty on performance due to the large number of triangles in the scene. This research therefore investigated rendering different parts of the scene at different levels of detail to reduce the triangle count and so reduce rendering time.

It is posited that the further the aircraft is from a particular terrain feature, the coarser that feature can be rendered for two reasons. Firstly, since the feature is at some distance, it does not represent an immediate hazard to the aircraft and so is of limited interest to the crew. Secondly, under the perspective projection used to construct the three-dimensional scene, the visual angle subtended by the projection of an object of fixed objective size decreases the fur ther the object is from the viewpoint. Eventually, the projected sizes of the individual triangles comprising the terrain mesh will be comparable with or smaller than the pixel size of the display. Thus there is no point in rendering parts of the surface at a high level of detail if they are at some distance from the viewpoint.

It makes more sense to display portions of the terrain surface at levels of detail appropriate to their distance from the viewpoint, rather than displaying the whole surface at the same LOD. It was found that dynamically varying the level of detail of the gridblocks depending on their distance from the aircraft gave a similar visual appearance to rendering the entire scene at a fixed, high LOD. (Compare Figure 9(a), which shows a scene rendered with a fixed LOD, with Figure 9(b), which shows the same scene rendered with dynamic LOD.)

There are two potential visual artefacts which can result from the use of dynamic LOD.

One is discontinuities (cracks) which can occur between areas rendered at different LODs. These cracks can be eliminated by relocating the border vertices of the higher LOD area to match the edges of the lower LOD area. The second artefact is to do with the distance-dependency of LOD — the change of LOD of a feature as it draws closer to the aircraft will be perceptible.

Rendering the Terrain

The terrain view is generated using a perspective 3D projection with a 70° horizontal field of view and a back clipping plane distance of 35 km. Rendering proceeds in two stages. In the first stage, the set of visible gridblocks is computed by testing their upper and lower bounding planes against the viewing frustrum. If an intersection occurs, the gridblock is marked as being visible. The set of visible gridblocks is called the active set. After the active set is computed, all gridblocks in the active set which are not already resident in the memory cache are loaded from hard disk. If necessary, gridblocks in the cache which are not in the active set may be overwritten to make space for them.

An optimisation may be employed in computing the active set, exploiting inter-frame coherence. Given a previous active set and a small change in viewpoint position and view direction, it is only necessary to test the gridblocks in the previous active set and those adjacent to it for visibility, rather than to test the entire gridblock array. More intelligent gridblock manage-

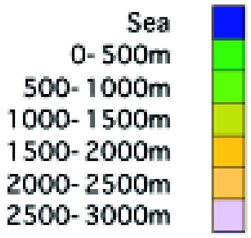


Figure 7 : Terrain Colour Coding by Height Interval AMSL

ment policies may be devised, such as prefetching gridblocks which are likely to be required in that near future to reduce loading delays (especially as disk I/O may potentially be overlapped with graphics operations) but it was beyond the scope of this research to investigate these.

Once the active set is loaded into memory, the LOD of each block is computed and the blocks are then rendered individually. In fact, each gridblock is divided into four quadrants for the purposes of rendering. The distance from the viewpoint to a point in the centre of each quadrant whose height is the maximum of all vertices in the quadrant is computed and these values are compared with a set of threshold values to set the appropriate LOD for the quadrant. Edge vertices should be adjusted to avoid cracks between areas of different LOD, but this was not implemented.

A hardware z-buffer was used for surface visibility determination but this may be redundant if gridblocks are rendered in depth order (and the polygons are rendered in depth order within the gridblocks). Depth order can be determined by examining the viewpoint position and orientation.

Triangles were colour-coded with respect to the average height of their vertices above MSL, as shown in Figure 7. A relatively large height interval between different colours (500m) was chosen to minimise the number of different colours required. Selection of appropriate colour was found not to be straightforward — since the terrain display should be in the background with respect to the PFD instruments and symbology, there should be a high level of contrast between the two, and the colours for different height intervals should be sufficiently distinct while the relationship between colour and height should be fairly intuitive. Although fairly saturated colours were chosen, the display was rendered with intensity cueing, where colours are desaturated according to distance from the viewpoint, so that they would not clutter foreground instruments and symbology (compare Figures 14(a) and 14(b)).

5 PFTD Proof-of-Concept Evaluation

5.1 Introduction

An initial proof-of-concept version of the PFTD was constructed and evaluated with the aim of gaining pilot opinions as to whether such a display would in principle be practical and acceptable to pilots[35,36].

5.2 Apparatus

The proof-of-concept display is shown in Figure 4. As described in §4.3.1, round dial formats were used for the altimeter, vertical speed indicator and radio altimeter instruments instead of more conventional strip formats in order to reduce the display area occupied by instruments and to investigate pilot preferences as to instrument format. These instruments and the heading indicator were rendered as overlays on the terrain image in order to maximise the area available for the terrain image. The airspeed indicator was rendered separately from the terrain image in a strip format for comparison.

Popup time-to-impact symbol and radio altimeter were incorporated to see if they would be effective cues to terrain proximity.

The terrain was rendered as flat-shaded (Lambertian shading) with dynamic LOD, the foreground (minimum) grid interval being 500m.

Software ran on a Silicon Graphics Indigo 2 workstation, and the subject controlled the simulator via a BG Systems Flybox joystick unit. The display window measured 16 × 16 cm on the video monitor, of which the terrain image occupied an area of 13.5 × 13.5 cm. Viewing distance was approximately 55 cm, although eye position was not tightly controlled. The round-dial instruments measured approximately 25 mm square, subtending a visual angle of approximately 2.6° at the nominal viewing distance.

5.3 Method

A single subject, a pilot employed by NAL, participated in the evaluation. The subject regularly flew NAL's Do228 research aircraft, and had test pilot (flight evaluation) experience.

The evaluation consisted of a briefing followed by a free-form flight simulation session (i.e. at the subject's discretion) which lasted for approximately two hours during which the subject flew a number of different flight conditions including steady and turning flight at altitude, level flight towards terrain, nap-of-earth flight and runway approach and landing. The researcher sat next to the subject and noted his comments. Following the simulation, a debriefing was conducted and a questionnaire administered which asked for opinions regarding the instruments, the depiction of the terrain surface and the terrain proximity cues incorporated into the display.

5.4 Results

The analogue format of the altimeter, VSI, radio altimeter and heading indicator was liked and considered to have the merit of allowing rates of change to be perceived more readily than with a conventional strip instrument. These instruments were felt to be a little small, although adequate for the distance at which they were viewed. The fact that the instruments were overlaid onto the terrain background was not considered adversely to affect their legibility.

The information provided by the conformal flight symbology was well appraised. In particular, the use of the flight path acceleration symbol made power setting straightforward, while the fact that the flight path vector could be directly compared against the terrain to check for hazardous flight paths was also appreciated, particularly during near-terrain manoeuvering. The time-to-impact symbol was also appreciated as a cue to terrain proximity.

The popup radio altimeter was appreciated as a cue for terrain proximity awareness. It was further suggested that its visual salience be increased as radio altitude decreased, for example by increasing the size of the digits or by colour-coding.

The subject reported the presentation of the terrain as being "natural", and agreed with the choice of only a few different colours to represent different elevation bands. However, the subject seemed to be confused by the shading of the terrain surface; he had been informed that different colours represented different elevations and initially confused this with shading due to lighting effects. He also reported difficulty in perceiving the shape of the surface, especially over flat areas. However, the shape of the surface was reported as being much more discernable when a display with a foreground grid interval of 250 m was demonstrated during the debriefing.

No problems were reported with visual artefacts due to dynamically changing LOD, although the cracks between areas of different LOD was commented on.

5.5 Discussion

It should be stressed that this was only a general evaluation using a single subject, so caution must be observed in extrapolating the results. This caveat notwithstanding, the evaluation seemed to indicate the following.

- The concept of using a 3D display as an aid to terrain situational awareness appears to be acceptable, at least in principle.
- The overlaying of symbology and instruments onto the terrain image does not appear to cause problems regarding legibility and therefore may be a feasible method of maximizing the area of the display devoted to the terrain image so long as careful attention is paid to clutter.
- With different shades of the same colour resulting from lighting effects (due to different orientations of surfaces with respect to virtual light sources), the colours used to represent different elevations should be selected carefully to minimise confusion.

The main problem highlighted was the difficulty in perceiving the shape of the terrain surface when a lower maximum LOD was used (500 m). The modulation of polygon colours due to the effects of flat shading was initially confused for elevation-related colour coding and in any case does not give a particularly "natural" appearance. Furthermore, flat shading gives no indication of surface shape or impression of height above a surface when the surface is flat (all polygons having the same orientation and therefore the same colour).

The impression of surface shape was found to be considerably improved when the maximum LOD was increased to 250 m. As a side-effect, the flat shading introduced another powerful depth cue, *viz* a texture gradient due to the faceted appearance of the surface. The polygons form texture elements of objectively equal size and objectively consistent density if their orientations are sufficiently different that they can be distinguished by their shading. It is hypothesised that this depth cue strongly contributed to the perception of terrain surface shape when a high LOD was used. However, the problem of perception of surface shape when viewing uniformly-shaded, flat areas remains.

6 Depth Cues to Depict the Terrain Surface

6.1 Introduction

The preliminary evaluation found that display depth cues in the preliminary display were inadequate for conveying the three-dimensional form of the terrain surface to the viewer. A preliminary investigation was therefore conducted to find a suitable combination of depth cues which would permit adequate perception of terrain features without imposing too great a burden on the graphics generation hardware ¶. Although the power of graphics hardware is expected to increase in the future, certain typed of rendering will remain more expensive than others and in the interests of minimising hardware complexity and cost, a minimum of complex rendering should be used to give acceptable image quality.

In the proof-of-concept evaluation, it was found that a flat-shaded scene was a little unnatural in appearance and that there could sometimes be difficulty in perceiving the form of the terrain. It was also found that although the texture gradient due to the faceted appearance of the flat-shaded surface provided a powerful depth cue, this faceting was absent in areas where the surface triangles are in approximately the same orientation and so are identically lit, and this made it difficult to perceive the height above and shape of such areas. The challenge therefore is select a suitable combination of depth cues which overcome the problems of flat shading while enabling perception of the form of terrain surface over flat areas.

This section first discusses possible candidate depth cues, considering those due to the effects of light. Observer-centred depth cues (those represented by the state of the human visual system, such as muscular sensations) and depth cues due to the effects of movement, occlusion and interposition, and height in the visual field are not discussed. The impact on rendering performance of each candidate depth cue was investigated by benchmarking. Finally, candidate displays incorporating various combinations of depth cues were constructed and evaluated subjectively by a test pilot.

6.2 Benchmarks

Simples benchmark tests were used to assess the effect of implementing a particular depth cue on graphics performance. Graphics performance depends on many factors, including scene complexity (number of polygons), shading and lighting, hidden surface removal, CPU/memory issues, graphics hardware, and software (algorithms, implementation, language efficiency, operating system overheads etc.). It should be recognised that relative performance timings quoted in this report apply only to the specificper hardware and software used.

Benchmark tests were conducted on a Silicon Graphics Indy R5000 workstation. With the terrain rendering program executing on this computer, performance is limited by the graphics engine rather than being CPU-bound, and is sufficient only for development purposes. (For the evaluation of the candidate displays, Silicon Graphics Onyx and Indigo 2 workstations were used to give adequate frame rates.)

The benchmark program was a flythrough of a landscape, with only the terrain being drawn (i.e. flight symbology and instruments were omitted) for 300 frames. Timings were averaged over 5 runs.

6.3 Depth Cues

6.3.1 Level of Detail

Different levels of detail are obtained by resampling the underlying grid on 500 m, 1000 m and 2 000 m grid intervals and then tessellating the resulting data. Figure 8 shows a flat-shaded scene rendered at different levels of detail. Decreasing the LOD decreases the number of polygons in the scene and hence decreases rendering time, but increases the size of the smallest surface feature which may be depicted.

In the proof-of-concept evaluation, it was found that LOD influenced the perception of terrain surface shape. The subject's reported ability to perceive the shape of the terrain was poor when a grid interval of 500 m was used, but improved substantially when the grid interval was reduced to 250 m (compare Figures 8(a) and 8(b)). Level of detail not only determines the minimum depicted terrain feature size but when combined with the faceted appearance of a flat-shaded scene also provides a texture which aids the perception of the three-dimensional shape of the surface.

Rendering times for 300 frames of a landscape

¶ For a comprehensive survey of depth cues the reader is referred to Wickens, Todd and Seidler[15].

Table 1 : Rendering Times for Different Levels of Detail

Grid interval (metres)	Triangles/ Grid block	Total Time (sec)
250	8192	253.6
500	2048	82.6
1000	512	32.3
2000	128	17.4
Dynamic (250m max.)	-	79.8
Dynamic (500m max.)	-	40.6

flythrough with the terrain rendered at different levels of detail are shown in Table 1. As expected, rendering time varies linearly with the number of triangles per gridblock. Dynamic level of detail gives significantly improved performance while being visually similar to comparable static LOD scenes—compare Figures 9(a) and 9(b).

A high LOD requires a large number of polygons, and the number of polygons increases fourfold with each increase in LOD. Given that the pilot may not necessarily need to see terrain features of the scale depictable at the highest LOD, it may be more practical to render at a lower LOD.

In the proof-of-concept evaluation, which incorporated dynamic LOD, the lower LOD of more distant areas was not negatively appraised, suggesting that the pilot is primarily interested in the foreground. The change of LOD of parts of the scene as they drew nearer was not commented upon, which suggests that this artifact is tolerable.

6.3.2 Shading

In flat shading, the surface normal of each triangle is computed prior to rendering and this is used in the lighting calculations to determine the shade of the whole triangle according to Lambert's Law. Gouraud smooth shading provides a more natural appearance than flat shading, but requires that the normals to the surface at each triangle *vertex* be known. The colour at each vertex is then computed according to its normal and the directions to the virtual light sources, and the shading across the surface of the triangle is interpolated between the vertex colours. Since the surface normals at the spot heights are not known, suitable normals must be estimated. To this end, each spot elevation was treated as the common apex of the group of eight triangles formed by it and its eight neighbouring spot elevations. The normals of these triangles were computed and averaged to give an estimate of the surface normal direction at the spot elevation in question.

Figure 10 shows scenes rendered with Gouraud shading with dynamic LOD. The scene in Figure 10(a) is rendered with a foreground grid interval of 250 m, while the scene in Figure 10(b) is rendered with a foreground grid interval of 500 m. As can be seen, there is little readily apparent difference between the two, in contrast to a flat shaded scene (compare Figures 8(a) and 8(b)). However, there is no texture in the smooth-shaded scene, so while being more natural in appearance, the lack of faceting may remove a valuable depth cue present in flat-shaded scenes, as shown in Figure 11.

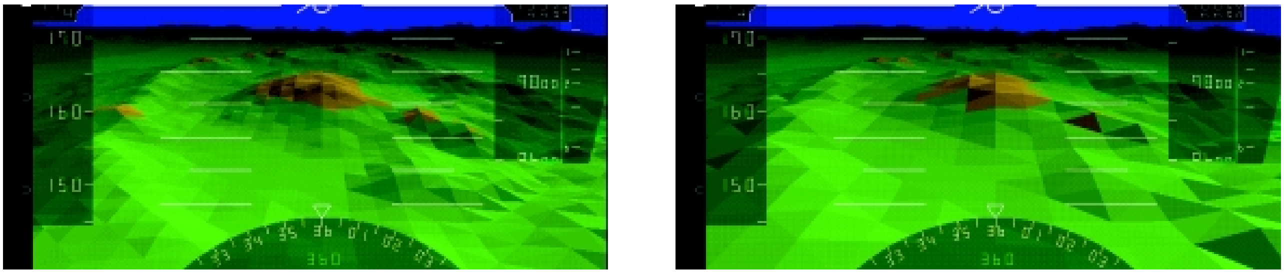
Benchmark tests showed that the rendering times for a smooth-shaded scene and a flat-shaded scene were comparable.

6.3.3 Grid Overlay

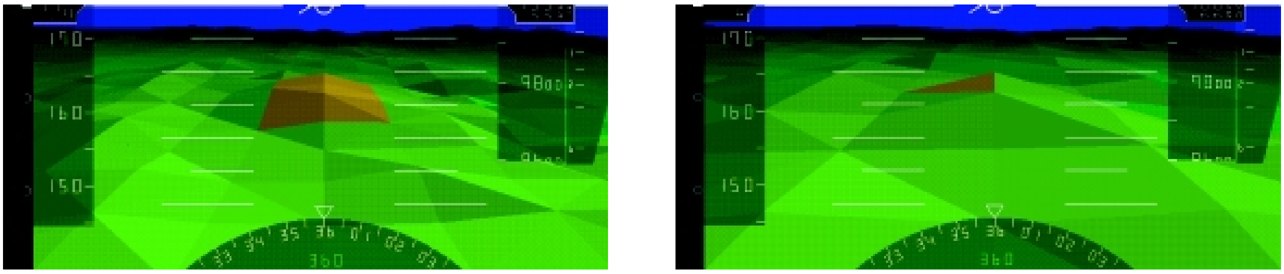
It was hypothesised that overlaying a wire mesh grid onto the terrain surface might improve perception of depth and surface shape by providing the texture gradient lacking in a smooth-shaded scene and would assist the perception of surface shape and distance of flat areas in a flat-shaded scene.

A potential problem with rendering a grid in a scene with variable LOD is that differences in LOD between adjacent gridblocks are more obvious as the size of the mesh is different. Moreover, given that the need to perceive surface shape might be less important in the background, it might be better to render only those blocks with the highest LOD with a grid overlay rather than having the grid cover the whole scene. Figure 12 shows a scene rendered with dynamic LOD with a foreground grid interval of 250 m, (a) with a full grid overlay and (b) with the grid overlay only on the highest LOD gridblocks (partial grid). The grid was rendered using hardware stencil and *z*-buffers (see the OpenGL Programming Guide[34]), page 397).

Figure 13 shows averaged rendering times for 300 frames for three levels of grid (none, partial and full) at two different maximum LODs (250 m and 500 m

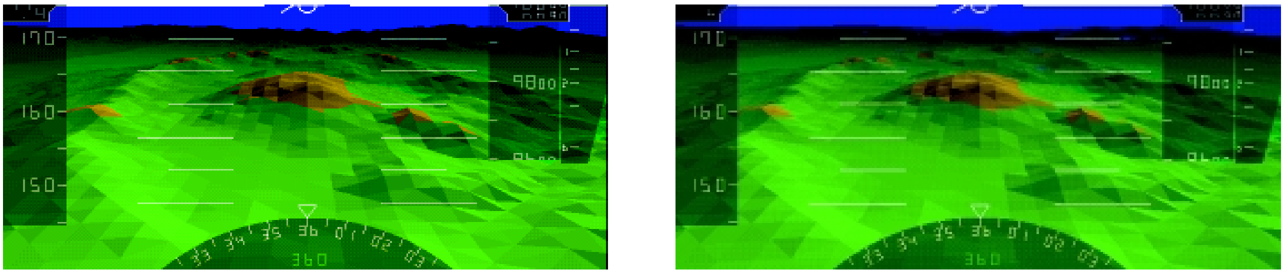


(a) 250m grid interval (b) 500m grid interval



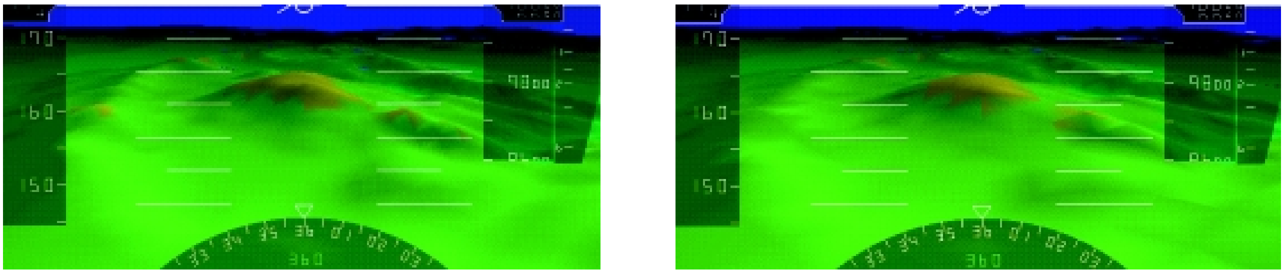
(c) 1000m grid interval (d) 2000m grid interval

Figure 8 : Levels of Detail



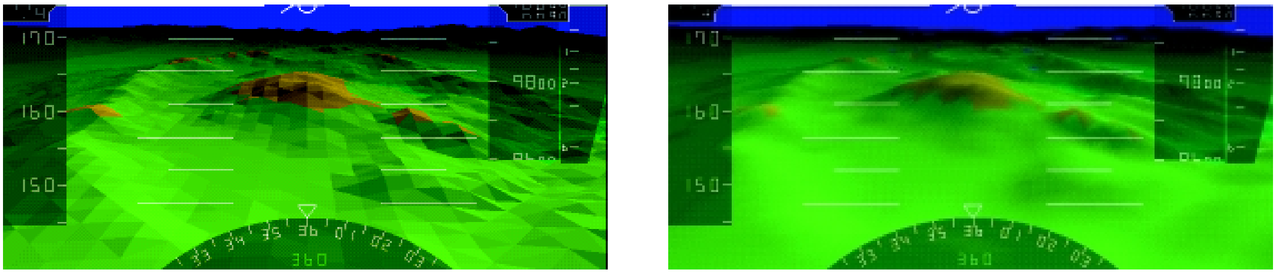
(a) 250m grid interval fixed LOD (b) Dynamic LOD, foreground 250m grid interval

Figure 9 : Dynamic versus Static Level of Detail



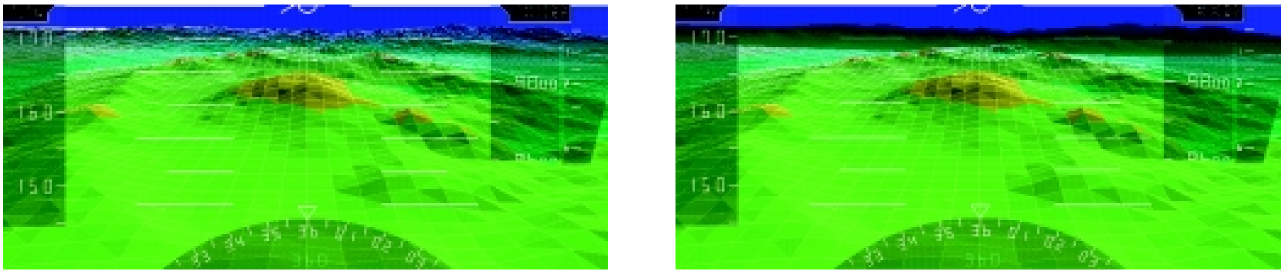
(a) 250m grid interval (b) 500m grid interval

Figure 10 : Gouraud Shading with Different Levels of Detail



(a) Flat-shaded Scene (b) Gouraud-shaded Scene

Figure 11 : Flat-Shading versus Smooth-Shading



(a) Full Grid (b) Partial Grid

Figure 12 : Grid Overlay

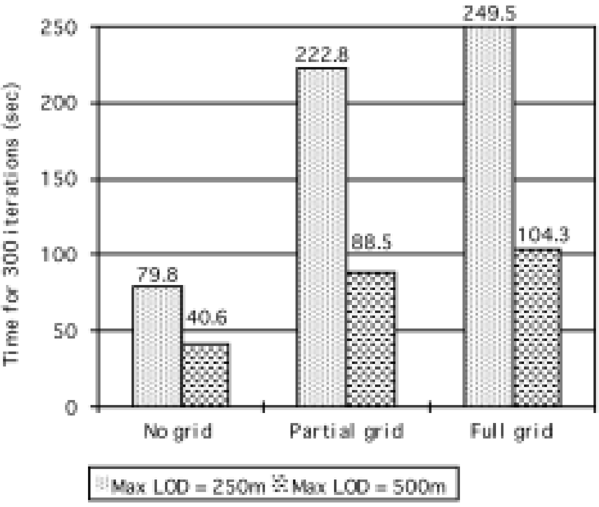
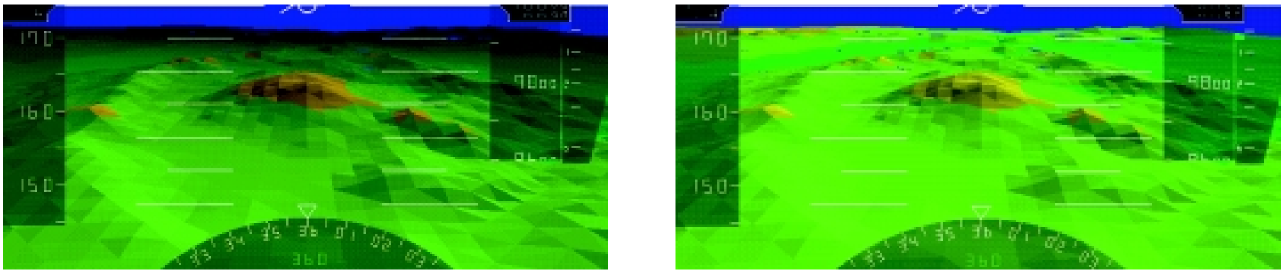


Figure 13 : Benchmark Timings for Grid



(a) With Intensity Cueing (b) Without Intensity Cueing

Figure 14 : Intensity Cueing

foreground grid intervals, both with dynamic LOD).

It can be seen that rendering the grid incurs a large performance penalty, more than doubling the per-polygon rendering time. It is more expensive to render the terrain at a 500 m maximum LOD with partial grid than it is to render the terrain at a 250 m maximum LOD with no grid.

6.3.4 Intensity Cueing

The colour saturation and brightness of an object can influence its perceived depth since in viewing real scenes, atmospheric scattering of light leads to desaturation of an object's subjective colour. Figure 14 shows a scene with and without intensity cueing (implemented using the OpenGL fog function) — the intensity-cued scene can be seen to have a greater sense of depth. Intensity cueing had minimal impact on performance.

6.3.5 Texture Mapping

Texture mapping has long been used in 3D graphics in order to represent surface detail which would otherwise be prohibitively expensive to generate (e.g. vegetation, rivers, built-up areas) and in flight simulation, texture can enhance the sensations of speed and height, particularly when flying close to the terrain surface.

Despite the fact that it can be extremely effective, however, there are a number of problems with texture mapping in this application. Aside from performance issues, there are issues such as the selection of a suitable texture (whether the texture should reflect actual surface land use or be some more generic pattern) to be considered. It was therefore considered that texture mapping should be investigated only should further enhancement of depth be required.

6.4 Subjective Evaluation

6.4.1 Introduction

A subjective evaluation was carried out in order to assess the effectiveness of various combinations of the depth cues under consideration. The evaluation was carried out by the same subject who took part in the proof-of-concept evaluation.

6.4.2 Display Changes

Minor changes were made to the display format following the proof-of-concept evaluation (compare Figures 4 and 5). Because of the small size of the round-dial instruments in the proof-of-concept display, and the fact that strip format instruments are better able to incorporate various markers and tapes, the altimeter and VSI were replaced with strip representations. The pop-up radio altimeter retained its analogue dial/digital readout format, and the altimeter strip was shortened compared to the ASI strip to make room for it.

To increase still further the proportion of the display window occupied by the terrain depiction, the ASI was rendered as an overlay onto it. Minor changes were also made to the pitch ladder as a result of recommendations made in the proof-of-concept evaluation.

6.4.3 Method

Three factors were varied to produce a number of different displays for evaluation, as summarised in Table 2, *viz* level of detail, shading type and grid overlay. Combinations of these factors resulted in twelve candidate displays for evaluation, as outlined in Table 3 and shown in Figures 15 – 18.

Due to the fact that there was only a single subject to evaluate a large number of candidate displays, it was considered to be impractical to perform a detailed

Table 2 : Display Variables

Depth Cue	Levels
Max. LOD	2 (250m, 500m)
Shading	2 (flat, smooth)
Grid Overlay	3 (none, partial, full)

Table 3 : Candidate Displays

Dpy. No.	Shading	LOD	Grid
1	Flat	250m	None
2	Smooth	250m	None
3	Flat	500m	None
4	Smooth	500m	None
5	Flat	250m	Partial
6	Smooth	250m	Partial
7	Flat	500m	Partial
8	smooth	500m	Partial
9	Flat	250m	Full
10	Smooth	250m	Full
11	Flat	500m	Full
12	Smooth	500m	Full

evaluation of each by flight simulation. Instead, a preselection stage was used to select a smaller number of candidates for more detailed consideration. Still colour pictures of the twelve displays were shown to the subject, who was asked to select three or four for further evaluation. These were then evaluated in a free-format flight simulation session. No objective measures were taken; throughout, the subject was asked to "think aloud" and to comment to the researcher.

6.4.4 Apparatus

For the preselection stage, twelve colour pictures, one for each candidate display, were produced by "screen dumping" a scene to a file which was then printed using a colour laser printer.

For the simulation evaluation, because of the high graphics performance required, the flight simulation and display programs were run on a Silicon Graphics Onxy Infinite Reality computer. Control was via a BG Systems Flybox joystick attached to a Silicon Graphics Indy workstation which communicated with the Onyx via an Ethernet local area network.

6.4.5 Results

Referring to Table 3, in the preselection phase the subject selected displays 5 (flat shading, high LOD, partial grid: Figure 15(b)), 10 (smooth shading, high LOD, full grid: Figure 17(c)) and 12 (smooth shading, low LOD, full grid: Figure 18(c)) for further evaluation. The results of the evaluation are discussed below.

Primary Flight Display

It was suggested that the marks indicating 0°, 30° and 60° bank angles should be made more visually salient. The pitch ladder 10° interval ticks should be labelled to facilitate rapid reading of pitch attitude.

The subject made no comments regarding the instruments.

Terrain Representation

Regarding colour-coding of the terrain, the subject suggested that a mixture of MSL-relative and ownship-relative colour-coding be adopted; for example, terrain should be colour-coded relative to its elevation above MSL, but areas closer to the aircraft's altitude than a certain threshold should be gradually shaded more towards red. However, even with ownship altitude-relative colour-coding, it was suggested that pilots are likely to be interested in information such as precise clearance over obstacles and the precise elevations of those obstacles. It was therefore suggested that the display show spot heights, selectable by the pilot to mitigate the effects of clutter.

As anticipated, after comparing flat- and smooth-shaded displays, the subject reported that the facteting in the flat-shaded displays provided a valuable cue as to surface shape. However, he expressed a preference for smooth-shading over flat-shading. This necessitated a grid overlay to assist the perception of surface shape.

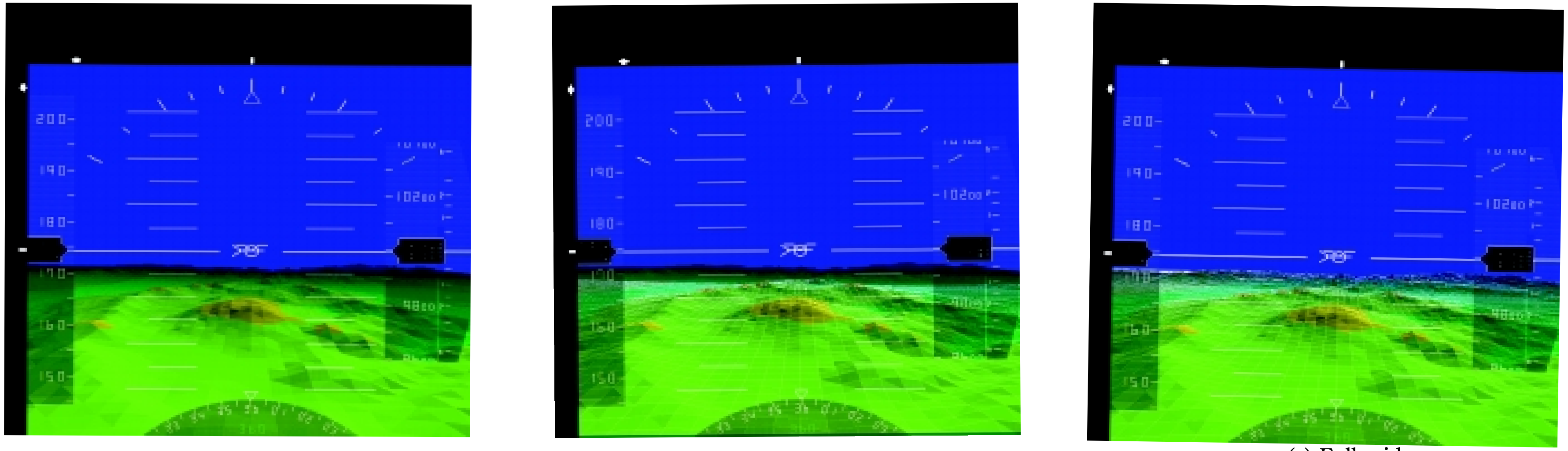
With a smooth-shaded terrain image with a grid overlay, the lower LOD (500 m grid interval) was preferred; the subject felt that the higher LOD was excessive. However, this preference may also have been due to the apparent density of the grid, as discussed below.

Grid Overlay

Three issues were raised as regards the grid overlay: Its density, the way in which the grid pops up onto blocks in a partial grid display, and the orientation of the grid lines.

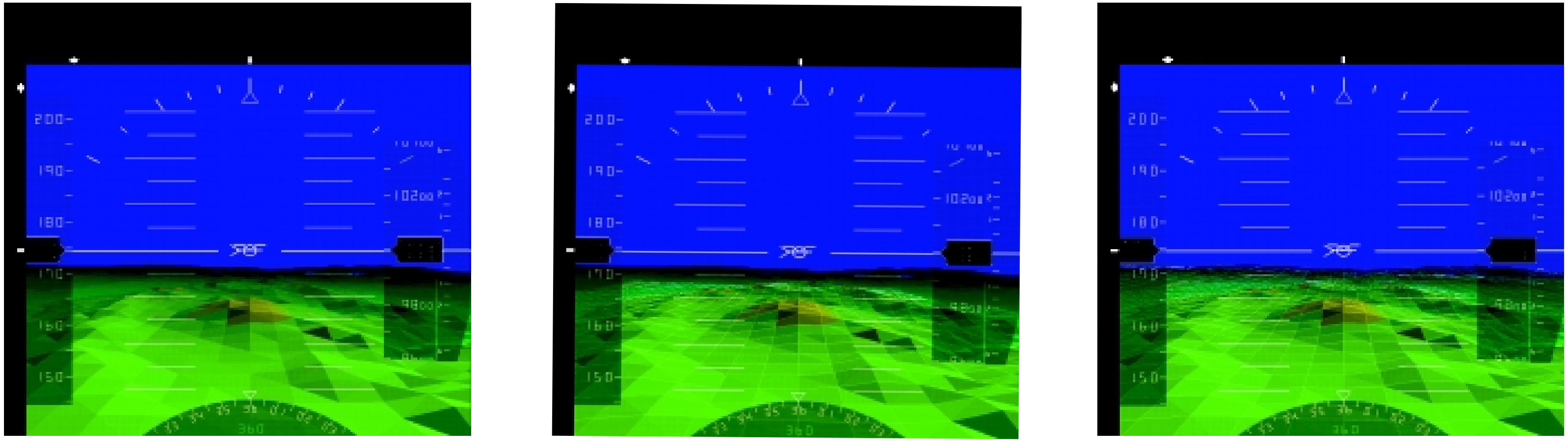
The apparent density of the grid lines at a point on the terrain surface depends on the grid interval, the distance from the viewpoint and the angle of view. A problem encountered was that in certain situations, the grid lines became very dense in localised areas. This particularly tended to occur at low altitudes above the terrain and at the tops of ridges, where the angle between the line of sight and the terrain surface is acute. This was at least distracting, and raised concerns about clutter and effect on the legibility of flight symbology.

In partial grid displays, the grid is rendered on the blocks which are at the highest LOD (i.e. those closest to the viewpoint). As the aircraft travels, the grid is seen to "pop up" onto blocks as they draw nearer. With the experimental implementation, the way in which the grid pops up is not uniform, and this was not liked by the subject. Here, the LOD of a block is computed based on the distance from the viewpoint to a point at its centre whose height is the maximum of all spot heights in the block. Assuming that the air-



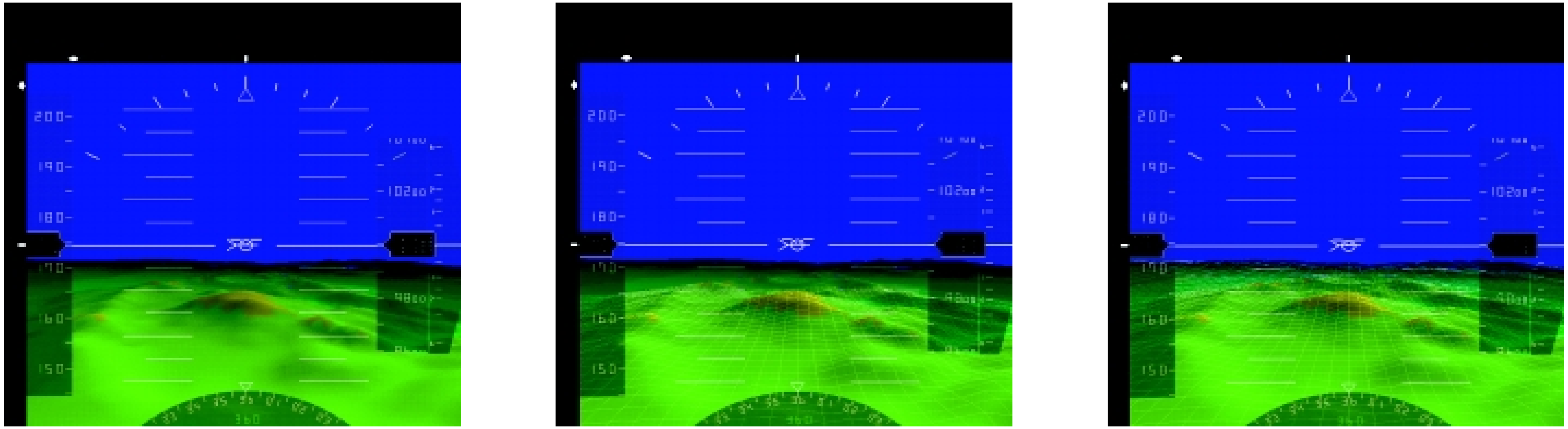
(a) No grid (b) Partial grid (c) Full grid

Figure 15 : Candidate Displays : Flat Shaded, High LOD



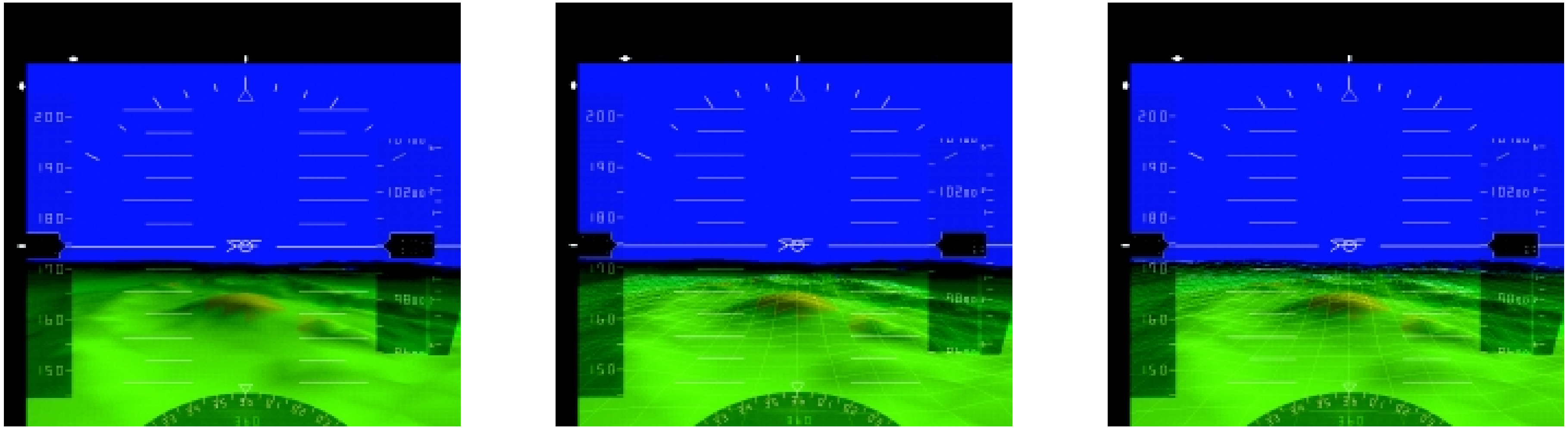
(a) No grid (b) Partial grid (c) Full grid

Figure 16 : Candidate Displays : Flat Shaded, Low LOD



(a) No grid (b) Partial grid (c) Full grid

Figure 17 : Candidate Displays : Smooth Shaded, High LOD



(a) No grid (b) Partial grid (c) Full grid

Figure 18 : Candidate Displays : Smooth Shaded, Low LOD

craft is travelling in a direction orthogonal to the grid, the far edge of the visible gridded area will not in general be straight. The pilot's preference was the far edge of the grid to be a straight line perpendicular with the direction of flight at all times and at a fixed distance.

A positive aspect of the partial grid display was the pilot's opinion that the popping up of the grid gave a sense of progression of the flight and a "safe for another *x* km" feeling.

The orientation of the grid lines was another issue — the subject expressed a preference that the grid lines should be always aligned parallel and perpendicular to the aircraft's heading rather than with the geographical N/S and E/W axes.

6.4.6 Summary

The improved display was seen overall as superior to the proof-of-concept display regarding display layout and legibility of the terrain surface. The subject preferred a smooth-shaded display with a 500 m minimum grid interval, but although the results suggest that a cue such as a texture gradient is necessary to give a sense of depth and surface shape with such a display, there are problems with the method of providing such a cue using a grid overlay. The partial grid was preferred to the full grid, but several implementation issues were raised.

Some of these issues are relatively straightforward to address. The grid can be made to pop up uniformly by computing block LOD (and hence the presence of absence of grid) using block *z*-depth. The far edge of the grid should be a straight line perpendicular to the aircraft's heading, and this can be realised by suitable selection of back clipping plane distance when rendering the grid.

Issues such as whether the grid should be orientated with geographical or aircraft body axes and the problem of increased apparent grid density at acute viewing angles remain to be investigated. A possible solution to the latter problem is to generate the grid using texture mapping with textures appropriately filtered according to distance from the viewpoint. Such a solution might also be faster than the current method of generating the grid.

7 Further Issues

This section conjectures other issues which, although not explored in this research, are relevant to it.

7.1 Robustness against Error

Advanced terrain displays rely on accurate position and terrain information, and there will inevitable be errors in both of these. Ultimately, the magnitude and probability of errors set limits on the application for which the information can be used.

For devices used only for terrain warning and to assist situational awareness, the accuracy requirements for the terrain database are not as demanding as for flight-critical application (such as guidance and navigation) and a certain amount of leeway can be built into the system in order to accommodate minor uncertainties as to position and small database errors. Such leeway could be provided as follows.

It is assumed that advanced terrain display devices of the type discussed in this report will be aimed primarily at commercial transport aircraft operating on a well-surveyed fixed-route network. Under normal visual and instrument flight rules, in cruising flight an aircraft fly no lower than 1 000 ft (305 m) above the highest local obstruction, and in terminal areas when required to fly below the level of obstacles, should be laterally well separated from those obstacles. Fine surface features are not relevant to aircraft operations and so there is no need to store elevation data to a high level of detail. It might therefore be better not to store actual elevations but to store a "convex hull", i.e. a coarse surface which completely encloses the underlying terrain. The coarseness of this representation accommodates some lateral navigational uncertainties and might be easier to maintain to a given degree of accuracy than a finer terrain map.

Tolerance of error can also be provided in the design of the warning logic of the device. For example, EGPWS warning logic is based on two "envelopes" which perform simple extrapolation of the aircraft trajectory and are compared against the terrain database. The more generous the warning envelope, the greater the chance of false positive warnings but the lower the chance of false negative warnings due to minor errors in the database and in navigation position.

Some advanced terrain warning systems use pressure altitude in computing terrain clearance and so are vulnerable to mis-setting of the altimeters. Some latitude can be introduced to account for altimeter mis-setting in the warning envelope of the device. As a final backup, EGPWS and GCAS still retain GPWS functions and radio altimetry, but on some systems (such as GPS/MAP) there is no independent method of verifying terrain clearance.

For applications which may require manœuvering in closer proximity to the terrain surface, such as rotary-wing, emergency service or military operations, the required level of detail and accuracy of the database and the required accuracy of the navigation system will need to be greater and in such cases, it may ultimately be very difficult or impossible to guarantee the accuracy of the terrain database; in this case, an independent system for verifying terrain clearance may be necessary.

7.2 Image Fidelity and Realism

The potential compellingness of pictorial displays presents a conflict in their use —they can convey terrain awareness very effectively, but there is the danger that they can lead the crew to place too much faith in the depicted image at the expense of more reliable but less easily accessible sources of information. Further, it might also encourage inappropriate use or mis-use of the display (for example, to provide references for visual flight in instrument meteorological conditions).

It is possible to generate computer graphic images in real time which are highly realistic, and such imagery is used in flight simulators. It is posulated that the more realistic an image is, the more compelling it becomes to the observer. However, image realism must not be confused with image fidelity, which is how accurately the image reflects the real environment which it is depicting. It may therefore be advisable to display information at a level of realism appropriate to its fidelity.

EGPWS provides an example of a display where realism is fairly well matched with fidelity. The device is intended only for terrain alerting and situational awareness, not for navigation. The display shows a plan view of terrain in front of the aircraft, above it and up to 2 000 ft below it, as colour-coded patterned blocks and so provides terrain clearance information while being of low realism. No navigation information is displayed, nor can any be overlaid.

While the 2D PVD has the advantage that it is not a particularly "natural" representation of three-dimensional spatial information, 3D perspective images are "natural" -looking and although they may be preferred by pilots, there may be some argument for rendering the terrain image at a lower level of realism than might be possible to counteract some of the possible compellingness.

Navigation and database error may also limit the scope for using conformal symbology to show aircraft flight parameters and flight path relative to the terrain if there is not sufficient accuracy to support their use, partly negating one of the benefits of a 3D representation.

8 Conclusion

8.1 Introduction

The aim of this research has been to explore a technological solution to the problem of Controlled Flight Into Terrain accidents.

A primary factor in CFIT accidents is the lack of awareness on the part of the flight crew of the position of the aircraft with respect to the terrain. A cockpit display which supports terrain awareness by showing graphically the relationship between the aircraft and the terrain might allow the CFIT causal chain of events to be broken before a hazardous situation develops[‖].

New-generation TAWS such as the EGPWS present terrain information to the pilot in the form of a 2D plan view. This research has explored the use of perspective 3D displays as an alternative means of providing terrain situational awareness and alerting. To test whether such a concept would be acceptable to pilots, a prototypical display, the Primary Flight and Terrain Display, has been developed and subjectively evaluated by a professional test pilot.

8.2 The PFTD

This research has shown that a test pilot was receptive to the concept of a 3D terrain display integrated with a primary flight display for providing terrain situ-

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[‖] However, it can be argued that such a device shifts the potential for error from the crew into other areas, for example into the terrain database or navigation system, which may be not amenable to human monitoring.

ational awareness. Several design issues were raised; some of these have been investigated but others require further exploration.

- The problem of incorporating instrumentation and a 3D image into a limited display area can be addressed by overlaying instruments onto the terrain image on a semi-transparent background.
- Clutter in the display was controlled by separation of the foreground (symbology, instruments, etc.) and background (terrain image) using a "visual layers" concept based on luminance and saturation of hues.
- Care must be taken to provide sufficient cues to surface shape and depth in the synthetic 3D image. However, the selection of depth cues is not straightforward. Rendering performance penalties and implementation issues have to be considered.
- A "raw" terrain image may not alone be sufficient for conveying precise terrain separation information, due to problems of perception of absolute distance to and height above surface features in a 3D display. Aids must be provided to assist the pilot in extracting parameters of interest (notable immediate and future predicted terrain clearance) using for example colour-coding, spot heights, symbolic enhancement and predictive features. A basic time-to-impact symbol and pop-up radio altimeter were reported to be effective cues to close proximity to terrain in this research.
- The integration of a PFD and synthetic terrain image raises the possibility of being able to use conformal symbology, with reduced access cost for information which must be integrated between the domains of the aircraft and the external environment and subsequently greater situational awareness. However, if the conformal symbology is used for flight guidance, concerns are raised over the required integrity and accuracy of position, orientation and elevation data.

The most prominent omissions from the prototypical PFTD are predictive features. Displaying a predicted flight path with indications of terrain clearance (vertical and, where appropriate, lateral) and colour-coding the terrain according to predicted proximity, similar to the SSI display described in §3.2, is one possibility. Other cues for situational awareness should also be considered; for example, a coloured tape in the altimeter strip display to indicate MSA in the terminal area would be relatively simple to implement.

8.3 Perspective versus Plan-View Terrain Displays

This research has posited that a terrain awareness display should serve three tasks:

1. As a warning device to alert the flight crew actively to immediate hazards and possibly to issue guidance for terrain evasion manoeuvres.
2. To support immediate terrain situational awareness by depicting the relationship between the aircraft and the terrain.
3. To support strategic planning.

Each display format, plan view or perspective, provides information which cannot easily be provided by another format, and so they may be complementary. A PVD conveys lateral spatial information very effectively and may be offset, scaled and zoomed, making it useful for strategic planning functions such as reviewing terrain clearance over different segments of the flight plan. A perspective display, on the other hand, presents both horizontal and vertical spatial information in an integrated pictorial form which is easy to interpret and to relate to the real environment. It can also be overlaid with conformal symbology which has the potential to increase situational awareness and to reduce workload in extracting proximal information. With the notable exception of the research described in §3.1, few studies have been carried out which directly compare 2D and 3D terrain avoidance displays, and further research is required to explore the merits and demerits of each display type.

The PVD is effective for conveying lateral spatial information but can be deficient when it comes to depicting vertical information. On the other hand, while a perspective display can show vertical as well as horizontal spatial relationships pictorially in a "natural" form, it may be difficult to make precise judgements of distance and height. Due to these characteristics, it may be necessary to provide aids to assist the viewer in interpreting the display, for example:

- Colour coding of terrain based on current and/or predicted terrain clearance to enable crews rapidly to identify potentially hazardous terrain. This is especially useful in PVDs, where extraction of vertical clearance information along a non-level flight trajectory may be particularly difficult.

- Particularly in perspective displays, symbolic enhancements to convey distance to (e.g. the PFTD's time-to-impact indicator) and height above (e.g. the SSI's terrain clearance "whiskers"), and possibly dangerous lateral clearance from , obstacles along the predicated flight trajectory.
- Terrain collision prediction and alerting functions to bring potential hazards actively to the attention of the crew in sufficient time such that an escape manœuvre can be executed by a normal crew with a high probability of success.

However, such features inevitably complicate the design of the display and carry their own problems, such as clutter.

A potentially major drawback of perspective displays is that they can be highly compelling. The ease of information extraction from a perspective display may make it less likely that the flight crew will cross-check with "raw" data (which may be harder to interpret) particularly at times of high workload. Further research is required to address this potential problem.

With sufficient enhancements to address inherent deficiencies of plan-view presentations, a PVD may well be adequate for the goals laid out in §2.1 provided that concerns over database and navigation accuracy and the potential for display mis-use are addressed. However, perspective displays do provide a more natural and intuitive method of presenting 3D spatial information, and for this reason alone they have considerable appeal and cannot easily be discounted. Synthetic and enhanced vision systems research continues to advance and address the issues of accuracy and integrity of navigation and terrain data, as well as to explore human factors issues likely to be of relevance such as inappropriate fixation and attentional tunnelling. Research in support of cockpit applications of 3D displays is therefore likely to remain an important goal in the future.

References

1) Wiener, E.L. : Controlled Flight into Terrain Accidents : System-Induced Errors, *Human Factors*, Vol. 19, No.2 (1977).

2) Corwin, W.H. : Controlled Flight Into Terrain Avoidance : Why the Ground Proximity Warning System is Too Little-Too Late, in *Proc. Western European Association of Aviation Psychologists (WEAAP) Conference* (1994).

3) Khatwa, R. and Roelen. A.L.C.: An Analysis of Controlled Flight Into Terrain (CFIT) Accidents of Commercial Operators 1988 through 1994. Technical Report NLR TP 94558 U, National Aerospace Laboratory of the Netherlands (1996).

4) The Interface Between Flightcrews and Modern Flight Deck Systems (1996), United States Federal Aviation Administration.

5) Bateman, D. : Enhanced GPWS improves situational awareness and provides more effective protection near terrain, *ICAO Journal,* Vol. 52, No.4, pp. 7-8 (1997).

6) 加藤匠 : Enhanced Ground Proximity Warning System (EGPWS) の導入について, in *Proc. JSASS* 34the *Aircraft Symposium,* pp. 93-96 (1996). In Japanese.

7) Proctor, P. : Major Airlines Embeace Enhanced GPWS, *Aviation Week and Space Technology* (1997).

8) Proctor, P. : Dassault Electronique Enters Advanced GPWS Market, *Aviation Week and Space Technology* (1998).

9) Kuraya, N. : The aircraft GPS／MAP system with terrain proximity warning function, in *Proc. 14th SICE Guidance and Control Symposium* (1997). In Japanese.

10) Takasaki, M., Kuraya, N.and Yabe, R. : Development of the GPS／MAP system with terrain proximity warning function, in *Heli Japan* '98 (1998). Paper D2-8.

11) Brown, M. A. : *An Investigation of Three-Dimensional Displays for Real-Time, Safety–Critical Command／Control Applications : With Application to Air Traffic Control,* PhD thesis, Dept. of Computer Science, Queen Mary & Westfield College, University of London (1996).

12) Brown, M. A. and Slater, M. : Three-Dimensional versus Two-Dimensional Displays for Air Traffic

Control, in *Proc. AIAA Modeling & Simulation Technologies Conference* (1997).

13) Wickens, C. D. and Carswell, M. C.: The Proximity Compatibility Principle: Its Psychological Foundation and Relevance to Display Design, *Human Factors,* Vol. 37, No. 3, pp. 473-494 (1995).

14) Wickens, C. D. and Todd, S. : Three-dimensional display technology for aerospace and visualization, in *Proc. Human Factors Soc. 34th Annual Meeting,* pp. 1479-1483 (1990).

15) Wickens, C. D., Todd, S. and Seidler, K. : Three-Dimensional Displays : Perception, Implementation and Application, CSERIAC report (1989), Crew Systems Ergonomics Information Analysis Center, Wright-Patterson Air Force Base, Ohio, USA.

16) Stokes, A. F., Wickens, C. D. and Kite, *K.* : *Display Technology* : *Human Factors Concepts*, Society of Automotive Engineers (1990), ISBN 0-89883-530-5 (hardcover).

17) Chappell, A. R., Crowther, E. G. and Mitchell, C. M.: The VNAV Tutor : Addressing a Mode Awareness Difficulty for Pilots of Glass Cockpit Aircraft, *IEEE Transactions on Systems, and Cybernetics*, Vol. 27, No. 3, pp. 372-284 (1997).

18) Vakil, S. S., Hansman, R. J. and Midkiff, A. H. : Impact of Vertical Situation Information on Vertical Mode Awareness in Advanced Autoflight Systems, in *Proc. 14th IEEE／AIAA Digital Avionics Systems Conference,* pp. 106-111 (1995).

19) Funabiki, K. : A Method of Enhancing Autopilot Mode Awareness, in *Proc. SICE 14th Guidanace and Control Symposium* (1997). In Japanese.

20) Funabiki, K.: Tunnel-in-the-Sky Display Enhancing Autopilot Mode Awareness, in *CEAS Symposium on Simulation Technology "Free Flight"* (1997).

21) Ellis, S. R. amd Hacisalihzade, S. S. : Symbolix Enhancement of Perspective Displays, in *Proc. Human Factors Society 34th Annual Meeting* (1990).

22) Slater, M. and Davison, A.: Liberation from Flatland : 3D Interaction based on the Desktop Bat. in *Proc. Eurographics* '91 (1991).

23) Weintraub, D. J. and Ensing, M. : *Human Factors Issues in Head-Up Display Design*: *The Book of HUD, SOAR CSERIC State of the Art Report* 92-2, Crew Systems Ergonomics Information Analysis Center, Wright-Patterson Air Force Base, Ohio, USA (1992).

24) Möller, H. and Sachs, G. : Synthetic Vision for Enhancing Poor Visibility Flight Operations, *IEEE Aerospace and Electronic Systems*, Vol. 9, No. 3, pp. 27-33 (1994).

25) Helmetag, A., Kaufhold, R. and Purpus, M. : 3D Flight Guidance Displays, Institue of Flight Mechanics and Control, Darmstadt University of Technology, Germany : Undated.

26) 白川昌之：エンハンスト・ビジョン・システムの概要 (The Outline of Enhanced Vision System), in *Proc. JSASS 35th Aircraft Symposium,* pp. 145-148 (1997). In Japanese.

27) Todd, J. R., Hester, R. and Summers, L. G.: Seeing Through the Weather : Enhanced／Synthetic Vision Systems for Commercial Transports, in *SAE Aerotech* '92 (1992). Paper 921973.

28) Rogers, R. : Flight Test Results of the Controlled-Flight into Terrain Avoidance Maneuver in Fly-by-Wire Transports, Technical report, Air Line Pilots Association, Airworthiness Performance Evaluation and Certification Committee (1999).

29) Foyle, D. C., Ahumada, A. J., Larimer, J. and Sweet, B. T.: Enhanced／Synthetic Vision Systems: Human Factors Research and Implications for Future Systems, in *SAE Aerotech* '92 (1992). Paper 921968.

30) Regal, D. M., Hofer, E. and Pfaff, T.: Integration of primary flight symbology and the external vision system of the high speed civil transport, in *Proc. 1996 World Aviation Congress* (1996).

31) Kuchar, J. K. and Hansman, R. J. : An Exploratory Study of Plan-View Terrain Displays for Air Carrier Operations, *The International Journal of Aviation Psychology,* Vol. 3, No. 1 (1993).

32) Kuchar, J. K. and Hansman, R. J. : Part-Task Simulator Evaluations of Advanced Terrain Displays, in *SAE Aerotech* '93 (1993), Paper 932570.

33) Williams, J. A. and Mitchell, C. M. : Effects of Integrated Flight Path and Terrain Displays on Controlled Flight Into Terrain, in *Proc.* 1993 *IEEE International Conference on Systems, Man and Cybernetics,* pp. 709-714 (1993).

34) Neider, J., Davis, T. and Woo, M. : *Open GL Programming Guide,* Addison-Wesley (1993) , ISBN 0-201-63274-8.

35) Brown, M. A., Sasa, S. and Ninomiya, T. : Three-Dimensional Cockpit Terrain Display : Concept and Prototype, in *Proc. JSASS 11th International*

Sessions in 35th Aircraft Symposium, pp. 627-630 (1997).

36) Brown, M. A., Sasa, S. and Ninomiya, T.: Integrated Three-Dimensional Terrain and Primary Filght Display: Concept and Prototype, in *Proc. SICE 14th Guidance and Control Symposium,* pp. 87-94 (1997).