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TITLE

Embedded Training - An explorative study providing requirements for the display of virtual targets on a Helmet Mounted Display in simulated air-to-air engagements within visual range.

PERMISSION

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ABSTRACT

Since Embedded Training (ET) has numerous Beyond-Visual-Range (BVR) benefits, and because wars cannot be contained to the BVR regime -- that is, pilots involved in an air-to-air engagement will eventually enter within visual range of their opponents and/or their weapons -- to preserve the value of ET, the transition to the visual arena needs to be natural and realistic. Therefore, the focus of this report will be to discuss and establish requirements of a Helmet Mounted Display (HMD) to support ET within the visual arena. More specifically, the question that will be addressed in this study is:

What are the requirements for virtual targets, to be superimposed on the outside world as seen through the pilots' eyes, in order to simulate the presence of those targets in the outside world?

The requirements for imaging virtual targets depend on properties of the human visual system and on the visual information elements ('cues') required for dealing with a WVR engagement. On this basis, it is concluded that current HMD technology is not yet mature for ET of WVR engagements. This conclusion is based on assessment of parameters such as: required scene update rate, display refresh rate, time delay, field size, resolution, luminance levels, scene-management principles, etc.

However, it is worthwhile to stimulate developments in this direction to enable WVR-engagements to be trained with ET in some useful form. If this technology can be realistically achieved within the medium time frame (it is estimated that the technology is mature in 5-10 years, e.g. current helmet mounted display technology is progressing quickly) it is sensible to proceed with the concept for future platforms, such as the JSF and Eurotrainer. Since ET also has potential outside the fighter community, spin–off of innovative display technology to other platforms/domains does not seem impossible.

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Summary

Since Embedded Training (ET) has numerous Beyond-Visual-Range (BVR) benefits, and because wars cannot be contained to the BVR regime -- that is, pilots involved in an air-to-air engagement will eventually enter within visual range of their opponents and/or their weapons -- to preserve the value of ET, the transition to the visual arena needs to be natural and realistic. Therefore, the focus of this report will be to discuss and establish requirements of a Helmet Mounted Display (HMD) to support ET within the visual arena. More specifically, the question that will be addressed in this study is:

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Note and acknowledgements:

This work has been performed as an explorative side study (restricted in scope and effort) of the embedded training demonstration of RTP 11.12. This technical publication is partly based on WE 3500 Report 11.12 (Roessingh, 2002). The contents of the latter report have been released for publication in the present form with authorisation of the Chairman of the EUCLID RTP 11.12 management group. The authors appreciated the comments by the NLR/NIVR subcommittee for Flying Qualities and Flight Operations on the latter report and attempt to address these comments in the current report.

Contents

(53 pages in total)

Abbreviations

A/A	Air to Air
AGARD	Advisory Group for Aerospace Research and Development
AGL	Above Ground Level
Arcmin	Minutes of Arc (here used in the context of visual angle)
AWACS	Airborne Warning And Control System
BVR	Beyond-visual-range
Cd	Candela
CG	Centre of Gravity
CGF	Computer Generated Forces
CGI	Computer Generated Image
Deg	Degrees
EADS	European Aeronautic Defence and Space Company EADS NV
EID	Electronic Identification
EO	Electro Optical
ET	Embedded Training
EUCLID	European Co-operation for the Long term In Defence
FAA	Federal Aviation Administration
FL	Foot-Lambert
FLIR	Forward Looking Infra Red
FoV	Field of View
GCI	Ground Control Intercepts
GPS	Global Positioning System
HMD / HMS	Helmet Mounted Display / Helmet Mounted Sight
HOTAS	Hands On Throttle And Stick
HUD	Head Up Display
IFF	Identification Friend or Foe
INS	Inertial Navigation System
IPD	Inter-Pupillary Distance
IPME	Integrated Performance Modelling Environment
IR	Infra Red
JND	Just Noticeable Difference
JSF	Joint Strike Fighter
JTIDS	Joint Tactical Information Distribution System
L	Luminance
LO	Low Observability
ML	MilliLambert

NIVR	The Netherlands Agency for Aerospace Programmes
NLR	National Aerospace Laboratory
NM	Nautical Mile
PRF	Pulse Repetition Frequency
RCS	Radar Cross Section
RTP	Research & Technology Project
RWR	Radar Warning Receiver
TRA	Temporary Reserved Airspace
UCAV	Unmanned Combat Air Vehicle
VID	Visual Identification
WASIF	WeApon System Simulation In Flight

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1 Introduction

Embedded Training (ET) is a form of pilot training in which simulated threats are fed into the various avionics systems of a combat aircraft in-flight. It provides capabilities to train fighter pilots more effectively, using the real aircraft in real flight in combination with an on-board simulated world. A more detailed definition of ET, together with a list of its quantifiable benefits, is given in Appendix A. Previous research has demonstrated that ET is a technologically viable concept (EADS, 1997). It has been recently estimated that the gradual introduction and expansion of on-board simulation systems will lead to a share of the use of ET of about 20 to 30 percent in advanced and combat readiness training of military pilots. More background to this percentage figure is given in Appendix B.


Figure 1: WVR arena

An ET system, carried on-board of an aircraft, consists of three main simulation modules.

- First, the *simulation management module* performs many functions, such as starting and stopping training exercises and taking care that all players participating in the exercise have synchronised information.
- Second, the *own ship simulation module* stimulates the on-board sensors and simulates the own weapons and electronic warfare systems.
- Third, the *virtual world simulation* simulates the virtual players (Computer Generated Forces, CGF's) in the exercise. The virtual world simulation also comprises models for the terrain over which the exercise takes place and atmospheric conditions.

More details on the basic architecture of an ET system is included in Appendix C. Specifically the part of the architecture dealing with the virtual world simulation is important for the current study. This virtual world includes the CGF's, their signatures, weapons and dynamic behaviour, involving strategies, tactics, manoeuvres and counter measures. It is technically feasible to include BVR engagements in an exercise that is based on Embedded Training. However, Within-visual-range (WVR) (figure 1) engagements, that is, when opponents come closer to the own ship than approximately 10 nautical miles (depending on size and visibility conditions) provides major technical challenges, which is the topic of the current study. WVR engagements require that visual, but virtual, opponents (or more generally: physical objects) can be superimposed on the outside world as seen through the pilot's eyes, in order to simulate the presence of those objects in the outside world. Helmet Mounted Displays or other displays suitable for realistic visualisation of virtual opponents in the outside world as seen from the fighter cockpit do not yet exist. The development of a ‘sufficient’ visual display could make an interesting business case (possibly with interesting spin-off to other domains). This study focuses on the system requirements for such a display. The goal of this side-study is to identify and describe the requirements that are needed to train *within-visual-range* (WVR) engagements using embedded simulation. More specifically, we investigate the possibility that pilots in a flight engage in a virtual air-to-air scenario with WVR targets in the visual environment. Hence, the question that will be addressed in this study is:

- What are the requirements for virtual targets, to be superimposed on the outside world as seen through the pilots’ eyes, in order to simulate the presence of those targets in the outside world?

The requirements for imaging virtual targets depend on properties of the human visual system and on the visual cues required for dealing with a WVR engagement. However, there is a lack of generalizable knowledge for defining the visual cues needed for embedded training, at least as much as there is a lack of knowledge of defining the perceptual cues in ground-based simulations (see e.g. Padmos and Milders, 1992). Therefore the requirements put forth in this document must be considered as first estimates.

<u>Current applications of Helmet Mounted Displays</u>
Currently, the applications of see-through Helmet Mounted Displays (HMDs) fall into one or more of the following categories:

- In-flight display of flight data. This includes the presentation of symbology and alphanumerical information, similar to that of the HUD;
- Weapon aiming. An aiming reticle is presented on the HMD. One or more weapons are head-slaved (slaved to a helmet-tracker);
- Vision enhancements. A synthetic sensor image, such as a Forward Looking Infra-Red (FLIR) sensor image, is projected on the HMD, thus superimposed on the pilots’ view of the outside world;
- Simulation, in which a virtual world is displayed on an HMD, the latter being a ground-based training device, rather than an in-flight applicable device.

To our knowledge, HMDs have never been used for embedded training of WVR-engagements, thus we are exploring a new application. In general, the fidelity of current display technology appears to be insufficient for training of all facets of WVR engagements (i.e. all potential geometries of own ship and targets). However, it may be possible to define a subset of (part-) tasks within WVR engagements for which current technology of HMDs is sufficient, i.e. tasks for which a colour display, high resolution, low-hysteresis head- and eye-tracking, and a wide field-of-view are not overly important. Examples are tasks in which a target is relatively distant

(say, visible at a few miles) and information for tactical manoeuvres such as 'aspect' (which requires that certain features of the target can be distinguished) must be judged.
It has been speculated that non-helmet solutions such as canopy projectors and retinal projection using micro-lasers will enter the commercial marketplace. However, the precise capabilities and drawbacks, in particular those relevant for military in-flight applications, are not yet clear.

Points of departure

Within EUCLID RTP 11.7, which dealt with 'training simulation using real and simulated systems', some human factors aspects of embedded training were investigated (Reus and Stokkel, 1997). According to this study, the three main visual tasks for the pilot in WVR engagements in air-to-air scenarios were:

- target detection and localisation;
- target recognition and identification;
- target tracking (maintain visual acquisition on the target).

On the basis of mission/task analysis, factors were listed that influence the detection, identification and acquisition tasks. Those factors were classified as (1) target features, (2) target behaviour, and (3) environmental characteristics, some of which will be discussed in more detail in the current study. Reus and Stokkel concluded (see appendix E) that training requirements exceeded the capabilities of state-of-the-art HMDs, in particular for the visual target identification task. To further investigate this type of restrictions, the current study reviews how targets appear within-visual-range, and how the pilots involved in a flight perceive targets, handle information related to these targets, execute the appropriate actions and acquire skill.
On the basis of analysis of the capabilities and limitations of the human pilot, provisional guidelines can be derived for inclusion of virtual WVR targets in the visual scene.

Structure of the study

Further objective of this document is to define the functional requirements for a suitable visualisation device, independent of technologies that will sooner or later emerge on the marketplace, and to indicate the bottlenecks for implementation. The current study is restricted in scope by *not* considering:

- operations with head/helmet mounted vision enhancements (such as NVGs);
- targets other than fast jet aircraft (that is: UCAVs, helicopters, etc);

The decision to develop technical solutions for implementation of virtual visual targets will be largely a matter of training effectiveness. Virtual visual targets should only be incorporated in embedded training if a significant contribution towards training effectiveness can be expected. However, virtual WVR targets can possibly enhance existing training, namely, if due to practical restrictions (e.g. financial, logistic or environmental restrictions) no adversaries are available during live training. In either case, the design requirements for virtual visual targets should be a direct function of the training needs, and consequently, essential for the fulfilment of the training objectives. In addition to the training value of virtual targets in the visual environment, we discuss aspects of feasibility, safety, and cost effectiveness in the remainder of this document. The managerial reader may want to go directly to Chapter 8 (Conclusions & Recommendations).

2 Description of the Within-Visual-Range engagement tasks

The following tasks are deemed relevant to the WVR regime:

2.1 The detection and localisation task

We assume that A/A targets can be visually picked up at around 10 NM (Haringa, 1998), i.e. approx. 18 km, maximum. However, obtaining possible hostile aircraft locations within-visual-range is not restricted to visually detecting the target through scanning the out-of-the-window environment. The following options are available:

- the locations are communicated by GCI or AWACS via datalink or voice communication;
- the locations are obtained by scanning the radar display for possible targets (autonomous detection via radar is common, even with AWACS/GCI present). In the latter case the possible targets need to be in the radar scan volume;
- using RWR indications (when under attack);
- using electro-optical means (infra-red);
- via adversary's electronic counter measures;
- via datalink/ link 16;
- via a head-up scan by the pilot.

All pilots in a flight participate in detection and localisation. Flight members will usually concentrate on different, pre-briefed, sectors. When a possible target is detected, the information is shared with all flight members via radio (verbally) and/or via datalink (digitally). The subsequent tasks (from identification through actual attack) are always governed by the rules of engagement of the friendly force.

2.2 Identification task

Identification (ID) is necessary to assure the identity of the intercepted aircraft – a mandatory step prior to weapons employment. Although identification is preferably accomplished via electronic means at longer (BVR) ranges, sometimes these electronic means fail, lead to ambiguities, or are not present onboard the aircraft. In these circumstances, visual identification must take place prior to weapons employment. Whether ID is obtained electronically (EID) or visually (VID), all members of the flight perform the identification task. The flight leader, however, typically retains ‘engage authority’ for the flight.

Electronic means of identification range from:

- Identification Friend or Foe (IFF) response. Modern fighters can ‘interrogate’ military and civilian IFF codes of targets on their radar. Targets responding incorrectly may be deemed hostile depending on rules of engagement.
- RWR indications
- Aircraft emissions
- RCS or IR signature

Visual identification is only possible when the pilot can clearly see discernible features on the target[1], such as planform shape, number of vertical tails, inlet shape, etc. For the pilot to visual identify the aircraft type with the naked eye, the range between the two aircraft is typically inside 5 NM, and may be as close as 1-2 NM when similar looking aircraft types are on opposing sides (e.g. Hornet vs Fulcrum). Slewable electro-optical devices, such as targeting pods (carried on most multi-role fighters) and/or high-magnification EO lenses (such as carried on the F-14D) can greatly assist in VID by showing the pilot a magnified visual image in the cockpit, providing VIDs out to 10 NM against fighter-sized targets.

Finally, once target ID is determined, the pilot must further decide if the target is ‘hostile’. For example, ID may render that the aircraft is a ‘Mig-29’, but the pilot may still need to verify that it is from the enemy nation (e.g. neighbouring nations not involved in the conflict may also fly the same aircraft). While BVR, aircraft origin may be determined by noting where the aircraft first appeared. In the WVR regime, the pilot may have to get close enough to see the flag painted on the aircraft. Targets may also be deemed hostile by their actions, such as by firing on friendly forces. Soviet air-to-air missiles were seen out at 20 NM launch ranges during the first Gulf War.

2.3 Prioritisation and targeting/sorting task

Targeting is the process of assigning each flight member’s radar to a unique enemy group so that the maximum number of enemy can be engaged. Sorting is the further division of responsibilities within an enemy group when there are two or more friendly fighter radars assigned to that group (e.g. a four ship of F-16s, but only two enemy groups). Targeting and sorting responsibilities are addressed in unit standards and are also typically covered in the

[1] At 10 NM all you see is a dot, at 5 NM you start to see some planform features, and at 3 NM, you can count tails and count motors and see inlet features, at 1-2 NM, you can start identifying external stores.

flight brief. Flight members target and sort at a pre-planned range, which preferably occurs BVR. In order to engage the maximum amount of enemy forces, radars will only be assigned to targets of unknown ID, or hostile ID (that is, known friendlies will be excluded).

In the visual arena, 'visual' sorting can also occur. For example, if the pilot detects a target WVR, he/she will usually pull the target into the HUD in order to facilitate visual acquisition and attempt a VID (while possibly simultaneously working an EID). If in this process other targets are visually detected in the same general area (e.g. threats flying in formation), the flight members will use a very precise, heads-out radar mode to lock a specific target within the visual formation. Thus, in even in the WVR arena maximising the number of enemy engaged remains critical.

2.4 Attack task

The attack task starts when the targeting/sorting task is complete or when the flight is attacked. The WVR attack phase is heavily intensive, decision times are short and the attack is characterised by a highly dynamic environment.

Make visual acquisition on target

When not already done, each flight member must find the target visually. This is performed by visually scanning the direction (bearing and altitude) indicated by the flight leader by voice or read from the tactical situation display.

Maintain visual acquisition on the target

The next task it to keep visual contact with the target in order not to lose situational awareness and advantage. Target manoeuvring must be assessed by frequently crosschecking the target. The crosscheck favours a high percentage of looking at the target, with only looking inside or elsewhere when time is available.

Maintain situation awareness with friendly aircraft

In order to maintain situational awareness, visual contact with friendly aircraft must be brought into the crosscheck (see previous point).

Monitor ownship energy state

The own-ship energy-state is an important parameter for keeping advantage in an air-to-air engagement. Important parameters for the energy-state are airspeed and altitude. The feel of the aircraft provides an important 'subjective' measure of energy-state.

Manoeuvre

The pilot must manoeuvre in order to keep advantage in the engagement, to regain advantage or to disengage (temporarily or permanent) when necessary. Manoeuvring is based on the following four types of visual target information:

- Range (which can be primarily determined by the visual angle covered by the target, when the target has a known size, but also the relative position to other objects such as mountains and clouds and the occlusion of those objects is important).
- Aspect (the angle-off-tail of the target as viewed from the own-ship, which can be primarily determined when features of the target can be distinguished).
- Closure (the relative speed between own-ship and target, which can be primarily determined by the change in visual angle, growth or shrink, of the target).
- Line-Of-Side (the drift of the target across the own-ship canopy).

Select weapon

The pilot must select the appropriate weapon for the attack. The following weapons are possible for WVR engagements:

- gun;
- short-range missile (typically infra-red guided);
- medium-range missile (typically radar guided).

Selection is based on various considerations (such as target range and relative position). When a missile is selected, the pilot must wait a few seconds (while the weapons solution is calculated) until it can be released.

Release weapon

The next task is to release the weapon. For the gun, this task is obvious. When a missile is employed, there are multiple options.

- For fire-and-forget missiles, the pilot can immediately decide to disengage.
- For missiles that require guidance from the own-ship, the pilot must guide the missile until it becomes active. This usually means that the nose of the aircraft must be kept pointed at the hostile aircraft within certain limits.

For WVR-engagements, the weapon effect can be checked directly. For example, the missile track and impact can be observed. Depending on multiple factors, the pilot can then decide to either disengage (temporarily or permanent), or to continue the attack. When the weapon employment is successful, the pilot may need to undertake a manoeuvre to avoid the debris. Nowadays, the avoidance of debris is seldom a factor because off-boresight launch-angles and further launch ranges put the fireball far enough away such that it is unlikely that evasive manoeuvres are needed.

2.5 The disengage task

When the decision is made to disengage, first the expected follow-on threat-axis is cleared and then the 6 o'clock of team members. Disengagement manoeuvres are then performed in the most advantageous direction.

Note to the task descriptions:

We have not gone into details with respect to the capabilities of the aircraft that are involved in above WVR-tasks. De Fontenilles et al. (1998) shortly describe the capabilities of a 'generic' modern fighter/bomber class combat aircraft (see Appendix D). For the current study, more specific capabilities of the aircraft systems than those listed in Appendix D are of subordinate interest, since these may be type-specific and/or since it is not clear how these affect the Within-visual-range engagements.

3 Visual aspects of Within-visual-range engagements

3.1 Introduction

Detection occurs when the pilot is able to detect a target against its background. When he is able to class the detected target(s) into a particular category (e.g., aircraft, birds), the target is *recognised*, and when the subject is able to class the recognized target, the target is *identified* (e.g., Rafale, MIG-29).

We start this chapter with a basic notion of the detection, recognition and identification tasks (in paragraph 3.2 through 3.4). Subsequently (paragraph 3.5 through 3.14), we discuss some factors with respect to the capacities and limitations of the human visual system when dealing with targets, such as the position of targets in the visual field, luminance, contrast, colour vision, distance perception, and the perception of target motion.

As a matter of fact, many more factors are known to affect target detection, recognition and identification. However, we feel that a discussion of all these factors would unnecessary complicate the discussion for the current purposes. We therefore made a selection on factors that are important for in-flight WVR-engagements and may pose problems for technical solutions.

3.2 Detectability of the target

A basic condition for target detection is that the target information displayed in the visual scene must be detectable (or 'legible'). This means that the human eye must be able to react to one (or several) visual parameter(s) of the target and its background (such as target luminance, location of the target in the field of view, etc.). Thus, these parameters (or rather, physical properties of the target) must have a value above the perception threshold. This reaction does not need any prior knowledge and is essentially based on a sensory process, which leads to determining whether a target is present in the field of view (detection). The threshold values of the various parameters determine the *detectability* level of the target information.

Minimum perceptibility

A pilot must be able to detect distant targets that subtend small angles at his/her eye ('small targets'). Visual acuity is the ability to discriminate fine objects. The visual acuity of the pilot importantly determines the detectability of targets. More specifically, we could measure the ability of a pilot to detect a small target against a featureless sky, which we define as the minimum perceptibility. We will use this definition when discussing the required resolution, luminance and contrast ratio of the projection of visual targets in Embedded Training.

3.3 Meaning of the target

A basic condition for target recognition and identification is that the target information displayed in the visual scene must be meaningful (or 'intelligible'). This concerns the possibility to use the meaning of the target in order to successfully deal with the WVR-enagagement. The meaning of a target plays a decisive role for recognition and identification and is referred to as the *intelligibility* level of the target information in the visual scene.

Minimum separability

The visual acuity of the pilot is not only important for target detection but also for target intelligibility. However, in this case, visual acuity concerns more advanced abilities than for a simple detection. The pilot must, for example, be able to distinguish that two targets, which are very close together, are in fact two separate aircraft. This ability of the human visual system to resolve fine detail is most often described by 'minimum separable acuity' i.e. the smallest distance between two objects which allows them to be seen as separate rather than as a single unitary object (Buffet, 1986). Luminance level and contrast (the latter in the form of either a luminance-contrast or a colour-contrast) both affect this acuity. We will use this definition of minimum separable acuity (or simply 'minimum separability') when we address the required resolution of a target projection system.

3.4 Familiarity of the target

The meaning of target information is not strictly separable from the detectability of the target. It is a well-known fact that *familiar* targets are more quickly detected than unfamiliar targets. Thus, there is a higher probability that a familiar aircraft will be detected at a certain range, whereas an unfamiliar aircraft at the same range may be overlooked as a bug splatter on the canopy. Generally, detection is easier when the target is familiar and expected. The familiarity of the background can also have a significant effect on target detection (Theeuwes, 1991).

However this may be more relevant for ground targets than for airborne targets, in which the background (the sky) has fewer features that can be considered familiar.

3.5 The target in the visual field

The maximum acuity of the eye is centred around the fovea, a retinal area aligned with the eye's optical axis and covering approximately two degrees in the centre of the field of view. Thus, visual acuity is greatest for targets that are at the line-of-sight, because these targets are projected on the fovea. However, since the fovea is only two degrees wide, which is the very narrow high-acuity detection area, 178 degrees of the detection area can be considered as peripheral vision. Outside the foveal area, the acuity progressively reduces, until, at the limits of the field of view, the observer is only capable of detecting sudden large object movement. However, the use of voluntary eye, head and body movements allow the high-resolution foveal area to be brought to bear on any region of visual space around the observer.

Visual acuity and resolution of the display system

Under laboratory conditions (with optimal viewing conditions) we can *detect* the presence of, well illuminated, high-contrast, very small targets that only subtend an angle of a few arc seconds. However, under cockpit viewing conditions and when vision is degraded by vibration, visual acuity (the ability to discriminate fine objects) will be worse.

Under optimum viewing conditions in the laboratory, very small Snellen letters (the typical letters used in an eye test) can be read. Boff and Lincoln (1988) report that Snellen letters as small as 0.8 arc minutes visual angle can be identified. However, Boff and Lincoln also report that outside visibility in an aircraft with a clean unscratched windscreen, facing away from the sun in very clear air on a sunny day with no buffeting would probably be no better than 2 arcminutes for high-contrast Snellen letters. Theoretically (in a crystal clear atmosphere), this would mean that a Snellen letter with a size of 10 m (a standard NATO size for a target) could be identified at a range of 17 km. However, acuity could be much worse and realistic atmospheric conditions prevent visual identification at this range.

For the identification of targets at large distances, the capability of a display system to make small details visible is critical. This capability is expressed by a system’s resolution. Resolution can be quantified in many ways. However, we use limiting resolution (Padmos & Milders, 1992), expressed in lines/degree, to quantify the resolution of a display system.

Limiting resolution is defined as the number of lines per degree of a high-contrast grating at the input of the display system at which the observer can no longer distinguish the separate lines in the resulting display image. This limiting resolution depends on the addressable resolution of the graphics processor (expressed in pixels per degree visual angle in horizontal/vertical direction) and the resolution of the display (which in turn depends on such factors as pixel-size and video-bandwidth).

Acuity; central and peripheral vision

Visually detecting other aircraft at a range of several miles is difficult and in some circumstances it is virtually impossible. When the pilot makes a visual scan to search for a target, his eyes jump in a series of ‘saccades’ from one position to the next with fixations in between. During these saccadic movements, visual acuity decreases sharply, leaving large gaps in the distant field of regard. It is thought that a pilot can gain most by improving the skill to detect targets in the peripheral visual field (Schallhorn, 1990).

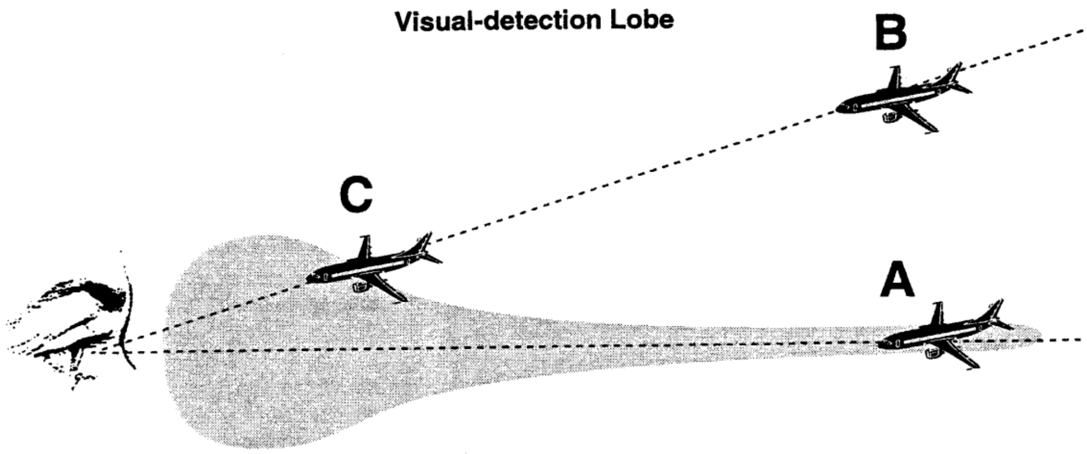

Figure 2: The visual-detection lobe (Source: Stamford-Krause, 1997)

Detection range and visual detection lobe

Given a fixation at some distant point, the detection range for central vision is narrow but extends relatively far (depending on atmospheric conditions), whereas the detection range for peripheral vision includes a wider area but extends a much shorter distance. The visual detection lobe (Stamford-Krause, 1997) represents the range in which detection has a certain probability (Figure 2). The cone-shaped form of the detection lobe implies that, when searching for targets at a closer range, fewer fixations are required. This is a consequence of the increased probability of detecting a target though peripheral vision at close range. Given a target in a cross-sectional area of the detection lobe we can define an area around the target for which it is probable (e.g. 95 percent) that the pilot detects the target with a single foveal fixation in this area. This area increases with experience or expertise. Thus, a more experienced pilot is more likely to detect the target in a single fixation.

Empty-field myopia

In the absence of a visual stimulus (for example, when searching in empty airspace) the muscles in the eye relax, preventing the lens from focusing. This creates a problem for a pilot who is

attempting to scan for a target in a clear featureless sky. Because the eye cannot properly focus on empty space it remains in a state of unfocused, or blurred, vision. The eyes will tend to accommodate at the resting point of accommodation at 1 meter. This phenomenon, known as ‘empty-field myopia’ hinders effective search and detection.
However, the pilot can prevent empty-field myopia to occur by:

- anticipating the target in the location and range of search,
- locating a sizeable, distant object (e.g., a cloud formation, mountain peak, etc.) that is within the range of an anticipated target and focussing the eyes on it at the beginning of each scan pattern,
- varying the range of search in order to ensure a thorough scan and to reduce visual fatigue.

3.6 Luminance

Luminance (light intensity L) is a physical property of a surface, such as a target or the sky. Luminance is defined as the luminous flux reflected or transmitted by a surface per unit solid angle per unit of projected area in a given direction. The most commonly used units of measurement are candelas per meter^2 (cd/m^2), footlamberts (fL), and millilamberts (mL). The relationship between these units is given by the equation: 1 cd/m^2=0.292 fL = 0.314 mL.

The following luminance levels are examples of relevant in-flight situations:

- Velger (1997) reports that background luminance of the sky (near the horizon) in twilight can be as low as 1 fL. On a very dark day, luminance is typically 10 fL, on an overcast day it is typically 100 fL and on a clear sunny day 1000 fL to 1500 fL (approximately 5000 cd/m^2).
- A background luminance of 120 fL (400 cd/m2) is sufficient for comfortable reading of non-illuminated cockpit instruments (Kent, 1990).
- Boff and Lincoln (1988) report that a white object in sunlight has a luminance of approximately 8760 fL (30.000 cd/m^2). Velger (1997) reports that sunlighted clouds can have a luminance of 10.000 fL (34.250 cd/m^2).

To put these figures in perspective of the current technology, we found in the specifications of a state-of–the-art (MicroVision, 2002) military HMD, that such device can provide a monochrome image (with symbolic imagery) with a maximum luminance level of approximately 2000 fL (6850 cd/m^2). An HMD in use for military ground-based simulation (deployable training), the CAE Gemin-Eye 3 (Joseph and Cahill, 2002) can provide full colour computer generated images of only approximately 5 fL.
For the projection of simulated targets not only maximum attainable luminance of the projection system is important, but also the ability of the projection system to provide different luminance

levels. According to Padmos and Milders (1992), 30 luminance steps are sufficient for simple tasks. For more realistic and complicated scenes, with curved surfaces, texturing and shading, 300 luminance steps are maximum required.
State-of-the-art HMD's for in-flight representation of symbolic information, have traditionally been used to depict symbolic information at a 'constant' (user-adjustable) luminance level.
In most displays the luminance of the pixels or image lines forming an image is not truly constant, but varies with a constant frequency (e.g. with a 60 Hz. Refresh Rate), depending on how the image is generated. However, if the frequency is too low, the image appears to flicker. When the field of view of the display extends more than 20 degree and the luminance exceeds 100 fL (only the background luminance on an overcast day is already 100 fL) than the display appears to flicker for frequencies up to about 80 Hz. (Velger, 1998). We have no information on higher luminance levels and larger field of views. Apart from probably destroying the illusion, prolonged viewing of a flickering display increases tiredness and discomfort.

3.7 Contrast Ratio

Contrast is the difference in luminance between two areas. It can be mathematically expressed in several ways. Here, contrast ratio is defined as the luminance difference between adjacent areas, divided by averaged luminance, or rather:

$$CR = 2\frac{|L_T - L_B|}{L_T + L_B}, \qquad (1)$$

in which L_T is the luminance of the target and L_B is the luminance of the background.
When targets are projected against a uniform background (such as a featureless sky), contrast ratio is the major factor for target detection. The perception of contrast is optimal at luminances of 100 fL and above, at which contrasts as low as 0.02 can be perceived.
If contrast ratio is low, the noise level of the projection and light variations in the cockpit will affect minimum perceptibility of the simulated target. A high contrast ratio may give a more brilliant image appearance and is especially important for detecting objects with a low intrinsic contrast in a dark part of the scene. Note that, according to the FAA, the visual projection system of a civil Level D flight simulator (the most advanced civil simulator) should be capable to yield a contrast ratio (L_T/L_B) of 5:1. Point sources of light should have a minimum contrast ratio of 25:1. A contrast ratio of 1000:1 was cited by AGARD (1980) as ideal.
For dark targets against a bright background, acuity improves as background luminance increases. For light targets against a dark background acuity increases initially, then declines with increasing target intensity. When targets are embedded in complex surroundings, i.e. the stimuli around the target vary qualitatively and quantitatively, more factors are important. An overview is provided in Boff and Lincoln (1988).

3.8 Colour vision

The appearance of a single coloured target varies considerably depending on the conditions under which it is viewed. The variables known to affect the perception of target colour include its size, location, structure, orientation and illumination and the colour of the surrounding. Because the colour of the target depends widely on these viewing conditions, an observer judgement of colour appearance is seldom precise. For long-distance visual target detection, under circumstances in which the borders between the target and the surrounding sky are indistinct, prolonged, fixated viewing of the target may cause the contrast between the target and the background to decrease to zero, making the target disappear. Very small or dim targets may appear white, especially in the 400 nm and 580 nm regions of the spectrum.

3.9 Monocular cues for target distance

We define depth perception as the perception of the out-of-the-window scene that aids the pilot in understanding the configuration (layout) of the situation. We distinguish the following monocular sources of distance information (‘distance cues’) for the pilot when looking out:

- Occlusion (also called interposition), This source of information arises when (part of) the target is seen to overlap another object or target, partially obscuring part of it from the pilot's line of sight. The obscured target must obviously be at a greater distance from the pilot than the object or target that is completely visible.
- The relative height of targets in the visual field of view can be used as a source of information concerning the relative distance of these targets from the observer. The general rule is that the closer an object is to the horizon, the farther away it appears to be. However, for a pilot this is only a reliable source of distance information when he/she knows that the target is at a certain height, for which additional cues are needed.
- Relative size, a measure of the angular extent of the retinal projection of two or more similar targets.
- Aerial perspective refers to the increasing vagueness of targets with distance, determined by moisture and/or pollutants in the atmosphere between the observer and these objects. Aerial perspective occurs when the attenuation and scattering of light from objects is sufficient to make the surface details and outline contours indistinct. This only happens at great distances or when atmospheric conditions give reduced visibility e.g. haze or fog. It is therefore only a very rough cue to distance.
- Motion perspective (also: movement parallax), refers to the field of relative motions of static objects around a moving observer (i.e. when the pilot moves his/her head); it specifically does not refer to target motion. If there is self motion through a scene, static objects outside the direction of movement and closer to the observer move faster over

the retina than do more distant objects (Rogers and Graham, 1979, Padmos and Milders, 1992).

Monocular cues are most effective when they pertain to realistic, familiar objects or patterns of sizes that are known to the observer. An abstract texture pattern, for example, is of little value in this respect (Padmos and Milders, 1992).
Additional distance cues are dealt with in, for example, Gibson (1950), Buffet (1986) and Barter (1994). A frequently mentioned monocular cue for target distance is ocular accommodation, which is the change in the shape of the lens of the eye, allowing it to focus on objects near or far while keeping the retinal image sharp. Objects at other distances are blurred. The muscles of the eye provide feedback on accommodation and hence on the distance of an object. This is not a strong distance cue and is only efficient up to 10 m or less, e.g. depending on age. However, problems with strain and accommodation must be taken into account when projecting images on the visor of a Helmet Mounted Display.
Most importantly, for a veridical perception of the layout of targets in a simulated visual scene, it is of great importance that the different cues do not cause a perceptual conflict, which implies that these sources of information must be managed carefully. It is obvious that the management of these cues becomes increasingly difficult when simulated targets are superimposed on a real visual scene, because the real elements of the visual scene are impossible to manipulate or to manage, and can at best be masked.

3.10 Binocular cues for target distance

The main binocular cue is the retinal disparity. Stereopsis, the perception of depth in a scene, is based on this retinal disparity, which is the difference in relative position of an object as projected on the retinas of the two eyes, or, in other words, differences in retinal image location with respect to the fovea. Disparity can be an efficient cue for target distances up to 160 m (Roumes, Meehan, Plantier and Menu, 2001). However, stereopsis decreases with distance. At distances of less than 1 m, depth differences of less than 1 mm may be perceived stereoscopically. Stereopsis decreases at greater distances: at 50 m, the perceivable depth difference is about 3 m (Ogle, 1962, Walraven, 1980).
Retinal disparity can be provided in a binocular display. However, for the presentation of true stereoscopic display, convergence of the eyes must be taken into account. Convergence is measured as the angle between between foveal axes of the two eyes; when the angle is large the eyes are canted inward to focus near the nose; when the angle is small (approx. 0 deg.) the two eyes are aligned to focus near the horizon. According to Roumes et al. the technology for true stereoscopic displays is not yet mature.
In addition to the fact that binocular vision in natural viewing conditions affords us the advantage of stereopsis, many visual tasks can be performed better with two eyes than with one.

Binocular viewing conditions produce superior visual target detection, higher visual acuity, better form recognition and smaller reaction times.
It is thought that the advantage of binocular target detection is due to probability summation between the eyes. Each eye has an independent chance of detecting a target, such that two eyes have a better overall performance than one eye. However, additional explanations have been given (Boff and Lincoln, 1988, p. 392).

3.11 The relative importance of cues for target distance

The relative importance of the visual sources of distance information for airborne targets can be quantified by means of plots of 'Just Noticeable Differences' (based on Cutting, 1997).

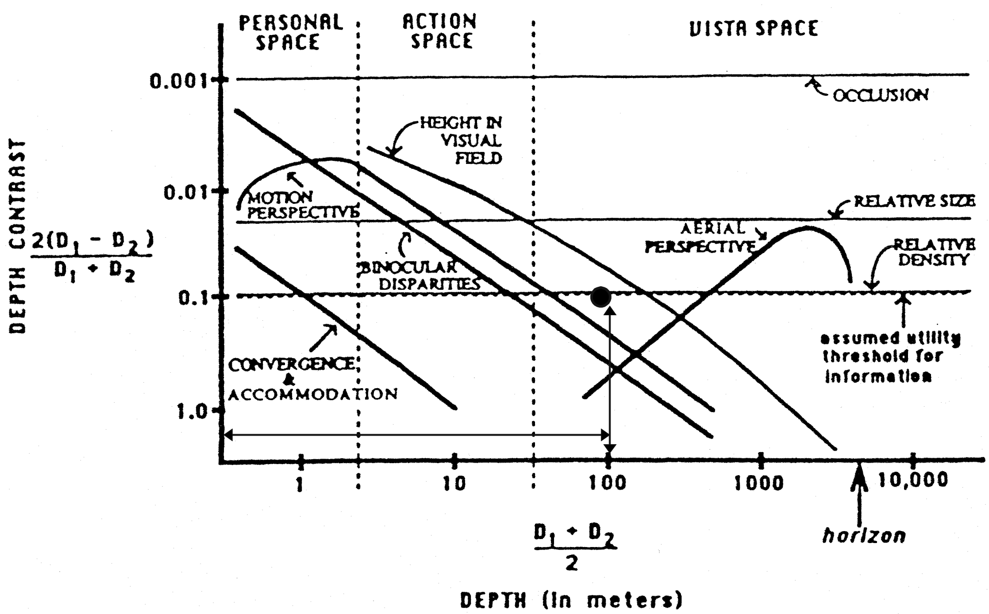

Figure 3: Just-discriminable depth-thresholds as a function of the log of distance from the observer, from 0.5 to 10,000 m, for nine sources of information about spatial layout of the visual scene. The underlying assumption is that more potent sources of information (e.g. occlusion) are associated with smaller depth-discrimination thresholds and that depth-information which is above the corresponding threshold function (i.e. below the corresponding curve) can be extracted from the scene. (Source: Cutting, 1997).

In Figure 3, 'distance thresholds' are plotted as a function of target distance from the observer. Namely, we consider the Just Noticeable Differences (JNDs) in the distance between two targets, which are at distances D_1 and D_2 from the observer, for each of the sources of information listed: occlusion, relative height, relative size, etc. Distance thresholds *ß* are obtained by scaling the Just Noticeable Difference D_1-D_2 by the mean distance of the targets [$(D_1 + D_2)/2$] to the observer, which is:

$$\beta = \frac{2(D_1 - D_2)}{D_1 + D_2}. \qquad (2)$$

Subsequently, we can plot distance thresholds for occlusion, relative height, etc., as a function of their mean distance [$(D_1 + D_2)/2$] from the observer.

For example, consider two targets in the visual field, the first on a distance of 95 m and the second on a distance of 105 m from the observer. The mean distance of those targets from the observer is then 100 m and, by using equation 2, the depth contrast is [2(105 - 95)/(105 + 95)] = 0.1 (i.e. 10%). The question is now, does the pilot perceive this configuration of targets and if yes, which cues contribute to this perception? To answer this question, consider the black dot in Figure 3, which represents the combination of mean distance and depth contrast of the two targets. From the figure, one can see that in this case, depth could be perceived in this scene through *occlusion, relative size, height in the visual field* and *relative density* (the latter only marginally contributing). In this case the following cues do not play a role: *convergence* and *accommodation*, *binocular disparities, motion perspective* and *aerial perspective*, either because the targets are out of range for each of those cues or because their depth contrast is below the threshold value (JND) of each of those cues. However, it must be taken into account that Figure 3 is based on a number of simplifying assumptions. Most important in the current context are the assumptions that (1) the observer is 1.50 meter AGL ('eye level') in flat terrain, (2) the targets are separated by less than 5 degrees visual angle measured horizontally, and (3) the targets do not move. However, it is relatively straightforward to determine how the threshold functions change when these assumptions are violated (Cutting and Vishton, 1995, Cutting, 1997).

3.12 Target motion and target detection

A moving target is generally detected more quickly than a stationary target with either foveal or peripheral viewing, but the advantage for the moving target is greater for peripheral viewing. The contrast threshold for moving targets varies little as target distance from fixation increases. However, the contrast required to detect a stationary target increases the further the target is from fixation. Acuity is not affected at low angular speeds of the target in the visual field, i.e. below 20 degrees/sec.

3.13 Target motion, target identification and target distance

Target motion is generally perceived easiest if there is a motion component that differs from the direction of gaze. Movements with retinal speeds between 0.03 arcmin/s and 200 deg/s may be perceived. Object motion in depth may be perceived by changes in angular size, texture density or lateral retinal speed of details.

An additional cue for distance to the target, which refers to its motion, is that when the pilot has some independent estimate of its real speed (after identification), the targets' speed on the retina provides a cue for distance. For targets in or near the direction of self-motion, speed of change (gradient) of the monocular depth cues (discussed in the previous paragraphs) may also provide distance cues.

3.14 Visual characteristics of target tracking.

When the target is identified as being hostile, the task is to keep visual contact at all times in order not to lose situational awareness and advantage, which involves own-ship manoeuvring. Target manoeuvring must be assessed continuously. In simplified terms, this task may be comparable with the kind of laboratory target tracking task, which is known in literature as 'pursuit tracking'. Pursuit tracking is tracking in which the operator's task is to keep a marker on a moving target symbol. The operator chases or pursues the target with the target position always displayed and the size and direction of tracking error is available from the positions of the target and the marker.

The reality in the cockpit is obviously more complex, since the pilot can move his eyes, his head as well as the aircraft to visually track the target. Thus, by shifting his field of view by one or more of those movements, the pilot shifts the position of the target in this field of view.

Moreover, the pilot not only needs to visually track a hostile target, but also friendly aircraft, in addition to 'sources of visual workload' within the cockpit. It is possible, however, to track a moving target in peripheral vision, i.e., from the "corner of the eye".

In addition to the capabilities and the limitations of the human visual system that we discussed under the heading of target detection, recognition and identification, additional human factors will be important for target tracking. These factors are generally those connected to human motor performance, in particular eye movements, head/neck movements and manual control inputs to manoeuvre the aircraft.

Scan patterns in tracking tasks have been investigated with eye movement tracking devices in studies in laboratory and aircraft settings and have always been shown to reflect an operators information needs, but could never be predicted.

It is however important that the projection of the target onto the retina will constantly change during the tracking task. Therefore, superimposing virtual targets on the outside world as seen through the pilots' eyes, in order to simulate the presence of those targets in the outside world, needs to take into account the changes in retinal projections of the target, caused by eye movements, head movements and aircraft movements.

If we restrict ourselves to eye movements, we can distinguish different types of eye movements, of which the most important are:

- smooth pursuit eye movements, for tracking slowly moving targets, up to 40 degrees/second.

- saccades, very fast eye movements to examine new targets and for visual search, which are very fast, up to 1000 degrees/second.
- vestibulo-ocular eye movements, to keep fixated on the target during head or body movement, up to 500 deg/second.
- vergence eye movements, very slow eye movements (10 degrees/second) to maintain convergence of both eyes on the same fixated target.

Furthermore, there are spontaneous drifts, microsaccades (flicks) and random eye muscle imbalances that will cause change in target position on the retina, for which the brain may 'automatically' correct.

In the case of a target that has a velocity of 25-30 degrees/second, an initial saccade brings about fixation on the target and then smooth movements of target velocity are used to track the stimulus. Occasional small saccades are superimposed on the tracking movement of the eye. With target velocities larger than 30 degrees, corrective saccades are often needed to reduce the discrepancies between actual position of the fixation point and the target. There will also be differences in eye movements for predictable and unpredictable target movements and intermittent and continuous visibility of the target.

4 Visual System Requirements

4.1 Introduction

A complete computer generated WVR-target visualisation system can be though of to consist of the following seven components: (1) a scenario controller (2) models of Computer Generated Forces, (3) a visual database, (4) a scene manager, (5) a geometric processor, (6) a graphics processor, and (7) a see-through display:

1. A scenario controller determines the events in a simulated WVR-engagement. It may specify the players, their missions, the rules of engagement, the start of the engagement, the end of the engagement, etc.
2. Models of Computer Generated Forces are models of the virtual targets that specify their behaviour, including interaction with other players, live or virtual.
3. A visual database contains a digital representation of the visual aspects of the targets (and possibly other objects) to be displayed.
4. A scene manager determines which targets may potentially be displayed and to what level of detail, given the position and orientation of the pilot's eyes.
5. A geometric processor calculates the projective transformations from the objects to an image plane. It removes objects or parts of objects that fall outside the field of view or are occluded by objects closer to the pilot's eyes.

6. A graphics processor scans the image plane and transforms it into pixels. It calculates the colour of each pixel and may add effects such as shading, fog, texture or anti-aliasing.
7. A (see-through) display presents the images of the targets to the pilot.

For the current purposes, only the four latter points (4-7) will be addressed at a global level.

4.2 Requirements for scene management and geometric processing

Update rate

The update rate is the frequency at which a total new image content is generated. It depends on such factors as the total number of polygons to be processed, the total number of pixels to be processed per second, and the angular speed of objects displayed. When displaying virtual targets, the required update rate will probably be determined by the angular speed of the targets in the visual field. This may pose particular high requirements when the targets are projected on the visor of a HMD. In this case, the projection of virtual targets depends on all types of motion (including head motion) of the pilot and the virtual target. The maximum displacement of a target per frame that gives an impression of continuous movement is approximately 15 arcmin. The consequence is that rather slow head movements of 20 degrees per second (1200 arcmin per second) would require an update rate of 1200/15 = 80 Hz. More specialised study would be needed to investigate this problem.

System Time Delay

Time delays in imaging the virtual targets may create some problems. Real world cues do no longer correspond to the display. In particular manual control performance in the target-tracking task will be degraded, control stability is reduced and workload is increased. System time delays as brief as 20 milliseconds have an effect on performance.

Field size

Field size (Field of Regard) refers to the angular size of the visual scene in which the simulated targets may occur. This depends on the field size available in the aircraft and on the task (target detection, acquisition and tracking) to be performed. Since a fighter aircraft may have a field size in the range of 300 degrees horizontally and 150 degrees vertically and since virtual targets may act anywhere in this field, the desirable field size of the simulated visual scene may also be 300 x 150 deg.

Depth of Field

The maximum distance at which targets can be detected determines the required depth of field visible. For the current purposes we assume that targets can be picked up at distances up to 18.52 km (Haringa, 1998). Kruk and Regan (1983) use a limit of 10 km.

Management of target information

The virtual target, for example projected on the visor of a HMD, is superimposed on the real world. As a consequence, occlusion of the target by real world objects which are at closer distance to the observer, such as clouds, mountains, aircraft structures is not possible. The scenario controller should avoid this problem or otherwise the scene manager must resolve this seemingly indecipherable problem.
In addition, when the pilot moves, the scene manager must manage the field of relative motions of virtual targets, in correspondence with real world objects. Obviously, such monocular cues as relative height of targets in the visual field, relative size of targets in the visual field and aerial perspective must be properly managed. The perception of object motion in depth must also be managed by changes in angular size, texture density or lateral retinal speed of details.

Shadow Effects

Shadow effects consist of cast shadows (e.g. the shadows targets cast on the ground or clouds) and of the shading of targets caused by the different orientation of its surfaces relative to the sun and clouds. These effects may provide additional cues for distance of the target and shape of the target.
Since the image generator only generates images of targets for the purpose of WVR engagements, inclusion of cast shadows seems neither possible nor an absolute necessity. However, shading of the target will be important for the detection, recognition and tracking tasks. This requires that the scene manager must know the position and orientation of the virtual target with respect to real world objects, more specifically the sun and clouds.

4.3 Requirements for graphics processing and display

Luminance

Luminance requirements depend on the luminance and luminance fluctuations in the visual out-of-the window environment and in the cockpit. The display system must be able to display targets with low luminance (of a few fL) against a background of higher luminance (for example, up to a few hundred fL). However, the display system must also be able to display targets with local surfaces of very high luminance (of a few 1000 fL) against a lower background luminance. Under daylight conditions, the required luminance of surfaces of the target may change very fast (glints are an important cue for detection), for example depending on its position or orientation with respect to the sun or clouds (see also the previous section on “Shadow Effects”). It appears that current generation display systems do not cater for this type of requirement. However, in the case of projection of the image on a helmet visor, it may be possible to automatically vary the luminance transmittance of the visor such that a more constant luminance can be achieved. More in-depth study would be needed to explore the exact requirements and the available display technology.

Contrast Ratio

A contrast ratio of 1000:1, cited by AGARD (1980) as ‘ideal’ is neither practically attainable nor necessary (Padmos and Milders, 1992). For most applications a contrast ratio between 10:1 and 25:1 is acceptable. However, a problem for the display of virtual targets in Embedded Training is that background luminance L_B is variable and depends on stray light in the cockpit, such that the requirement for a specific contrast ratio in the sense of Equation 1, independent of L_B, is not obvious.

Resolution

The size and distance of small targets determine the required limiting resolution of the image system and display. For the detection and recognition of targets at large distances the resolution is critical. Ideally the limiting resolution of the image system should at least be equivalent to the pilot’s visual acuity. We estimate that most fighter pilots might have a minimum separable acuity between 10 and 40 $arcsec^{-1}$, when tested in the laboratory. However, to set a minimum requirement for the ‘noisy’ cockpit environment we shall assume that the pilot has a visual acuity of only 1 $arcmin^{-1}$, which is reached by 85% of the population. For this case the limiting resolution is 60 lines per degree. To find the required addressable resolution (in number of pixels per degree) for TV-type of displays, we should divide the limiting resolution by 0.7 (the so called Kell-factor, Padmos and Milders, 1992) which results in a requirement of 86 pixels per degree. For a field of view of 200 x 130 degrees, we would need a monitor of 17200 x 11000 pixels. However, we could compromise this resolution when using an ‘area of interest technique’, in which a small field of high resolution is kept at the centre of gaze (possibly slaved to eye movements) while the surround is imaged at a much lower resolution.

For recognition of targets, we can use the criterion that at least eight image lines overlay a recognisable object. Under optimal conditions in the cockpit pilots may be able to recognize high-contrast Snellen letters subtending a visual angle of 2 arcmin. This would mean that we need a limiting resolution of 240 lines per degree (343 pixels per degree). However, taking into account more realistic conditions, Padmos and Milders propose a more relaxed guideline for the required limiting resolution for target recognition (in lines per degree):

- 0.10 x target distance / target size (expressed in the same unit of length),and for the addressable resolution (in pixels per degree)

- 0.14 x target distance / target size (expressed in the same unit of length),

Thus, to recognise a target with an exposed area of size 10 m at a distance of 6000 m requires 60 lines per degree or 86 pixels per degree visual angle.
On the basis of this crude analysis, we estimate that for foveal imaging of virtual (but realistic) targets one needs at least a display system with a limiting resolution of 60 lines per degree visual angle. This corresponds with 86 pixels per degree visual angle (in both horizontal and vertical direction). However, the required peripheral resolution may be much lower for the detection and recognition tasks.

Display Refresh Rate
Refresh rate (frame rate) is the frequency with which a whole frame of the display is written. A display refresh rate of at least 80 Hz is required to avoid flicker (which occurs with high luminance and large FoV).

Colour
The nature of the WVR-engagement tasks will probably not require the display of many colours simultaneously. It is likely that only a few colours are required for the imaging of targets, and then only when these are projected in central vision under daylight conditions. However, the more extreme lighting conditions may pose extreme requirements on colour contrasts and brightness and the luminance steps with which these few colours must be displayed.

Field-of-View (FoV)
The FoV of a display is the field that the pilot is able to ‘view’ from a fixed head position. The human visual field extends about 200 x 130 degrees. The FoV covered by central binocular vision is approximately 120 degrees horizontally. A large FoV, e.g. covering the human visual field, requires large optics. A trade-off must be made to achieve a sufficient FoV while keeping a reasonable size and weight of the optics.

Monocular, binocular or bi-ocular display
The image of the virtual target can be presented in three different ways (de Jong, 1999): (1) monocular, the display is viewed by a single eye, (2) binocular, two distinct images are presented to each eye, or (3) bi-ocular, the same image is presented to both eyes. For the presentation of virtual targets, superimposed on the real environment, a monocular display seems out of the question. When stereopsis is required in viewing the targets (when the target comes within a range of 160 m), a binocular display must be used to yield retinal disparity. If targets do not come closer than 160 m, a bi-ocular display will suffice.

A bi-ocular or binocular display must cater for different Fields of View (Biberman et al., 1992): (1) the FoV of each eye, (2) the overlap between the FoV's of each eye and (3) the total FoV. Best pilot performance can be obtained when the FoV's of the two displays (one for each eye) completely overlap each other (Jennings, Dion, Srinivasav and Baillie, 1997). It avoids problems such as 'binocular rivalry', i.e. perceptual conflicts between the visual fields of the two eyes.

Interpupillary Distance

The interpupillary distance (IPD) is the distance between the pupils of the pilot. In a system where images are presented to both eyes, this parameter has to be accounted for. The mean value of 63 mm is suggested (Ma et al, 1994), but it should always be adjustable for each pilot. When the IPD is not properly adjusted, the image may be distorted.

Visor

If the visor of a helmet is used for the projection of the image of the virtual target, than it must have a significant reflection. However, this seems to conflict with the transmissivity that is required to perform other visual flight tasks. In the future a completely opaque visor is thought to be a necessity, because of the emerging threats of lasers. A complete virtual world is then probably presented in the HMD of the future (de Jong, 1999). In this case, a large number of the anticipated problems with virtual target presentation will be resolved and more opportunities for embedded training will come into sight.

There is a potential conflict between accommodation and other monocular depth cues if simulated targets are displayed at a short observation distance. Moreover, if the wearer of an HMD is aware of the existence of the projection of targets on a display at short distance (e.g. on the visor), he/she may accommodate on this display rather than on infinity, i.e. the usual accommodation for perceiving airborne targets. In such instances the outside scenes appear blurred; hence with a lower contrast and as a result, real targets may not be seen or detected. Thus, the whole purpose of using the HMD to simulate the presence of targets in the outside world may be missed.

5 Safety Considerations

Negative training

It is possible that pilots learn skills, routines, knowledge or attitudes with Embedded Training that are different from the skills needed in the real WVR-engagements. In principle, one can not exclude the possibility of a negative effect of ET on performance in the real situation.

The primary purpose of Embedded Training for the individual pilot is to integrate a set of skills, such as tactical skills, perceptual skills, aircraft control skills and attention management skills. However, transfer effects of actual skills are thought to be highly specific (e.g. Logan, 1988). This means that transfer-of-training will only occur if the training scenarios are realistic and relevant for real WVR-engagements. If training scenarios are remote from real WVR-engagements, there will be neither negative nor positive transfer. Thus, the risk of negative training is small. In fact, there is very little empirical evidence for negative training from training exercises that lack fidelity.

Loss of Situation Awareness and Spatial disorientation

The interaction between the perception and the subsequent cognitive processing of virtual targets and spatial awareness is unknown and would need to be investigated. Spatial awareness is particularly important when embedded training scenarios are suddenly halted as a result of exceeding certain safety limits or when scenarios come to an end spontaneously. Spatial awareness may depend on the 'immersion' of the pilot in the simulated scenario. This leads to seemingly conflicting requirements; On the one hand, the training must be as realistic as possible, which implies a high level of immersion. On the other hand, the pilot must recover very fast from this immersion when the embedded training scenario is halted. The problem may be resolved with specific warnings and stopping procedures.

Helmet load, G-forces and Ejection-safety

A typical g-value for manoeuvring a fighter aircraft is 9 g with onset rates of 9 g per second. However, the maximum allowable helmet weight and centre of gravity (CG) depends on specific type and performance of the aircraft. A weight of 1.6 kg is considered the upper limit. The CG of the helmet has to be near the CG of the head, such that no discomfort and fatigue will be the result of improper balance of the helmet (de Jong, 1999). The mechanical properties of a HMD that enables projection of virtual targets superimposed on the real world should obviously not decrease pilot safety when in high-g maneuvers, in ejection or in a crash. However, helmet issues are beyond the scope of this document.

Virtual targets occluding actual aircraft

Maintaining deconfliction between flight members is always a high priority task. The USAF loses approximately 2 fighters/year due to mid-air collisions between flight members who lose sight/SA on each other during the tactical portion of the mission. If virtual targets projected on the HMD were to occlude a flight member, this could lead to an increase in mid-air collisions. The present-day introduction of fighter-to-fighter mid-air collision avoidance technology may offset this risk.

6 Training Effectiveness and Cost Effectiveness

Transfer-of-training (and hence training effectiveness) occurs when an individual is able to perform a task more satisfactorily as a result of prior training and is thus synonymous with the increase in skill level as the result of training.

It should be noted that the air-to-air tasks as described in chapter 2 involve complex tasks, not only execution of a procedures (such as IFF procedures), but also the execution of a series of difficult perceptual and cognitive tasks as well as high-g manoeuvring in a complex tactical environment. It seems difficult, if not impossible, to train the integrated skills for WVR-engagements with ground-based means.

Thus, in the current research we may ask the question whether ET with WVR capability is expected to result in satisfactory performance in real within-visual-range engagements, and what are the benefits over conventional training, such as live exercises with red air?

6.1 Realism of the visual scene

The overall results from ground-based simulator experiments tend to demonstrate that positive transfer can be attained using even a simplified (low fidelity) visual environment. The degree of simplification is, however, strongly related to the type of task. In other words, not all the tasks and skills require the same level of visual realism. When it comes to flight training, only relatively basic tasks, such as aircraft landing, have been used as the experiment task in transfer-of-training experiments. Some of these experiments considered the effect of out-of-the-window visual realism. However, we are not aware of specific transfer-of-training studies that considered WVR-engagements as the experimental task and explicitly addressed realism of target visualisation as an independent variable.

Carefully planned departures from engineering fidelity may sometimes positively contribute to skill-transfer of, as was demonstrated by experiments focusing on basic flying tasks (Lintern et al., 1997, Lintern and Garrison, 1992, Reisweber and Lintern, 1991, Lintern and Koonce, 1992). However, there are no theoretical guidelines that let us decide which simplifications of the visual scene are acceptable for transfer-of-training, let alone guidelines for simplified target visualisation in a simulated WVR-engagements. However, some more general 'common-sense' guidelines are provided by the Handbook of Simulator Based Training (Farmer, van Rooij, Riemersma, Jorna and Moraal, 1999):

- Keep in mind what sort of information the trainee should process and relate that to the content of the visual image. Subsequently, make a translation to technical requirements by using available research results.
- Consider the speed of movement required in the visual scene by both targets and own-ship movements. The update rates of the simulation should support them.
- Decide on the level of detail needed for the targets. Whenever a friend or foe identification is necessary, take great care to ensure that the required detail is provided.

6.2 Training benefits

The primary advantage of using ET in WVR (assuming that is technically feasible) is that it would allow a natural and realistic transition from BVR to WVR, thus the pilot gets to experience the full spectrum of the fight phases. If the WVR aspect were not there, the pilot would likely stop the fight ("knock it off") as it entered the WVR phase, which would interrupt training. Secondly, WVR ET would allow visual training against inbound missiles (which, of course, does not occur in non-ET training, since no munitions actually leave the opposing aircraft). Such visual training against inbound missiles would include:

- Practising the visual acquisition scan to detect the missile;
- Assessing if the missile is guiding on the own-ship by watching its flight path characteristics. For example, in real life, if countermeasure (chaff/flare) were effective in decoying the missile, the flight path of the missile would begin to trail off and follow the decoy. This instant visual feedback is only currently obtainable in combat. WVR ET gives this benefit.
- Practising last-ditch survival manoeuvres (aggressive last second turns to create sufficient miss distances so that the warhead fragments don't reach you). These manoeuvres are rarely practised because there is no way to get feedback with no inbound missile. Therefore, execution of last-ditch manoeuvres in combat often suffers. If ET could project a high-resolution missile on the HMD, then this valuable training could be gained. What does a real missile shot at you look like? A smoke trail at launch, which disappears once the motor burns out. At this point the missile is usually too small to see until it gets to about 1 NM from the own-ship, where the pilot *might* pick it up if s/he was looking exactly at the right place (thus, see the first point about visual training against inbound missiles above). Note that air-to-air missile motors burn for about 10 s. Thus, for shorter range shots, with less than 10 s time of flight (fired from within approximately 5 NM), the missile will be visible the entire time of flight due to its motor burning/smoking.

6.3 Red air replacement

The aforementioned training benefits are unique for ET with WVR. However, a more general argument for ET is 'red air replacement'. Conventional live exercises include aircraft that act as adversaries, i.e. 'red air', which are targets for the friendly aircraft ('blue air'). Thus, in conventional live exercises red air is needed, and, for the current purposes, ET could be considered as 'red air replacement'.
Now, assume that one might be able to estimate the average ratio between increase in performance of 'blue pilots' and increase in performance of 'red pilots', both as a result of a conventional live exercise. On the basis of this ratio, one would be able to calculate the minimal transfer percentage for which ET would be cost effective (the break-even point). We omit these cost effectiveness calculations, because they are beyond the scope of this study and would require assumptions about the specific scenarios to be trained during live exercises.
However, on the basis of ET as a means of mere 'red air replacement' (without the training benefits discussed earlier) it can be readily realised that, when 'red pilots' learn as much from an exercise as 'blue pilots', ET will not be cost effective. On the other hand, when 'red pilots' learn less from an exercise as 'blue pilots', the argument of 'red air replacement' holds, and on this argument only, significant cost savings are possible when technically feasible.

However, the argument of red-air replacement should not be over-emphasised for the case of ET with WVR capability. Although the read-air-replacement-argument is sensible in the BVR arena, is not really valid in the WVR arena. The reason is that when pilots from the West 'simulate' red air in WVR, they fly their full-up weapon system and thus don't lose any training. This is because real 'red air' aircraft (e.g. Soviet fighters) are more capable WVR than western fighters are. The Soviet strategy over the last 20 years has been to optimise the WVR aspects of the weapon system (high off-boresight aiming devices [HMS] coupled with capable short range missiles), while the western strategy has been to optimise the BVR aspects (excellent EID coupled with capable long-range missiles). With the West's current introduction of AIM-9X cued by a HMS (a capable, high off-boresight missile, cued by a high off-boresight aiming device) the Soviet WVR advantage is no longer present. In short, simulating red-air in WVR engagements can be highly motivating and can be considered good training. Other possible benefits of ET are listed in Appendix A.

7 Conclusions and Recommendations

It has been studied whether it is possible to display virtual visual targets on the visor of a HMD in such a way that these targets appear to the pilot to be in the outside world. It is concluded that current HMD technology is not yet mature for ET of WVR engagements. However, it is worthwhile to stimulate technology in this direction to enable WVR-engagements to be trained with ET. Particular attention was given to training tasks involving the detection and localisation of targets, the recognition and identification of targets and the tracking of targets, including the manoeuvring necessary to maintain visual acquisition on the target.

The required fidelity of the visual display depends on the specific task. For example, for tactical manoeuvring, a pilot ideally obtains visual range information, aspect information, closure information and LOS information. When some of this information is not represented in the visual scene, training (and transfer of skills to real missions) is at best partial.

The twelve requirements listed below reflect the most rigorous requirements for the simulation of virtual targets in WVR-engagements for all tasks listed. These requirements are:

1. An image update rate and a display refresh rate of at least 80 Hz, but possibly much more than 80 Hz, are required.
2. The time delay of the WVR-target visualisation system should be less than 20 milliseconds. In other words, the position in the display of simulated targets should not lag more than 20 ms behind on simulated target motions, actual aircraft motions, and actual head motions.
3. A field size (Field of Regard) of the simulated scene in the range of 300 degrees horizontally and 150 degrees vertically is required.
4. A field depth in the range of 10 to 18.5 km is required.
5. Scene management must be based on point-of-gaze measurement. Specification of the type of head- and eye- movements that must be measured would need to be determined and depends on other requirements.
6. Occlusion of virtual targets by real world objects must be managed, that is, the hiding of virtual targets or part of a virtual target behind real world objects which are at closer distance to the observer, such as clouds, mountains and aircraft structures, must be managed. For safety reasons the operational community maybe even more concerned of the reverse, i.e. when a real target/object is occluded by a virtual target, possibly resulting in a mid-air collision.
7. Shading and illumination of virtual targets by real world objects (sun and clouds) must be managed.

8. Quickly varying luminance levels, ranging from a few feet-Lambert to several hundreds feet-Lambert, in a sufficient number of luminance steps, should be supported by the display system.
9. A resolution of the foveal image of 86 pixels per degree visual angle (in both horizontal and vertical direction) should be supported. However, a decreasingly lower peripheral resolution is required.
10. A bi-ocular display with hundred percent overlap between the field of view of each eye is required. When targets comes within a range that is less than 160 meters, support of stereopsis must be considered. The latter implies a binocular display with different images for each eye corresponding with retinal disparity.
11. The display method should avoid potential conflicts between accommodation and other monocular depth cues if simulated targets are displayed at a short observation distance.
12. The mechanical and optical properties of a device that enables projection of virtual targets superimposed on the real world should not compromise pilot safety (e.g. in high-g manoeuvres, in ejection or in a crash).

When only a subset of the discussed WVR tasks need to be trained with ET, some of the requirements can be moderated. For example, training for assessment of target aspect or the geometry of the visual intercept may require a smaller field-of-regard, a lower display resolution and would probably not be negatively affected by a monochrome display. It should not be overlooked that also in WVR engagements the target is often at large distance and will thus subtend a visual angle of only a few arc-minutes (and hence covers a number of pixels in the same order of magnitude). The emergence of the next generation missiles, such as a supersonic, short-range, guided infrared air-to-air missile of the Sidewinder FOX 2 AIM-9X type (see e.g. Boe & Miller, 2000) will only contribute to the importance of these geometries.

It is notable that a specific technology, so called "retinal image projection" is developing rather fast. Basically, this technology entails that low-power laser beams 'draw' images directly on the retinas of both eyes. Today, in-flight products of this type (manufacturer: Microvision™) do not yet meet the display requirements as outlined above. However, multi-coloured images of moderate resolution (comparable to EGA resolution) can be generated already. Although technology has not been assessed in detail in the current study, it is estimated that this and/or other type of technologies enable simulated WVR-engagements in ET (in some useful form) within the next five to ten years.

For further investigation into simulated WVR-engagements in ET it is recommended:

- To do a more detailed analysis of current and future technologies that would enable ET with WVR engagements.
- To do more detailed analysis into the most rigorous requirements (in particular those concerning scene-management and head-tracking), for example using a task/operator-modelling tool such as Micro Saint of IPME (Micro Analysis and Design, 1999).
- To investigate the possibility of using a fully virtual out-of-the-window-view for ET to overcome the problems associated with superimposing virtual elements on a real out-of-the-window-view.
- To do a detailed investigation into the cost effectiveness of ET of WVR-engagements.
- To investigate the possibility of using symbology rather than realistic virtual targets. For example virtually and conformally projecting (‘scene-linking’) symbology onto a visor, such that the symbology appears to be part of the out-of-the-window environment (e.g. cf. Foyle, McCann and Shelden, 1995).

8 References

AGARD (1980). Fidelity of simulation for pilot training. Advisory Group for Aerospace Research and Development, Advisory Report 159, Neuilly-Sur-Seine, France.

Bartoldus, K.H., Sijll, M.C. van (1998). Weapon system Simulation in Flight (WaSiF) “virtual onboard scenarios for air defence training”. Paper presented at the International Training and Education Conference (ITEC), April 1998, Lausanne, Switzerland.

Biberman, L.M. & Aluissi, E.A. (1992). Pilot Errors involving Head-Up Displays (HUDs), Helmet Mounted Displays (HMDs), and Night Vision Goggles (NVGs).

Boe, E.A., Miller, C.R. (2000). “FOX 2” – AIM-9X, The next generation sidewinder. Report of the 40th Flight Test Squadron, 46th Test Wing, Eglin AFB, FL, US.

Boff, K.R., and Lincoln, J.E. (1988). Engineering Data Compendium – Human Perception and Performance. Armstrong Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio.

Buffet, A.R. (1986), Visual cueing requirements in flight simulation, in proceedings of RaeS Simulation Symposium : Advances in flight simulation, visual and motion, RaeS, London, UK.

Joseph, D. & Cahill, K. (2002). Future requirements for deployable training drive HMD development. CAE’s Military Simulation and Training News. In MS&T. Issue no.6. Spring/Summer 2002.

Cutting, J.E. (1997). How the eye measures reality and virtual reality, Behaviour Research Methods, Instruments and Computers, 29(1), 27-36.

Cutting, J.E. and Vishton, P.M. (1995). Perceiving layout and knowing distances: the integration, relative potency, and contextual use of different information about depth. In W. Epstein and S. Rogers (Eds.): Perception of Space and Motion, Academic Press.

EADS (1997) Final Report EUCLID CEPA 11 RTP 11.7: Training simulation combining real and simulated systems. Federal Office of Military Technology and Procurement (Fighter Aircraft Branch), Germany.

Farmer, E., van Rooij, J., Riemersma, J., Jorna, P., Moraal, J. (1999). Handbook of Simulator-based Training, Ashgate Publishing Company, UK.

Fontenilles, H. de, Roessingh, J.J.M., Moscato, M., Krawies & González Vega, N. (1998). Physical System Parameters and Skill Acquisition: Guidelines. Deliverable C1.4. EUCLID MASTER project RTP 11.1.

Foyle, D.C., McCann, R.S., and Shelden, S.G. (1995). Attentional issues with superimposed symbology: Formats for scene linked displays. In R.S. Jensen and L.A. Rakovan (Eds.), Proceedings of the Eighth International Symposium on Aviation Psychology, (pp. 98-103). Columbus: Ohio State University.

Gibson, J.J. (1950). The perception of the visual world. Boston: Houghton Mifflin.

Haringa, T. (1998). Helmet Mounted cueing system study program on the F-16 MLU. Report EPAF-FR-98-01. Air Force Material Command, Aeronautical Systems Center, Wright Patterson AFB, Ohio.

Jennings, S., Dion, M., Srinivasav, R., and Baillie, S. (1997). An investigation of helmet mounted display field-of-view and overlap tradeoffs in rotorcraft handling qualities. In Proceedings of the 23rd European Rotorcraft Forum, Dresden, Germany pp. 43.1-43.10.

Jong, T. G., de (1999), MMI Aspects of HMDs and NVDs in an operational context. Unpublished Report. National Aerospace Laboratory NLR, Man Machine Integration and Human Factors Department.

Kent, W.S. (1990). Visual simulation in the commercial airframe manufacturer's training environment. In E.G. Monroe (Ed.) Proceedings of the IMAGE V conference (pp. 231-239). Tempe, AZ: Image Society.

Stamford Krause, S. (1997). Collision avoidance must go beyond "see and avoid" to "search and detect". Flight Safety Digest, issue May 1997, Flight Safety Foundation.

Kruk R., and Regan, D. (1983). Visual test results compared with flying performance in telemetry-tracked aircraft. Aviation Space and Environmental Medicine, 54, 906-911.

Lintern, G. and Garrison, W. (1992). Transfer effects of scene content and crosswind in landing instruction. The International Journal of Aviation Psychology, 2(3), 225-244.

Lintern, G., Koonce, J. M. (1992), Visual augmentation and scene detail effects in flight training, The International Journal of Aviation Psychology, 2(4), 281-301.

Lintern, G., Roscoe, S.N., Koonce, J.M. & Segal, L. (1990). Transfer of landing skills in beginning flight training. Human Factors, 32, 319-327.

Lintern, G., Taylor, H.L., Koonce, J.M., Kaiser, R.H. and Morrison, G.A. (1997). Transfer and quasi-transfer effects of scene detail and visual augmentation in landing training. The International Journal of Aviation Psychology, 7(2), 149-169.

Ma, J., Hollerbach, J., Hunter, W. (1993) Optical design for a head-mounted display. Presence, Vol. 2, No. 3, pp. 185-202.

MicroVision (2002). Products: Military HMD: WEB: http://www.microvision.com/prod_mil_hmd.htm.

Micro Analysis and Design (1999). Micro Saint-Human Operator Simulator: WEB: http://www.maad.com.

Ogle, K.N. (1962). Spatial localization through binocular vision. In H. Davson (Ed.), The Eye, Vol. 4, pp271-324. New York: Academic.

Padmos P., Milders M.V. (1992), Quality criteria for simulator images, a literature review, Human Factors, 34(6), 727-748.

Reisweber, D.A. and Lintern, G. (1991). Visual properties for the transfer of landing skills. In R.S. Jensen (Ed.), Proceedings of the Sixth International Symposium on Aviation Psychology. Columbus: Ohio State University.

Reus, A. de, and Stokkel, F. (1997) Man-Machine Interface Aspects. In EUCLID RTP 11.7 Training Simulation Combining Real and Simulated Systems (WASIF). Document ID. EUC/RTP11.7/NLR/TN230/I2.

Rogers, B. & Graham, M. (1979). Motion parallax as an independent cue for depth perception. Perception 8, 125-134.

Roumes, C., Meehan, J., Plantier and Menu, J.P. (2001). Distance Estimation in a 3-D Imaging Display, International Journal of Aviation Psychology, volume 11 - issue 4.

Schallhorn, S., Daill, K. (1990). Visual search in air combat. US. NAMRL Monograph 41. U.S. Naval Aerospace Medical Research Laboratory, Pensacola, Florida, US and US Navy Fighter Weapons School, Miramar, California, March, 1990.

Theeuwes, J. (1991). Visual selection: exogenous and endogenous control. In A.G. Gale, I.D. Brown, C.M. Haslegrave, I. Moorhead & S. Taylor (Eds), Vision in vehicles, 3, 53-61.

Velger, M. (1998). Helmet mounted displays and sights, Artech House optoelectronics library, Artech House Publishers, London, Boston.

Walraven, J. (1980). Evaluation of spatial task performance with the Oldelft PC1MC nightvision goggle. Report IZF-1980-C-5, TNO Human Factors Research Institute, Soesterberg, The Netherlands.

Appendix A What is embedded training?

Figure A.1: Airspace temporarily reserved for Embedded Training – Virtual adversaries and missiles are generated in simulation equipment on-board the own ship (on the right-hand side in the reserved airspace).

Embedded Training (ET) is a form of pilot training in which simulated threats are fed into the various avionics systems of a combat aircraft in-flight. This allows training against a virtual force, or virtually augmented real force with a mission debrief playback capability on the ground. ET enables the operator to use the weapon system in a situation where it was designed for, while this situation is not available in every day life. Thus providing capabilities to train fighter pilots more effectively, using the real aircraft in real flight in combination with an on-board simulated world.

An ET mission potentially provides the context of a real fighter mission, but without the need for the actual presence of mission-critical air/ground vehicles, such as enemy aircraft, ground targets and friendly forces. While the aircraft, capable of ET, manoeuvres through a reserved airspace sector (figure A.1), the interaction with these air/ground vehicles is simulated with on-board equipment. Although the stress of real combat will probably never be accurately simulated, ET can come closer than traditional forms of training by representing assets in the real environment.

Previous research has demonstrated that ET is a technologically viable concept (EADS, 1997). Now R&D needs to focus on the operational needs for ET capabilities. If the operational use and benefits can be demonstrated, it is worthwhile to equip the next generation training aircraft and fighters, such as the Joint Eurotrainer and the Joint Strike Fighter, with these capabilities. In the next sections the reader is given a brief account of some of the principles underlying ET.

Why combine real and simulated systems?

The ET system feeds additional players, such as targets and threats, into the Mission System of the aircraft. These data are treated by the aircraft as if being real data and will be displayed as such. The simulated players interact with the fighter pilot based on his/her actions and their predefined role. In the preceding section we argued that ET is a form of high fidelity combat mission training. This is a strong argument for serious consideration of implementation. However, some more direct and quantifiable advantages can be argued for as well.

<u>Less red air flights needed.</u> In live combat training without ET, aircraft are needed that act as the enemy. Most often, young wingmen and flightleads play these thankless roles, therefore slowing down their process of growth. These so-called red air flights are costly and obviously only have a restricted training value for the pilots involved. It is clear that with budgetary constraints on flight hours, ET as mere 'red air replacement' will be very cost effective.

<u>ET only needs a relatively small volume of airspace.</u> Many of today's and future air-to-air engagements with enemy aircraft are Beyond-visual-range (BVR), which means that detection of the enemy target, identification, weapon delivery, and electronic warfare all take place at relatively long distances between the players. Airspace in Europe where such skills as electronic warfare and employment of medium range radar missiles can be trained is very limited. In live combat training of BVR engagements, a training area is needed with a size of 40 x 80 NM, which although is available in the North Sea TRA's, it leaves little airspace remaining for anyone else. Moreover, no overland airspace can accommodate 40 x 80 NM in the Netherlands.

With ET, however, much smaller ranges are needed, simply because it allows virtual entities (enemy aircraft) to fly outside the designated area as long as the real aircraft remains within the designated airspace. Because airspace for military training is a scarce commodity, particularly in Europe, ET will give significant training advantages.

<u>Realistic simulation of ground threats.</u> In current tactical combat training, participation of realistic ground threats in the scenario, such as Surface-to-Air-Missiles is expensive, and sometimes

technically not feasible. However, ET technology has the potential of realistic simulation of ground threats.

The physical experience of ET is unrestricted. The current alternative of live tactical combat training is training in a full mission simulator. Although ground-based simulators have proven to be effective for training of many fighter skills, there are a number of perceptual sensations that can only partly be provided by these devices, such as sensations due to sustained accelerations of the aircraft (high g) and the sensations related to unusual attitudes. While fully realistic aircraft dynamics are present in ET, this form of training is to prefer over ground-based simulation when the pilot has to combine various skills and knowledge in an integrated manner, such as tactics, leadership, perceptual skills, control skills and attention management.

Simulation of GCI/AWACS anywhere. In combat and training fighters often operate under control of Ground Control Intercept (GCI) or an Airborne Early Warning platform (AWACS). During training however these systems are not always available. ET is able to provide the control capabilities in case these systems are not available. Thereby ET trains the pilot the necessary skills on a day to day basis.

Security benefits. Certain capabilities of fighter aircraft are not being used during training due to security or safety reasons. Specifically for JSF, Low Observerability (LO) or Stealth characteristics are expected to be issues that may not be used to the full extent during training because of security aspects. ET allows training with the LO/Stealth characteristics with virtual systems. This increases the pilot readiness for real combat. Another aspect is the training of specific weapons like lasers. These weapons can only be trained in a specific environment due to safety reasons. ET allows the deployment of these weapons in a virtual environment.

Appendix B Training during a fighter pilot's career

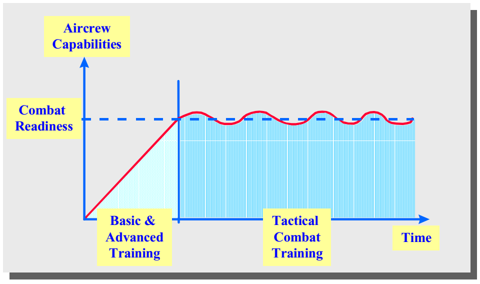

Figure B.1: aircrew capabilities during basic, advanced and combat training (schematically).

Pilot training, from screening to tactical combat training is an extremely complex and costly undertaking. The student, after being selected to become a military pilot first receives about hundred flight hours on a light propeller aircraft. In this 'screening stage' about 25 percent of the students drop out and hence more costly drop-out in further stages of training is prevented and a group with relatively uniform capabilities is formed. The students selected to become fighter pilots subsequently receive 'basic flying training' (see figure B.1). This includes about 250 hours of jet training and provides the student with the general knowledge, skills and attitudes of the military fighter pilot. Basic training is followed by 'advanced flying training'. In this stage students learn basic fighter skills on a jet aircraft, including formation training, fighter manoeuvres, tactical intercepts and weapon deliveries. Subsequently the student follows 'operational conversion training', which involves flight training with the specific operational aircraft type. On graduation the fighter pilot receives the classification 'limited combat ready' and will be assigned to an operational squadron where his/her combat ability will be further developed through 'tactical combat training'.

Fighter pilot training, today and tomorrow

When aviation started, the aircraft was the only medium for flight training. In the late twenties of the previous century simple devices for flight training on the ground were introduced. Gradually these simple devices evolved into the highly developed simulators and other ground training devices as we know them today. As a consequence, these devices have now replaced in the order of 30 per cent of the flight hours in basic, advanced and combat training.

In the future, the share of the use of training devices for ground-based training is likely to increase further. It has been estimated by European industry (EADS, 1997, Bartoldus and van Sijll, 1998) that soon ground-based tactical combat training will gain about 60 percent of the overall tactical combat training hours, leaving only 40 percent of the training hours for actual flying. Main causes for the increase in ground-based training are the limited availability (and hence costs) of airspace, aircraft and training time. To nonetheless cope with the ever increasing demands for training of tactical combat tasks, improved computing power, computer graphics techniques and networking of simulators now allow ground-based training to be effective for the development of tactics and practice of war roles. Mission practice and rehearsal, using networked Full Mission Simulators and Pilot Stations will include training of air defence tasks against a variety of targets and threats.

A more recent advancement in training of fighter pilots is live training in the aircraft combined with on-board simulation (embedded training). It has been recently estimated that the gradual introduction and expansion of on-board simulation systems will lead to a share of the use of ET of about 20 to 30 percent in advanced and combat readiness training of military pilots. Joint exercises with other nations, using ET with on-board generated virtual air defence scenarios combined with networked full mission simulators are pictured for the near future.

Appendix C The architectural concept of Embedded Training

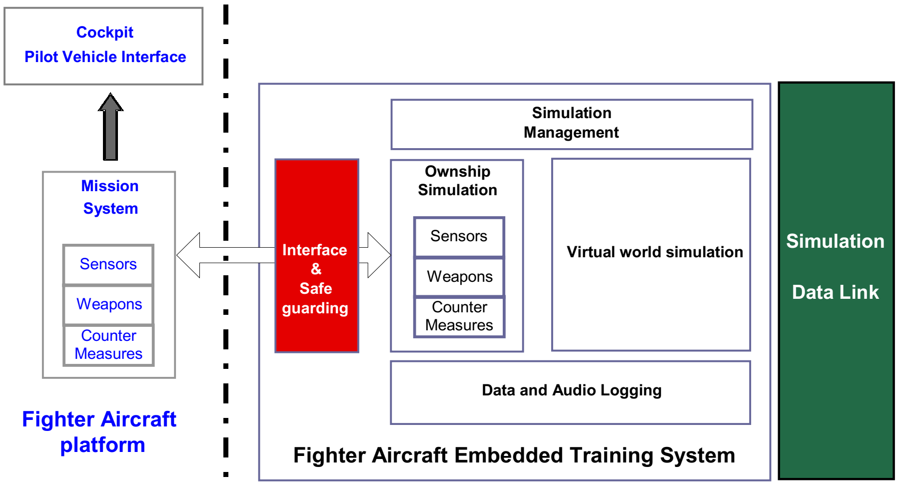

Figure C.1: Basic architecture of an Embedded Training system

<u>Basic Architecture</u>

An ET system, carried on-board of an aircraft, consists of three main simulation modules (figure C.1).

– First, the *simulation management module* performs many functions, such as starting and stopping training exercises and taking care that all players participating in the exercise have synchronised information.
– Second, the *own ship simulation module* stimulates the on-board sensors and simulates the own weapons and electronic warfare systems.
– Third, the *virtual world simulation* simulates the virtual players (Computer Generated Forces, CGF's) in the exercise. The virtual world simulation also comprises models for the terrain over which the exercise takes place and atmospheric conditions.

To make the pilot believe that he/she is in a real mission, the three simulation modules maintain an intensive two-way communication with the aircraft's standard mission system. The mission system consists of modules that handle sensor data, weapon data, and electronic warfare data. Every time the pilot gives an input to one of the cockpit systems, the simulation needs to be updated and, as a result, new simulation data need to be fed into the mission system. To ensure a safe exercise a specific safety layer that safeguards both the aircraft mission system and the pilot has been developed.

The above described basic architecture is sufficient for the training of engagements in which one ET carrying aircraft is involved and all other players are CGF. However, in more complex and realistic exercises, that is, beyond the one-versus-one/two engagements, an airborne datalink between ET carrying aircraft and an air-to-ground datalink between aircraft and ground-based entities are needed to ensure that all players have matching sensor information.
A scenario for the exercise needs to be prepared in advance on a dedicated ground-station. After sufficient verification of the scenario, its digital representation can be loaded in the ET carrying aircraft, either by physically inserting a credit-card-size memory card into the system or by datalink. The ground-station can also be used for after-action review or debriefing purposes.

Simulation Management

During the exercise, the simulation management module must control all simulations as well as the overall course of the exercise. In addition, this module manages the recording of the exercise and performance measurement. Since complex exercises have many performance aspects, proper assessment of pilot performance is a major challenge to fighter pilot training in general and specifically to ET. The performance aspects include the use of weapons, sensors and countermeasures, selection of tactics, following the mission routes and selection/assignment of opponents. Intelligent methods are needed to keep track and analyse the pilots' activities, to categorise pilot error and to determine kill ratios (the ratios of wins to losses or wins to total engagements). Transfer-of-training will increase when such performance measures can be singled out, both during the exercise and in after-action review.

Own ship simulation

In the own ship simulation a complete dynamic model of the own ship is included. Because weapon delivery must also be simulated, own ship simulation includes models for fire control, the weapons loaded, such as medium- and short-range missiles, on-board guns, flares and chaff and the electronic warfare system. An important part of the own ship simulation is a realistic assessment of weapon effectiveness, including hit calculation and probability of kill. System displays on-board the own ship, such as the radar, the radar warning receiver and the air-to-air interrogator (for target identification) must interact as if real targets are present. These provisions make it possible that Beyond-visual-range (BVR) engagements, in which opponents remain outside a range of 10 nautical miles (about 18 kilometers) of the own ship, can be fully exercised.

Virtual world simulation

The virtual world includes the CGF's, their electronic signatures, weapons and dynamic behaviour, involving strategies, tactics, manoeuvres and counter measures. Moreover, the behaviour of the CGF's has to be in exact accordance with their individual role (ground-based or airborne, friend or foe, fighter or fighter-bomber, etc.). It is technically feasible to include BVR engagements in an exercise that is based on Embedded Training. However, Within-visual-range (WVR) engagements, that is, when opponents come closer to the own ship than approximately10 nautical miles (depending on size and visibility conditions) provides major technical challenges, which is the topic of the current study. WVR engagements require that visual, but virtual, opponents (or more generally: physical objects) can be superimposed on the outside world as seen through the pilot's eyes, in order to simulate the presence of those objects in the outside world. Helmet Mounted Displays or other displays suitable for realistic visualisation of virtual opponents in the outside world as seen from the fighter cockpit do not yet exist. The development of a 'sufficient' visual display could make an interesting business case (possibly with interesting spin-off to other domains).

Appendix D Capabilities of the aircraft

De Fontenilles et al. (1998) shortly describe the capabilities of a 'generic' modern fighter/bomber class combat aircraft. The aircraft has extensive multi-role capacities and has the ability to match future weapon systems still under development. With extensive multi-mission capability, this type of aircraft can perform:

- air-to-air multi-target stand-off interception at high or low altitudes. Agility offers total superiority in close combat and a Mach 2+ capability makes interceptions very fast,
- air-to-surface penetration and ground attack missions under day/night conditions, with conventional and smart weaponry, from saturation to precision strike weapons,
- air-to-sea missions with long range anti-ship missiles,
- reconnaissance and electronic warfare missions,
- etc.

This aircraft has in-flight refuelling capability. The multi-function radar offers all-aspect look-up and look-down multi-target intercept capabilities, even against very low altitude intruders. The integrated weapon system includes:

- Multi-function radar with high-medium-low PRF automatically selected for all altitude,
- FLIR pod and laser designation pod (IR and EO),
- Inertial Navigation System + GPS,
- Complete electronic warfare system (detection, jamming and decoying), internal and integrated,
- Computers for mission management,
- Displays giving the pilot all necessary information either "head-level" on a scope or "head-up" with data focused to infinity or on lateral and head-down displays,
- HOTAS controls,
- Multiplexed digital data transmission system (datalink) and mass memory for mission planning.

Appendix E Unresolved issues (Reus and Stokkel, 1997)

Transition between BVR and WVR

The information requirements for realistically training WVR engagements require the HMD to be able to display target aircraft up to a range of around 14 km. This is the range at which fighter pilots typically detect fighter-sized targets in good visual conditions. As discussed above, an important cue for target distance is its angular size. Displaying a fighter aircraft (exposed size in the order of 10 m) on an HMD at a virtual distance of 14 km, would require an angular resolution of 2.5 arcmin (displaying one line / pixel). This is at the extremes (in fact beyond) of what is possible with current HMDs. It should be noticed, however, that the exposed size of 10 m is very optimistic. A glint, one of the important detection cues, will never have a size of 10 m.

The effect of this resolution problem is a threshold in the target display. When a target is coming closer, its size at a certain point exceeds the HMD resolution (line width / pixel) and it suddenly "pops up" on the trainee's HMD. This discontinuity is an unnatural situation. The target will be detected later by the trainee, and thus it is closer, reducing the time to take decisions and also reducing the possibilities for a favorable outcome of the fight (all compared to real air-combat).

Although the effect on trainee behaviour is unknown yet, it probably hampers to some extent the use of the simulator for training of the transition between BVR and WVR during engagements. The precise consequences have to be investigated.

Visual target identification

The information requirements for realistically training visual target identification (VID) exceed the capabilities of state-of-the-art HMDs in at least the following areas:

- angular resolution
- use of colour

The main problem is in the optical area. Miniature high-resolution colour raster light sources (e.g. CRTs) suitable for fighter aircraft HMD applications are not available. The same holds for the HMD visors that on the one hand need to reflect more than one wavelength (band) for colour imagery and on the other hand need to have a relatively high transmission. This combination has not been demonstrated yet and the expectation is that it is also difficult to develop a fighter HMD with these specifications.

Image generation is not the limiting factor here, since this technology has advanced greatly in recent years. Up till now there has not been a need to use high-resolution raster image generators and colour in fighter aircraft. The expectancy is that the existing image generation technology that allows this kind of imagery, can be transferred to a fighter aircraft relatively easily.

A solution to the insufficient HMD performance is to display an identification (by means of symbology next to the virtual target or by means of a voice message) whenever the trainee is in the range and aspect angle that would allow identification under real WVR engagements. Note that although these so-called augmented cues allow target identification by the trainee, it does not train the identification itself. The precise effect on training effectiveness is an unknown issue.