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Augmented reality and night vision fusion

A primer

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IMPORTANT INFORMATIVE STATEMENTS

AUGMENTED REALITY AND NIGHT VISION FUSION: A PRIMER

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Abstract

The goals of this project were to assess the state of the art in augmented reality and fusion systems for use by soldiers, to research available commercial-of-the-shelf (COTS) and military-off-the-shelf (MOTS) systems, and to evaluate system capabilities and features against possible Canadian Army uses. Following a review of the state and goals of the Canadian Army's night vision program, the report then considers two seemingly separate and distinct areas--augmented reality (AR) and night vision fusion--that are merging and combining capabilities due to advancements in hardware and software technologies.

This report is organized into separate sections for AR and night vision fusion to keep common technologies and developments together. The AR section provides a definition and then expands on the continuum of extended reality. AR capabilities and functionality are described with examples from civilian applications, and enabling technologies are also discussed. These AR capabilities are then reviewed and discussed in the context of common soldiering tasks and activities. Infantry examples of AR use are provided, as well as examples of past and present Army AR programs. Finally, the hardware, displays, and software technologies within the worlds of mixed reality are described in more detail using developmental, Commercial-Off-The-Shelf (COTS) and Military-Off-The-Shelf (MOTS) systems.

The section on night vision fusion begins with an introduction to low-light sensor technology as well as image intensification systems. An introduction to thermal systems and long-wave infrared (LWIR) technology is provided. Major fusion programs and product lines are reviewed and discussed. Finally, novel research efforts are presented that have implications for future AR and sensor fusion systems.

Résume

Les objectifs de ce projet étaient d'évaluer l'état de l'art en matière de réalité augmentée et de systèmes de fusion à l'usage des soldats, de rechercher des systèmes commerciaux disponibles sur étagère (COTS) et militaires sur étagère (MOTS), et pour évaluer les capacités et les caractéristiques du système par rapport aux utilisations possibles de l'Armée canadienne. À la suite d'un examen de l'état et des objectifs du programme de vision nocturne de l'Armée canadienne, le rapport examine ensuite deux domaines apparemment séparés et distincts - la réalité augmentée (RA) et la fusion de la vision nocturne - qui fusionnent et combinent des capacités en raison des progrès du matériel et technologies logicielles.

Ce rapport est organisé en sections distinctes pour la fusion de la réalité augmentée et de la vision nocturne afin de maintenir ensemble les technologies et les développements communs. La section AR fournit une définition, puis développe le continuum de la réalité étendue. Les capacités et fonctionnalités de la RA sont décrites avec des exemples d'applications civiles, et les technologies habilitantes sont également abordées. Ces capacités de RA sont ensuite examinées et discutées dans le contexte des tâches et activités militaires courantes. Des exemples d'utilisation de la RA par l'infanterie sont fournis, ainsi que des exemples de programmes de RA passés et présents de l'armée. Enfin, les technologies matérielles, d'affichage et logicielles dans les mondes de la réalité mixte sont décrites plus en détail à l'aide de systèmes de développement, Commercial-Off-The-Shelf (COTS) et Military-Off-The-Shelf (MOTS).

La section sur la fusion de la vision nocturne commence par une introduction à la technologie des capteurs à faible luminosité ainsi qu'aux systèmes d'intensification d'image. Une introduction aux systèmes thermiques et à la technologie infrarouge à ondes longues (LWIR) est fournie. Les principaux programmes de fusion et gammes de produits sont passés en revue et discutés. Enfin, de nouveaux efforts de recherche sont présentés qui ont des implications pour les futurs systèmes AR et de fusion de capteurs.

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1. Background

The Strong, Secure, Engaged (SSE) Canadian Defence Policy (Department of National Defence, 2017) provides clear direction on Canadian defence priorities over a 20-year horizon. The policy states that the international landscape “is marked by the shifting balance of power, the changing nature of conflict, and the rapid evolution of technology. Increasingly, threats such as global terrorism transcend national borders. These trends undermine the traditional security once provided by Canada’s geography” (p. 14). To address these challenges, SSE states that Canada will, among other things:

- Field an agile, well-educated, flexible, diverse, and combat-ready military.
- Act as a responsible, value-added partner with NORAD, NATO, and Five Eyes partners.
- Field advanced capabilities to keep pace with allies and maintain an advantage over potential adversaries.
- Address the threats from terrorism and the actions of violent extremist organizations, including in ungoverned spaces.

To meet these objectives, Canadian soldiers must train to maintain readiness and develop their high-end war-fighting skills. Furthermore, the SSE goes beyond a strict emphasis on warfighting, noting that, “experience shows that highly trained, versatile and well-equipped combat forces can rapidly adapt to humanitarian assistance, disaster relief or peace operations”(p. 36).

SSE acknowledges that these objectives cannot be fulfilled without an investment in the Canadian Armed Forces (CAF) to recapitalize core capabilities. With respect to the Canadian Army, one such area for investment is Night Vision Goggles (NVGs) and Night Vision Systems (NVSs). For the purpose of this report, NVGs will refer to systems based on image intensification (I^2) technology while NVSs will refer to systems based on digital sensors. The term NVG will be used generically to describe a head- or helmet-mounted goggle system used by soldiers. While many of Canada’s partner nations have undertaken the task to modernize their soldier NVGs, the last major night vision investment within the Canadian Army was over 18 years ago. Since then, rapid evolution and improvements in the underlying technologies have taken place. To retain the ability to seamlessly integrate with coalition partners and to maintain an advantage over potential adversaries, a similar investment is needed within the CAF. This investment must be in sufficient quantity to provide soldiers with ready access to NVGs, for both operations and training, a situation that is not reflected in the current fleet of NVGs.

To ensure mission success, the Canadian Army requires technologically superior NVSs in sufficient quantities to allow for ready access during training for both the Regular and Reserve Forces. Under such conditions the Canadian Army will remain combat-ready, maintain a combat advantage over adversaries and be a valued partner to our allies, in accordance with SSE. A number of nations have countered the deficiencies in I2-based NVG performance with Infrared (IR) devices. I^2 devices require some existing environmental light to amplify and therefore have poor performance in very dark conditions, such as cloudy nights, tunnels, and caves. However, IR devices also possess a number of limitations such as difficulty operating in the rain or high humidity environments. IR devices are also not compatible with in-service Laser Aiming Devices (LADs), many cannot be used to see through windows, and they are not particularly effective during thermal cross-over times (transition between day and night).

The current fleet of NVGs (primarily AN/PVS-14s) is no longer technologically advanced relative to the potential adversaries that Canada may face. In-service NVGs do not allow commanders easy access to command-and-control (C2) information at night (i.e. NATO COMMAND capability area). Next generation NVSs will allow commanders access to navigation and command and control information at night using AR without the need to use shielding blankets to conceal light from flashlights. Data fusion systems are available that will allow data overlays (e.g., digital map information displayed on a commander's NVG). The ease of connecting legacy surveillance and target acquisition systems to the ground forces Defense Advanced Global Positioning System (GPS) Receiver (DAGR) system is deficient. Capturing GPS tagged information is complicated and prone to error. The need to consult a manual at a covert Observation Post (OP) in operations, to be able to tag an image with GPS coordinates, is undesirable. Next-generation NVSs could embed GPS receivers and direction pointing sensors in the systems, resolving the connectivity and ease-of-use issues faced today.

Next-generation NVGs will increase the range at which a soldier can detect, recognize, and identify hostile targets relative to current in-service NVGs (i.e. NATO SENSE capability area). Advanced NVS sensors and I^2 tubes available in today's NVGs are a significant improvement over the current level of performance, enabling effective operations under no- or limited-light conditions. Next-generation I^2 tubes have improved performance in urban environments where the presence of lighting significantly affects the ability of our soldiers to detect and identify combatants in complex environments where combatants shield themselves amongst civilians.

The technical performance of next-generation NVGs is superior to the performance of the current fleet of NVGs, offering the possibility of enhanced combat effectiveness for Canadian soldiers (ACT). Increased detection, recognition, and identification performance would enable commanders more time for decision making by detecting, recognizing, and identifying potential threats sooner. Once threats are identified and the decision is made to engage them, next-generation NVGs will be able to apply assisted target engagement capabilities like weapon-mounted laser range finders to enhance marksmanship. These section-level laser range finders should increase first-round hit performance by eliminating errors associated with range estimation, which is especially challenging at night. Next-generation NVGs should increase the engagement distances possible under low or no-light conditions by making the target easier to acquire and engage. Likewise, soldier mobility will improve with next-generation NVGs. The current NVGs provide limited depth perception cues under limited visibility. Soldiers cannot differentiate a hole in the ground from a shadow and driving at night with a monocular NVG is challenging. A lack of depth perception can lead to more trips and falls, resulting in solder injury, as well as compromising soldier stealth. Canada's current fleet of NVGs results in reduced speeds of traverse, whether mounted or dismounted. Next-generation binocular NVG systems are now available that are as light as the monocular PVS-14 but offer better depth perception through stereopsis, improving speeds of traverse, obstacle avoidance, and the ability to drive at night.

The current state of Canada's NVGs reduces our ability to detect, recognize, and identify the enemy outside of their ability to locate our soldiers, based on new technologies available in the military marketplace. Unlike Canada's rigorous rules of engagement, enemy forces will engage perceived threats without positive identification. Next-generation NVGs with AR capabilities will increase the survivability (SHIELD) of our soldiers by providing an increased ability to avoid contact by manoeuvring outside the range of previously detected, but not alerted enemies. The current generation of NVGs has a distinct and visible profile when flipped up and not in use. Dubbed the "rhino mount", the NVGs are projected up and forward of the soldier, creating snag and bump hazards, but more importantly providing an easily recognized identification signature at night.

As part of User Knowledge Elicitation project (Angel and Ste-Croix, 2018), a study was undertaken in 2018 to support the Director of Land Requirements in understanding the current state-of-the-art, identifying high-level operational, technical, and usability requirements for future night vision capability. The study identified business needs for NVGs to regain the operational advantage in limited- to no-light conditions that has been eroded by the proliferation of such capabilities amongst other foreign military and non-military groups. The capabilities must enable soldiers to negotiate terrain while detecting, recognizing, and identifying targets for follow-on effects without increasing exposure to the threat opposing forces. As summarized by Angel and Ste-Croix (2018), the business outcomes for the Night Vision Systems Modernization (NVSM) project were as follows:

Acquire Sufficient Systems for Operations and Training

The NVSM project will acquire NVGs in the quantities required to support operations and training for both the regular and reserve forces. Focused training is essential to ensure success and overmatch when fighting at night.

Reduce Head-borne and Carried Loads

The NVSM project will ensure that all new NVGs procured will be lighter than the current in-service fleet of NVGs. This will reduce the head-borne load of a soldier as well as reduce the overall load carried by the soldier.

Improve Target Acquisition and Engagement

The NVSM project will increase the ability of users to acquire and engage targets by improving the performance of sensors in detecting targets at greater ranges than the current fleet of NVGs and in various environmental conditions. The goal is to overmatch insurgent and near-peer opponents such that operational success is ensured in all missions.

Improve Manoeuvre Abilities

The NVSM project will improve the ability of users to move through complex terrain. Movement in urban environments requires the ability to quickly cross danger areas, move over walls and structures, pass through windows, breach holes, subterranean tunnels, move up and down stairwells, manoeuvre through rubblized terrain, etc. Critical to individual manoeuvre is the ability to avoid trips, falls, collisions, drop-offs, etc. that may cause injuries and announces the presence of soldiers to the enemy. Night operations result in significantly more accidents and incidents than their daytime counterparts.

Improve Situational Awareness

The NVSM project will improve the soldiers' situational awareness. Improving the performance of sensors will allow soldiers to observe the battlefield at greater ranges through various environmental conditions. It will also provide soldiers with an improved ability to discern friendly, threat, or neutrals to avoid fratricide and aid with positive identification.

Increase Interoperability

The NVSM project will increase the interoperability of its equipment. A core mission of the Canadian Armed Forces is to contribute forces to NATO (North Atlantic Treaty Organization) and coalition efforts to deter and defeat adversaries. Therefore, it is critical for the Canadian Army to be interoperable with its allies in order to deliver meaningful combat capability and meet Government of Canada objectives. Many of Canada's allies have improved or are in the process of improving their night fighting capability to surpass that of its adversaries, including the integration and advancement of AR displays. The NVSM project will facilitate Canadian Army interoperability objectives through the delivery of NVGs that have comparable capabilities, training, employment techniques, and compatibility with those systems utilized by allied armies.

Increase Sustainability

The NVSM project will minimize the support and sustainment burden by providing newer systems that do not have to be refurbished as often through increased reliability and be quickly repairable.

As part of the User Knowledge Elicitation project, (Angel and Ste-Croix, 2018) potential performance issues with new State of the Art systems were identified and are detailed below:

Issue: Binocular NVG versus monocular NVG form factor. Although Canada's allies are currently procuring binocular NVGs (e.g., the AN/PVS-31A) the proposed cost to performance benefits of a binocular versus monocular NVG have not been empirically validated. Arguments such as improved depth perception, reduced eye fatigue, etc. need to be confirmed. Binocular systems may cost three times as much as a monocular system.

Issue: NVGs with white phosphorous displays versus NVGs with the traditional green phosphorous displays. Although Canada's allies are currently procuring NVGs with white phosphorous displays (e.g., the AN/PVS-31A in Australia's case and in the USMC's current NVG RFI) the proposed benefits of white phosphorous displays have not been empirically validated. Arguments such as improved target identification properties and reduced eye fatigue need to be confirmed. The cost for NVGs with white phosphorous displays is higher than equivalent systems with green phosphorous displays.

Issue: Efficacy of combining existing AN/PVS-14 NVG into a binocular design. It is possible to use a bridge device such that two MNVGs can be combined to form a binocular system. The efficacy of this approach needs to be confirmed.

Issue: Requirement that a flipped-up mount must be lower profile. One of the current issues with the in-service NVGs is that in the flipped-up position the NVGs come into contact with vehicle interiors and produce a recognizable profile. There are systems that reduce the profile of NVGs when flipped up.

Issue: Requirement that could allow the user to transition from a binocular system to a monocular system on demand. There are systems that allow users to use their NVG either as a binocular or monocular system. Certain tasks and activities may benefit from a system that allows users to easily switch between modes.

Issue: NVG weight and balance. Subject Matter Experts (Angel and Ste-Croix, 2018) reported that NVG balance on the helmet was a greater issue than NVG mass. The efficacy of mandating counterweights on the battery pack should be explored. The acceptability of currently fielded NVG masses should be explored.

Issue: NVG detection, recognition, and identification performance. The current in-service NVGs utilize Generation III Omnibus IV I^2 tubes. It is known that the purchase of Omnibus VII or state-of-the-art European tubes will improve soldier detection, recognition, and identification (DRI) performance. The DRI performance increase should be quantified to see if systems can meet the minimum requirements identified.

Issue: NVG mounting and adjustment system. The current mounting system has a large number of deficiencies. There are commercial systems that may offer improvements over the currently fielded mount.

Issue: Efficacy of requesting NVGs with fused thermal capabilities, which can include Shortwave Infrared (SWIR) or Long Wave Infrared (LWIR). Several of Canada's allies have fielded fused NVGs that combine imagery from LWIR thermal and I^2 sensors to augment the ability to detect targets at night. These capabilities have been identified by a number of specialists like reconnaissance personnel, pathfinders, snipers, etc. Given the current state of the art it is not known if these systems can actually meet specialist task requirements. The United States Marine Corps (USMC) has investigated the Enhanced Clip-on thermal imager (E-COTI) (http://www.optics1.com/vas.php#Enhanced_Clip-On_Thermal_Imager_(E-COTI)) as an add-on component to their binocular AN/PVS-31.

The USMC is also about to investigate whether the Enhanced Clip-on SWIR imager (E-COSI) (http://www.optics1.com/vas.php#Enhanced_Clip-On_Thermal_Imager_(E-COTI)) can provide a SWIR capability as an add-on component to their binocular AN/PVS-31. While the capability gap analysis (Angel and Ste-Croix, 2018) identified the need for covert lasing (using SWIR) and visualization, it was believed that this may be just a sniper specialist requirement. The ability to offer snipers this capability may warrant further investigation.

Issue: Efficacy of requesting NVGs with fused digital information capabilities. Several of Canada's allies have fielded NVGs that allow users to project AR command and control or navigation information into their NVG. These capabilities have been identified by a number of specialists like leaders and reconnaissance personnel. Given the current state of the art it is not known if these systems can actually meet specialist task requirements. Beyond research undertaken in the Soldiers Information Requirements Technology Demonstration project (SIREQ-TDP), and some subsequent DRDC projects, the CAF does not have significant experience with AR. The introduction of AR capabilities in soldier day and night vision systems is a major effort in the US and Europe.

1.1 Scope of this Report

The goals of this project were to assess the state of the art in augmented reality and fusion systems for use by soldiers, to research available commercial-of-the-shelf (COTS) and military-off-the-shelf (MOTS) systems, and to evaluate system capabilities and features against possible Canadian Army uses.

At first glance it may seem that AR and night vision fusion are two separate and distinct topics. This perception is likely reinforced by the clear separation of AR and night vision products in the commercial and military domains. The AR marketplace has grown out of virtual gaming, smart phone applications, and widely marketed attempts at commercial smart glasses (e.g., Google Glass) and more recent struggles with mixed reality goggles (e.g., Magic Leap). Military applications and developments for soldier-based AR have been ongoing for more than two decades with limited commercial success or widespread uptake in military ground applications. However, recent developments over the last few years in hardware and software technologies in many critical AR areas have created a significant resurgence in AR commercialization due to greatly improved portability, display capabilities, image quality, usability, data reach-back, artificial intelligence applications, reduced cost, and universal accessibility among widely used commercial Android and IOS platforms. These advances have reinvigorated interest, developments, products, and applications for ground military operations.

The evolution and adoption of night vision technologies has been ubiquitous and ongoing for over 60 years, largely in the domain of military or law enforcement. There is a limited commercial civilian marketplace for older night vision technologies (once permitted to transition to the marketplace). Soldier-worn I^2 technologies have progressed somewhat linearly, with each new decade producing a significant development in sensitivity, amplification, resolution, image quality, field of view, weight, and power management. Soldier thermal imaging capabilities, in the medium and long wavelength infra-red (IR) radiation spectrums, have followed a similar path but started about a decade later than I^2 systems. Fusion systems that combine the I^2 and IR imagery to the soldier in a single display, were prototyped in the early 2000s and began producing military commercial products for fielding in the 2009 timeframe (Richardson, 2019). Advances in fusion technologies have provided soldiers with smaller, lighter systems with more seamless integration of I^2 and IR imagery, easier control of fusion features and settings to adjust for different mission-related requirements, intelligent automated display image optimization during different lighting conditions, and the capability to wirelessly overlay other information. Advances continue in sensor resolution, field of view, sensitivity, colour night vision, and so on.

By this description of their respective developmental pathways and their places of employment, AR and night vision fusion would appear to be distinctly separate ecosystems. While this statement would have been accurate through much of the timeline of their respective developments, this is no longer the case. Figure 1 seeks to explore this point in more detail. This AR/Fusion capability matrix places AR on one axis and night vision on the other. The dimensions of each axis are based on incremental steps in technological capability. The AR continuum includes: no AR, information overlays, situated visualization, embedded virtual entities, and the capability to manipulate entities and use gestures as a control interface. Progressing along this continuum involves more AR technologies and more complexity. The night vision continuum includes: no night vision, image intensification (I^2) alone, thermal infra-red (IR) alone, and I^2/IR fusion. The lines joining each pair of eyeball icons represent the range of a given product on a given dimension.

As Figure 1 shows, there are a number of products on the night vision continuum that have no AR capabilities. Example systems provide a singular capability for I^2 or IR, and a fusion system that can be adjusted for I^2 alone, IR alone, or combine them in a fusion image. In recent years, however, commercial military developers (e.g. Safrans E-COTI) and military programs (e.g., the U.S. HUD program) have supplemented their night vision capabilities with AR information displays. These range from simple information overlays to dynamic navigation information overlays, to weapons systems integration, and integration with digital soldier systems like the U.S. Nett Warrior. In this way, night vision devices are migrating into AR devices.

Similarly, there are a number of commercial AR products that offer no night vision enhancement; in fact, the vast majority of commercial products don't. Example systems include AR-integrated smart phones and smart glasses, and mixed reality devices such as Microsoft's Hololens and Magic Leap, that all provide a range of capabilities along the AR continuum. However, several recent developments have begun to integrate AR systems with night vision capabilities. For example, ARA's ARC4 system can be integrated with an existing NVG by situating the ARC4 prismatic display in front of the night vision tube. In this way, AR devices are migrating into night vision devices.

Figure 1 uses a rectangle rather than a line to represent the U.S. IVAS (Integrated Visual Augmentation System) Capability Set 3 system. A two-year, $480 million (USD) development program charged Microsoft to work with U.S. Army laboratories to create a fully integrated AR and night vision capable headset for dismounted warfighters, based on the Microsoft Hololens product. As the matrix shows, the IVAS Capability Set 3 provides the full range on the AR continuum and up to I2 and IR (switchable) on the night vision continuum. Capability Set 4, the final and current stage of development, promises to deliver an I^2/IR fusion capability in the next few months - thereby fully covering off capabilities on both continua. IVAS sets a new baseline for the discussion of AR and fusion by merging both capability sets into one soldier goggle system.

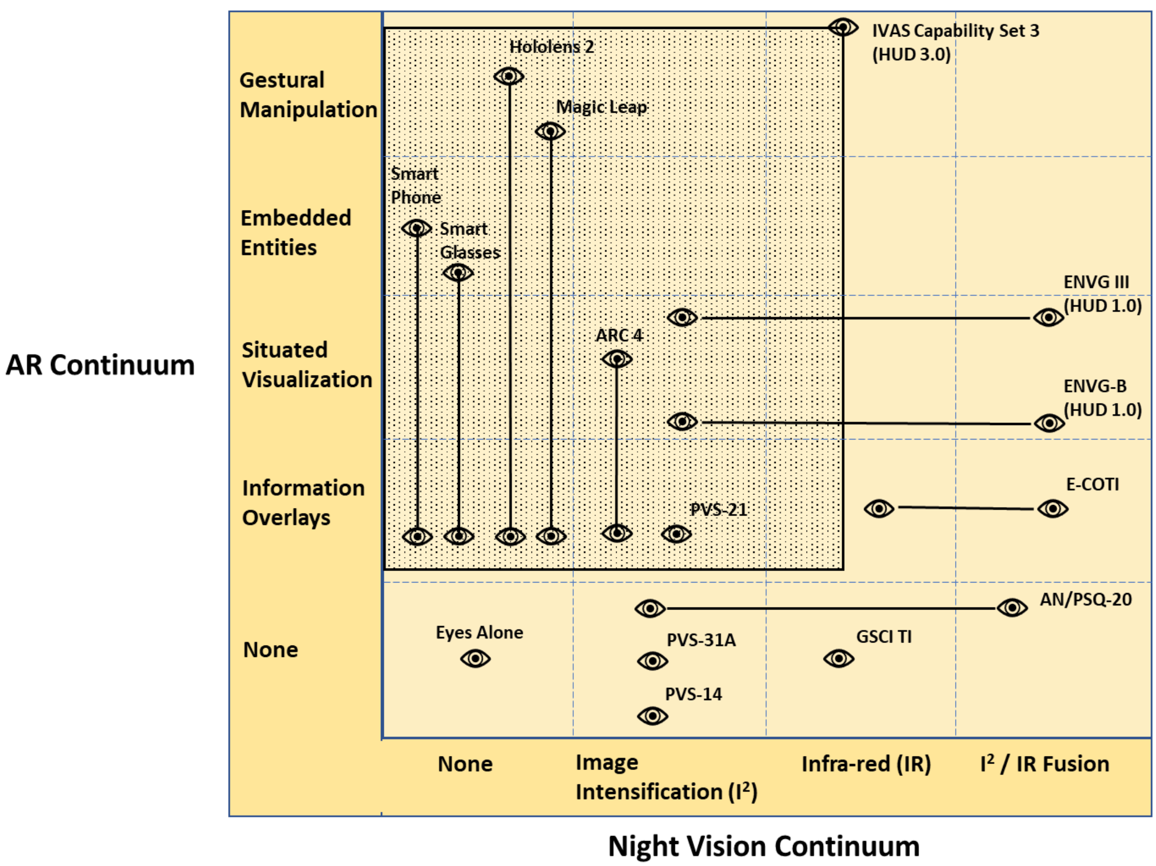

Figure 1: AR and Night Vision Fusion Matrix (Image copyright HSI®)

1.2 Structure of the Report

We noted in the previous section that AR and night vision fusion systems are merging. However, we elected to organize this report into separate sections for each of the AR and night vision fusion areas to keep common technologies and developments together for association and comprehensibility.

The content of this report is organized as follows:

1. What is Augmented Reality? AR definitions are provided, and the continuum of extended reality is discussed.

2. AR Capabilities: AR capabilities are described in terms of the different types of functionality provided to the user with examples from civilian applications. Enabling technologies are described and discussed.

3. AR for Soldiers: The AR use cases are then reviewed and discussed in the context of common soldiering tasks and activities. Infantry examples of AR use are provided.

4. Military AR Programs: Several past and present ground Army AR programs are described.

5. AR Systems: The hardware, displays, and software technologies within the worlds of VR, AR, MR, and XR are described in more detail using developmental, Commercial-Off-The-Shelf (COTS) and Military-Off-The-Shelf (MOTS) systems.

6. Introduction to fused night vision system sensors – An introduction to low light sensor technology as well as image intensification systems is provided. An introduction to long wave infra-red technology is also provided.

7. Fusion Systems: Major fusion programs and product lines are presented.

8. Fusion Research Trends: Two novel research thrusts are presented which may have implications on AR and sensor fusion in the future.

1.3 Abbreviations

2D	Two Dimensions
3D	Three Dimensions
6DOF	6 Degrees-Of-Freedom
ADF	Australian Defence Force
A GPS	Assisted GPS
AI	Artificial Intelligence
AITT	Augmented Immersive Team Training
AMLCD	Active Matrix Liquid Crystal Display
ANVG	Advanced Night Vision Goggle
ANVIS	Aviators Night Vision Imaging System
AO	Area Of Operations
AR	Augmented Reality

ARDST	Army's Augmented Reality Dismounted Soldier Training
ARES	Augmented Reality Sand Table
ARIELE	Singapore's Army Individual Eco-Lightweight Equipment
ATR	Automatic Or Aided Target Recognition
BAE	British Aerospace
BST	Barium Strontium Titanate
BsTFA	Broad Spectrum Thin Film Array
C3ARESYS	Combat Casualty Care Augmented Reality Intelligent Training System
C5I	Command, Control, Communications, Computers, Intelligence, And Interoperability
CA	Canadian Army
CAF	Canadian Armed Forces
CANSOFCOM	Canadian Special Operations Forces Command
CCD	Charge Coupled Device
CCIR	Consultative Committee on International Radio
CECOM	Us Army's Communications-Electronics Command
CHEUD	Conformal Enhanced Heads-Up Display
CISTI	Canada Institute For Scientific And Technical Information
CMOS	Complementary Metal-Oxide-Semiconductor
COA	Courses Of Action
CoM	Center Of Mass
C2	Command And Control
COTI	Clip-On Thermal Imager
COTS	Commercial Off The Shelf
CPU	Central Processing Unit
DAGR	Defense Advanced Global Positioning System Receiver
DND	Department Of National Defence
DRI	Detection, Recognition And Identification
DTED	Digital Terrain Elevation Data
DSTO	Defence Scientific And Technical Organization
EBCMOS	Electron Bombarded CMOS
E-COSI	Enhanced Clip On SWIR Imager
E-COTI	Enhanced Clip On Thermal Imager
EMCCD	Electron Multiplying CCD
ENMATS	Engineered Materials
ENVG	Enhanced Night Vision Goggle
FOM	Figure Of Merit
FOV	Field Of View
FPA	Focal Plane Array
FPS	Frames Per Second

FSAR	Future Small Arms Requirements
FWS	Family Of Weapon Sights
FWS-CS	Family Of Weapon Sights–Crew Served
GaAs	Gallium Arsenide
GaAsP	Gallium Arsenide Phosphide
GIS	Geographic Information Systems
GPNVG	Ground Panoramic Night Vision Goggle
GPS	Global Positioning System
GPX	GPS eXchange format
HD	High Definition
HF	Human Factors
HDMI	High-Definition Multimedia Interface
HMD	Helmet-Mounted Display
HSI	Humansystems Inc.
HUD	Heads Up Display
HUNTR	Heads-Up Navigation, Tracking, And Reporting
ICCD	Intensified CCD
ICMOS	Intensified CMOS
I2 / I^2	Image Intensified
IMU	Inertial Measurement Unit
InGaAs / InP	Indium Gallium Arsenide / Indium Phosphide
InSb	Indium Antimonide
IPD	Interpupillary Distance
IR	Infrared
ITARS	International Traffic in Arms Regulations
ITN	The Integrated Tactical Network
IVAS	Integrated Visual Augmentation System
ISW	Intra-Soldier Wireless
KML	Keyhole Markup Language
LAD	Laser Aiming Device
LADAR	Laser Detection And Ranging
LCOS	Liquid Crystal On Silicon
LCD	Liquid Crystal Diode
LED	Light Emitting Diode
LEOS	Litton Electro-Optical Systems
LIDAR	Light Detection And Ranging
LLL	Low Light Level
LLLT	Low Light Level Cameras
LLLTV	Low Level Light Television
LWIR	Long Wave Infrared
MCP	Microchannel Plate

MEMS	Micro-Electromechanical System
Mercad, MCT	Mercury Cadmium Telluride
MNVG	Monocular Night Vision Goggle
MOTS	Military Off The Shelf
MR	Mixed Reality
MWIR	Medium Wave Infrared
NFE	Night Fighting Equipment
NIR	Near Infrared
NTIS	National Technical Information Service
NVD	Night Vision Device
NVESD	Night Vision and Electronic Sensors Directorate
NVG	Night Vision Goggle
NVS	Night Vision System
OLED	Organic Light-Emitting Diode
ONR	Office Of Naval Research
OP	Observation Post
OS	Operating System
PbS	Lead Sulfide
PbS	Lead Selenide
PMMW	Passive Millimetre Wavelength
PPE	Personal Protective Equipment
PtSi	Platinum Silicide
QWIP	Quantum Well Infrared Photo Detector
RGB	Red Green And Blue
ROIC	Read Out Integrated Circuit
RTA	Rapid Target Acquisition
SA	Scientific Authority
SBUC	Scene-Based Non-Uniformity Correction
sCMOS	Scientific Grade CMOS
SENVG	Spiral Enhanced ENVG
SHADES	Shielded Advanced Eyewear System
SDK	Software Development Kit
SIREQ-TDP	Soldier Information Requirements -Technology Demonstration Program
SLAM	Simultaneous Localization And Mapping
SME	Subject Matter Expert
SNUC	Static Non-Uniformity Correction
SNR	Signal-to-Noise Ratio
SOAR	State Of The Art Review
SOW	Statement Of Work
SSE	Strong Secure Engaged

STE	Synthetic Training Environment
STP	Soldier Touch Point
SVGA	Super Video Graphics Array
SWIR	Short Wave Infrared
SXGA	Super XGA
TAK	Tactical Assault Kit
TAR	Tactical Augmented Reality
TI	Thermal Imaging
TRACER	Tactical Reconfigurable Artificial Combat Enhanced Reality
UHD TV	Ultra High Definition Television
ULTRA-Vis	Urban, Leader, Tactical, Response, Awareness - Visualization
USAARL	United States Army Aeromedical Research Lab
USMC	United States Marine Corps
UAV	Unmanned Aerial Vehicle
USARPAC	United States Army Pacific
UV	Ultraviolet
UWB	Ultra Wide Band
VGA	Video Graphics Array
VLWIR	Very Long Wave Infrared
VOx	Vanadium Oxide
VR	Virtual Reality
WFC	Wave Front Coding
WUXGA	Widescreen ultra extended graphics array
WWW	World Wide Web
XR	Extended Reality

2. Method

The following methodology was used in this technology review.

2.1 Keywords

The first step of the AR and fused NVG technology review was to conduct a search for current and emerging fusion technologies. Drawing on resident Humansystems® experience and expertise in AR and NFE, a keyword list was created for the search, with the intent to be thorough yet efficient. Table 1 shows the keyword list for the search. The results were screened by knowledgeable HSI® consultants, who have participated in empirical studies of NVGs, to ensure relevance of results and remove duplication.

The keywords allowed pairing of non-overlapping keywords for the search. Keywords were combined in any way that yielded a productive number of references (i.e., not too large a number to inspect or too few to provide reasonable coverage of the topic). The "core concept" category was included for two reasons. First, the keywords in that category focused the search on topics directly.

Table 1: Augmented Reality Keyword List

Core Concept	Military AR
Augmented Reality AR MR XR HUD HMD Commercial products AR sensors AR displays AR software	Soldier AR Military AR Night vision AR IVAS ARC4 TAR National programs by nation

Table 2: Fused Night Vision Keyword List

Core Concept	Night vision +	Night fighting+
Night Vision Fused	Goggles Devices Thermal IR Image intensification Color Colour Equipment NVG NVS	Goggles Systems

2.2 Databases

Searches of the following databases and sources were conducted:

- National Technical Information Service (NTIS)
- Canada Institute for Scientific and Technical Information (CISTI)
- HSI® Library
- World Wide Web (WWW) – Google search and Google Scholar

NTIS is an agency of the U.S. Department of Commerce's Technology Administration. It is the official source for government sponsored U.S. and worldwide scientific, technical, engineering, and business-related information. The database contains almost three million titles, including 370,000 technical reports from U.S. government research. The information in the database is gathered from U.S. government agencies and government agencies of countries around the world.

CISTI houses a comprehensive collection of publications in science, technology, and medicine. It contains over 50,000 serial titles and 600,000 books, reports, and conference proceedings from around the world.

2.3 The Search

We searched databases by applying core concepts in combination with keywords. For example, the core concept of "Night Vision" would be combined with the keyword "Goggles". The results of this pairing were used to determine whether the combination needed to be redefined to be more or less inclusive. If a combination yielded too many references, we systematically added keywords to focus the search. If the combination yielded too few references, we dropped one of the keywords from the combination or replace one keyword with a related term. Combinations of appropriate keywords were then examined.

Another source of potentially relevant references was the articles held in the internal HSI library. We identified articles cited in EndNote reference lists and obtained them for the review on the basis of their potential relevance to NVGs and AR.

A significant number of papers and articles were identified during the preliminary search. 1,520,000 hits were identified on the World Wide Web using the term "Fused Night Vision Goggles". Advanced search methods were then used to specify a combination of words appearing together on a page to eliminate unrelated hits and the search was limited to the past 10 years. This approach still identified a significant number of articles, as expected; some databases were technical in nature while others focused on human performance.

3. Augmented Reality

3.1 What is Augmented Reality?

Merriam-Webster defines augmented reality as "an enhanced version of reality created by the use of technology to overlay digital information on an image of something being viewed through a device" (Merriam-Webster, 2021).

While strictly correct, this definition fails to address the breadth and complexity of the augmented reality capability. Azuma (1997) defined AR as allowing the user to see the real world, with virtual objects superimposed upon or composited with the real world, thereby supplementing, rather than replacing, reality as in the case of virtual reality. He noted that AR systems typically have three characteristics:

1. Combines real and virtual.
2. interactive in real time.
3. registered in three dimensions.

Milgram (1994) suggested that a continuum exists between full reality and full virtuality (Figure 2) and is represented by various technological options that vary the mixing of the real and the virtual in this space, including augmented reality and virtuality. Mixed reality (MR) selects and combines image content from different parts of the range. Extended reality or XR uses all technologies in this spectrum.

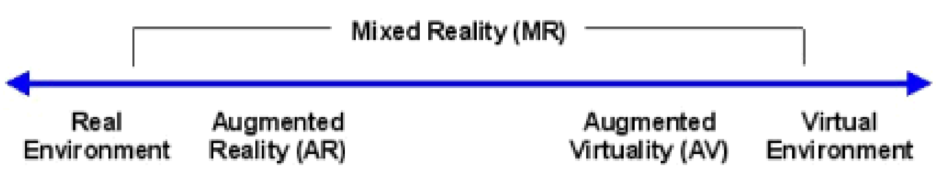

Figure 2: Full Reality to Virtuality Continuum (Image copyright Milgram, Takemura, Utsumi & Kishino, 1994)

The different classifications along this continuum, in the context of head-worn or hand-held systems, are depicted in Figure 3 and described below.

Virtual Reality immerses the viewer in a totally artificial environment that is disconnected from the real physical world around them. Augmented reality overlays digital content on the viewer's real-world view.

Mixed reality integrates digital content into the viewer's real-world view in a way that realistically relates this content to the physical scene (e.g. digital content can relate to surfaces and behave as though there was gravity, avoid physical obstacles in the real space, and represent the visual obstruction of real objects when virtual objects go under or behind them). Virtual objects can also be manipulated through gestural control in mixed reality so that the viewer can interact with and control the virtual content.

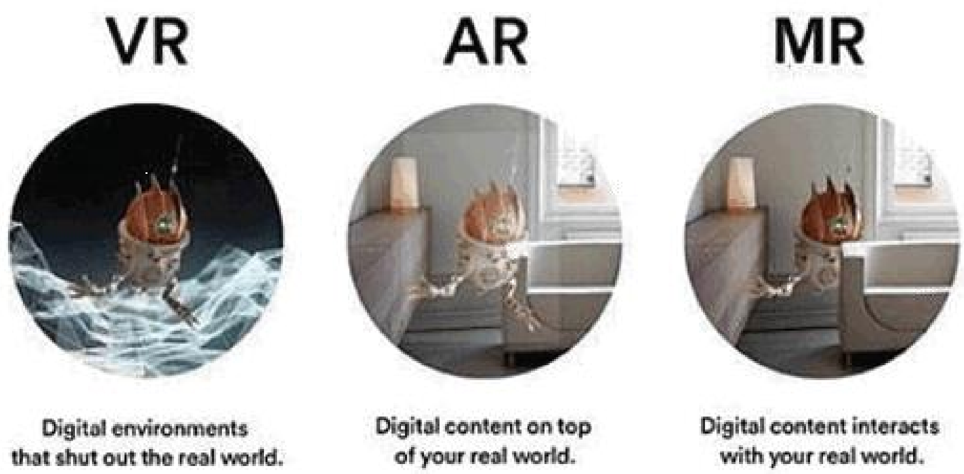

Figure 3: VR vs AR vs MR (Image copyright LivinSpaces, 2021)

This primer will largely focus on the AR and MR aspects of the XR continuum in an operational dismounted soldier context. For the sake of simplicity, both AR and MR technologies will be referred to as AR in this report.

3.2 AR Capabilities

AR technologies provide a unique set of functional capabilities to the wearer. These capabilities are introduced in the following sections according to the following organization:

1. Information Overlay
2. Situated Visualization
3. Embedded Virtual Entities
4. Gestural Interface and Virtual Object Manipulation

3.2.1 Information Overlay

In the simplest form of AR, digital information can be presented in the wearer's field of view as an overlay to the real-world scene. This intention is to enable the wearer to consult task-relevant information or receive alerts/notifications while retaining the view of the real-world scene.

This display of information is not spatially aligned nor registered with features or objects in the viewer's scene but rather serves as a means to display information without the viewer needing to look away from the scene to view a separate source (e.g. a digital display or paper source). As an example, Figure 4 demonstrated the display of simple date/time information in a pair of smart glasses.

Figure 4: Simple Smart Glasses Display (Image copyright North, 2019)

Figure 5 demonstrates a more complex display of technical information (equipment status) for a particular manufacturing robot. Again, this display of information is not anchored to anything in the scene but does provide the wearer with situational information about the equipment they are inspecting.

Figure 5: Complex Display of Equipment Status (Image copyright StudiousGuy, 2021)

In both examples, the technologies required to achieve this type of augmented reality are limited to integrating the display of information into the wearer's view of the real world.

Figure 6: Night Vision Information Display (Image copyright Steiner, 2021B)

Steiner Defence's Conformal Enhanced Heads-Up Display (CEHUD) introduces SVGA/VGA images on an SVGA OLED display positioned in the visual pathway to one eye in the AN/PVS-21 night vision goggle.

Overlaying this information over the real-world is typically achieved at the eye by either displaying a micro-display through a waveguide or by projecting a laser-generated image on a holographic combiner. These methods are each described in turn.

<u>Waveguide Technology:</u> In each of the examples above, the image being displayed to the viewer's eye is first projected from a light-engine image generator (e.g. micro-display or laser-based virtual retinal display with a microelectromechanical System (MEMS) mirror to "paint" the image) into an optical grating that redirects the image down the waveguide until it hits the output grating in the middle of the viewer's field of view, where it is redirected again off of the diffractive or reflective waveguide optics to the viewer's eye (Figure 7). The viewer combines this image with their real-world view of the scene through the largely transparent optical grating. Figure 8 shows a commercial version of this concept in the Lumis 760p Light-guide Optical Element waveguide technology.

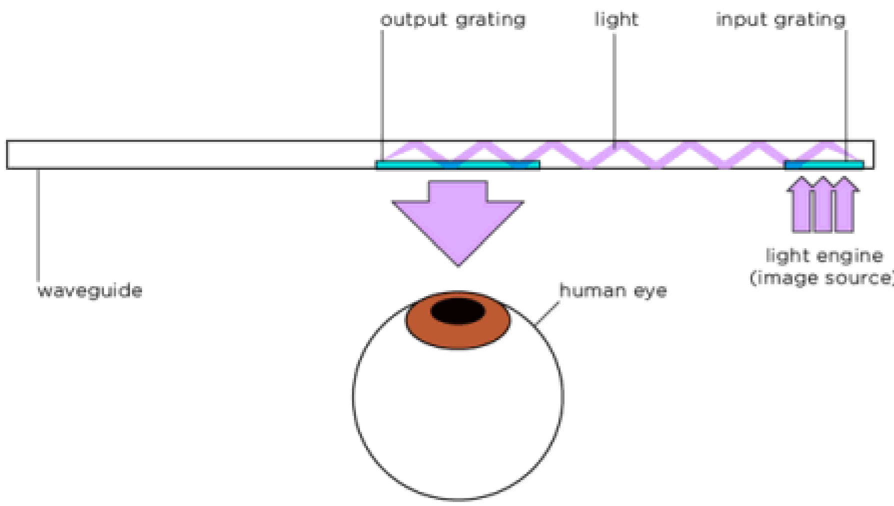

Figure 7: Example Waveguide Optic (Image copyright Grayson, 2019)

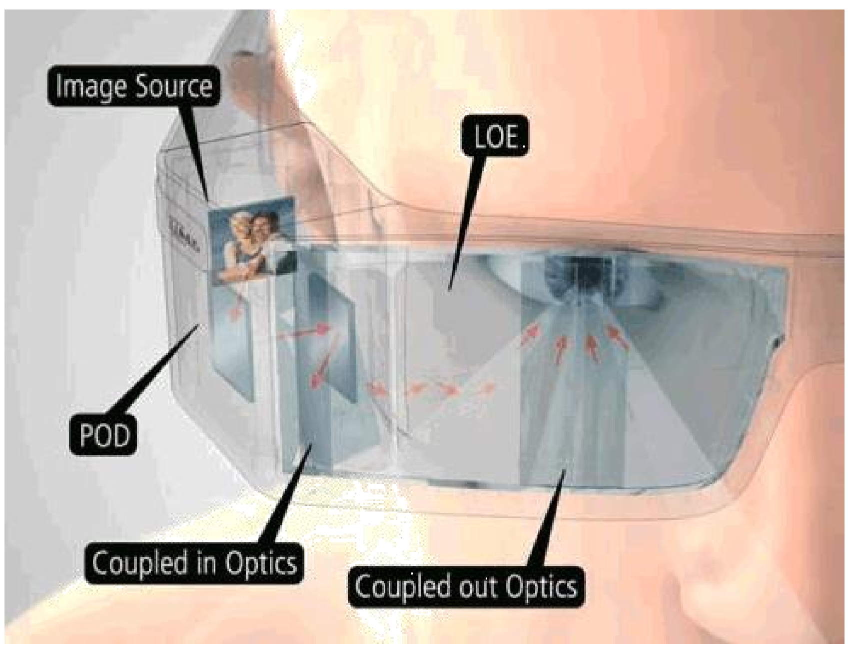

Figure 8: Lumux Waveguide Example (Image copyright Lang, 2012)

Laser/Holographic Combiner Technology: This method projects the image using a retinal laser to a high-speed MEMS mirror to "paint" each pixel from the image on a holographic combiner (micro-mirrors holographically etched into the lens) where it is redirected to the viewer's eye (Figure 9).

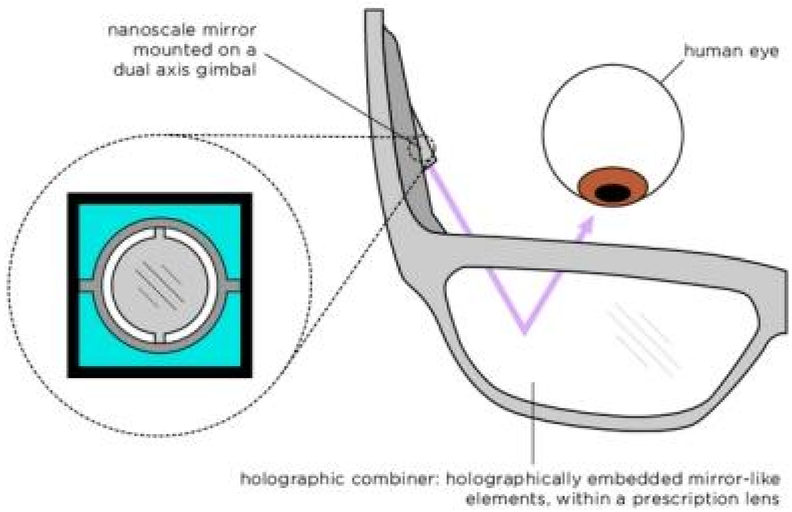

Figure 9: Laser/Holographic Combiner (Image copyright Grayson, 2019)

While these methods of overlaying information onto real-world scenes are effective, and widely used in most commercial AR systems, they are not without challenges.

1. Ambient Lighting Conditions: Light from the real-world scene shares the same optical pathway to the eye as the waveguide image from the optical image generator. This "sharing" can result in a mismatch when ambient lighting conditions are particularly bright, and the brightness of the optical image generator is insufficient to be readable over the real-world image. To address this challenge in day-time use, most commercial AR systems employ a tinted, darkened lens to improve AR readability. This tends to be much less of an issue in night vision systems employing these technologies to overlay information since the real-world background is darker.

It is generally accepted that the solution to viewing AR information in bright ambient light is not to increase the brightness of the AR imagery, because this requires too much power. U.S. Army DEVCOM is exploring the use of low contrast dimming (AUGANIX, 2021) to improve readability in bright conditions.

2. Field of View: One of the challenges of waveguide AR systems remains Field of View (FOV), which limits how much of the real-world scene can be overlaid with AR information. Many commercial AR glasses only have an FOV of 15-20 degrees, requiring the wearer to use additional head scanning to observe AR information in the real-world scene. Higher-end MR eyewear has significantly larger FOVs (Figure 10) but only provides a small display area relative to the available natural field of view (Figure 11). Commercial developments are ongoing to expand FOV with some already claiming they will achieve 150 degree displays.

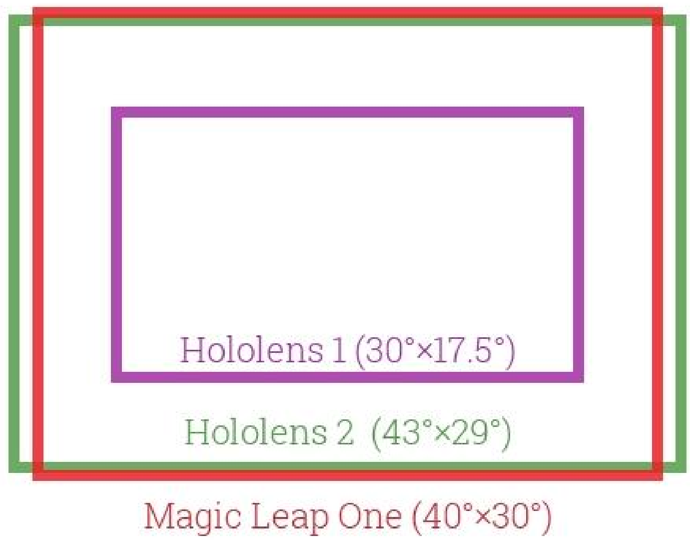

Figure 10: FOV of Different MR Displays (Image copyright Heaney, 2019)

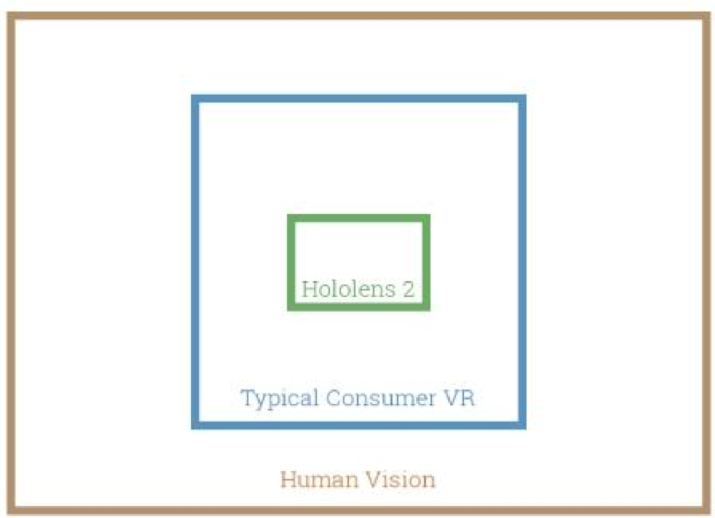

Figure 11: Display FOVs relative to Human Vision FOV (Image copyright Heaney, 2019)

An alternative technology to overlaying information into the optical pathway with a waveguide or prism is the video see-through display. With this technology the real-world image is captured by an external camera mounted on the head and the image is displayed to the eye. While this approach may be better for managing ambient lighting problems and optimizing the digital information overlay, it does tend to suffer from parallax and distortion issues because the camera(s) are offset relative to the viewer's normal line of sight. As well, the cameras can limit the FOV.

3.2.2 Situated Visualization

Beyond information overlay, a second functional capability for AR is situated visualization. In situated visualization information is overlaid in a manner that is locationally or positionally anchored in the scene. These overlays can be used to indicate key locations in a street or vista, route lines and directions, component parts labels, functions, animations, etc.

Figure 12 demonstrates a smart phone with an AR overlay of shop types and ratings according to their actual locations in the scene and distance from the viewer's location.

Figure 12: Smart Phone Streetscape AR (Image copyright Chen, 2018)

Figure 13 demonstrates a driving navigation application that places navigational cues (e.g., arrows, colours, chevrons, street names, embedded bird's-eye view) on the driver's view of the scene.

Figure 13: Driver's AR Display (Image copyright Matney, 2018)

In both examples the AR system must be accurately geo-registered to the location and to the scene being viewed.

In Figure 14 below, the user is observing a real-world pump and a virtual overlay of its internal components is shown on a tablet display. The user can walk around the pump and view the contents of the pump from different angles and develop a better understanding of how the surface geometry of the pump relates to the underlying content parts. This type of AR application requires two important technological capabilities: tracking and registration. Tracking is a form of dynamic sensing of a real-world view to determine the position and orientation of the AR display relative to real-world objects in real time (Schmalstieg, 2016). Registration refers to the alignment of coordinate systems between virtual overlays and the real world.

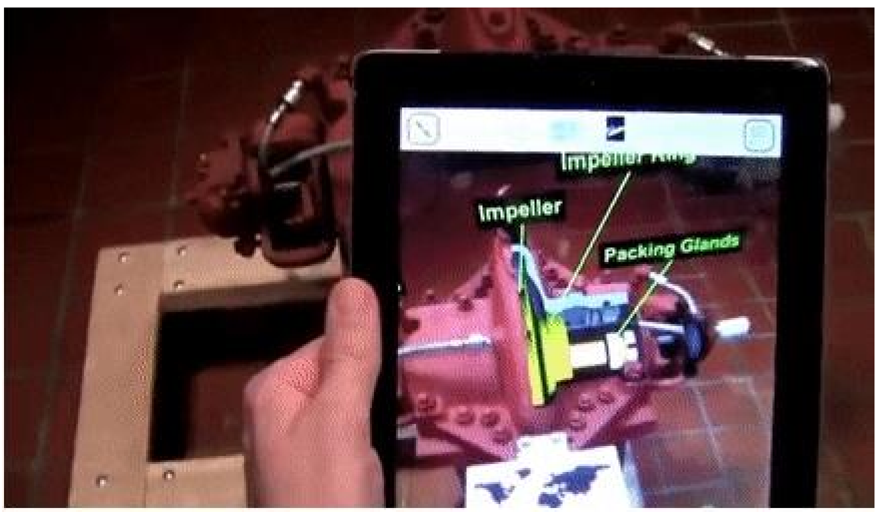

Figure 14: Example AR Registration to Equipment (Image copyright Studious Guy, 2021)

Tracking and registration in AR can take different forms, and require different technologies, depending on the nature of the object or scene and the intended AR enhancement. Fiducial markers are high contrast geometric shapes (examples are shown in Figure 15). These can be used for recognition, tracking, and registration, since the marker indicates the item type, distance, and orientation of the real-world object so that the AR system can generate an appropriately positioned, sized, and oriented AR overlay. Tracking and registration are continuously and dynamically updated to accommodate the viewer's position or orientation changes.

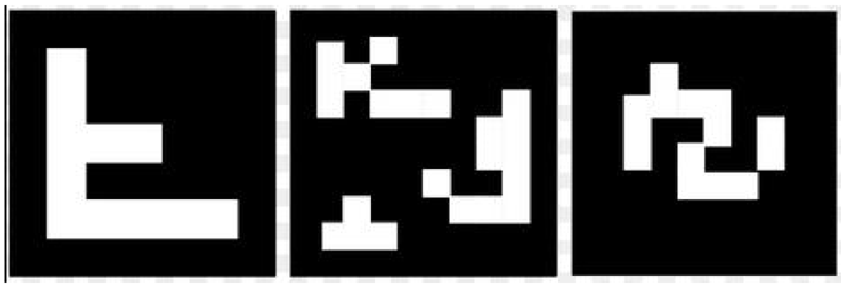

Figure 15: Fiducial markers

In the absence of markers, AR can also employ model-based tracking using databases of known 3D objects and scanning of the real-world scene using edge detection (Amin, 2015). Figure 16 below demonstrates a scene where AR overlays are positioned over components of an industrial machine to support maintenance. In this markerless example, the AR device scans and identifies the objects in the scene, tracks the position of those objects as the viewer manipulates the tablet and continuously registers the position of the information overlays.

Figure 16: Markerless AR Example (Image copyright Manufacturing Business Technology, 2019)

In an outdoor environment, the scene is often too complex to rely on marker or markerless tracking alone. In these cases, multi-sensor fusion and optical tracking, with potentially large terrain and object databases (e.g. building facades, statues, unique structures), are combined to achieve both gross and fine AR registrations (Schmalstieg, 2016). Common technologies (including GPS for location, magnetometers and gyroscopes for orientation, and linear accelerometers for movement from a known position) are used to locate the viewer and determine the facing direction (azimuth) and camera pose (attitude) to provide a gross registration with the real world. These technologies are combined with software algorithms for simultaneous localization and mapping (SLAM) to achieve suitable AR registration. Camera vision technologies can be fused with these technologies to provide a finer, more accurate registration of the AR coordinate system with the real-world coordinate system. In open terrain, camera vision can be used to observe terrain features and match these to known terrain databases. In urban terrain, camera imagery can be matched to known geometry and images from ubiquitous geographic information systems (GIS), such as Google Maps and OpenStreetMap to improve the accuracy and precision of AR overlay registrations.

3.2.3 Embedded Virtual Entities

The capability to realistically embed virtual objects into a real-world scene takes AR to another level. We have discussed the capability of relating virtual overlays to know objects and known locations, but those examples are related specifically to an object or defined scene. To be ubiquitous and effective, AR information needs to be able to be integrated into an unknown scene with unknown objects.

Examples include 'dropping' a 3D model of Mount Everest on a desktop (Figure 17) or placing virtual furniture from the IKEA catalogue into the scene of your home (Figure 18, IKEA PLACE app, 2019) or playing Pokémon Go outdoors (Figure 19). Realistic virtual/real world integration requires these overlays to be situated in a realistic way, not just floating over the real scene. To achieve this match requires technology that can map the surfaces in the scene with sufficient speed and accuracy to ensure a dynamic matching coordinate system of real and AR surfaces. This is traditionally achieved through computer camera vision for RGB (Red Green Blue) depth sensing and point-cloud generation, cameras with image and surface detection and tracking, light estimation mapping, and software to make sense of it all (Leon, 2018).

Figure 17: 3D Model on Desktop (Image copyright Noah_A_S, 2017)

Figure 18: IKEA PLACE AR (Image copyright IKEA, 2021)

Figure 19: Pokemon GO (Image copyright Gorden, 2018)

Technologies are continuing to improve the integration of virtual entities into real world scenes in both hardware and software. In addition to these camera technologies, Light Detection and Ranging (LIDAR) sensors are emerging. The size and cost of these sensors has made them suitable for smartphone, tablet, and head-worn AR systems. LIDAR introduces higher speed, accuracy, and stability to 3D scanning, providing a more visually compelling integration of entities into the real-world scene through real object occlusion. Software tools have also been advancing to take advantage of improved scanning by integrating artificial intelligence with 3D deep learning for real-time object detection and 3D shape prediction. Mixed Reality applications depend on these advances to achieve realistic visual integration and interaction in the scene environment.

Figure 20 demonstrates a first-person shooter game from Magic Leap where virtual alien entities are shown to maneuver through an office space to assault the viewer's position. Real physical structures and objects in the room obstruct the view of the virtual alien entity, so the entity can move behind a desk and its body will be seen above and below the desk but not in those regions that the desk occludes. The alien entity can seek cover behind low walls and file cabinets. This creates the illusion that the alien entity is actually moving through the room.

Figure 20: Embedded Virtual 1st Person Shooter Game (Image copyright Magic Leap, 2015)

3.2.4 Gestural Interface and Virtual Object Manipulation

Early AR systems employed hand-held controllers and pinch gloves to be able to interact in a limited way with virtual entities in the visual field. While this offered some functionality, the means were coarse, simple, and could require the viewer to look away from the scene to manipulate another device. Using depth-sensing camera technology and SLAM to track the position and orientation of the hands and digits, it is now possible for AR systems to sense dual hand gestures and relate those to discrete instruction about operation or interactions with virtual entities (Kim, Choi, Park, & Lee, 2019) (Figure 21).

Figure 21: AR Hand Gestures (Images copyright Kim, Choi, Park & Lee, 2019)

In mixed reality environments embedded virtual entities can be manipulated with hand gestures and actions. Virtual objects can be moved, sized, orientated and, in some cases, activated (see Figure 22). Control interfaces (e.g., buttons, knobs, wheels) can be included as virtual objects for the viewer to manipulate to control the information seen, a simulation performed, or to alter the parameters of a model being observed. A good example of this capability can be seen in a live stage demonstration of HoloLens 2 (https://www.youtube.com/watch?v=uIHPPtPBgHk&t=27s).

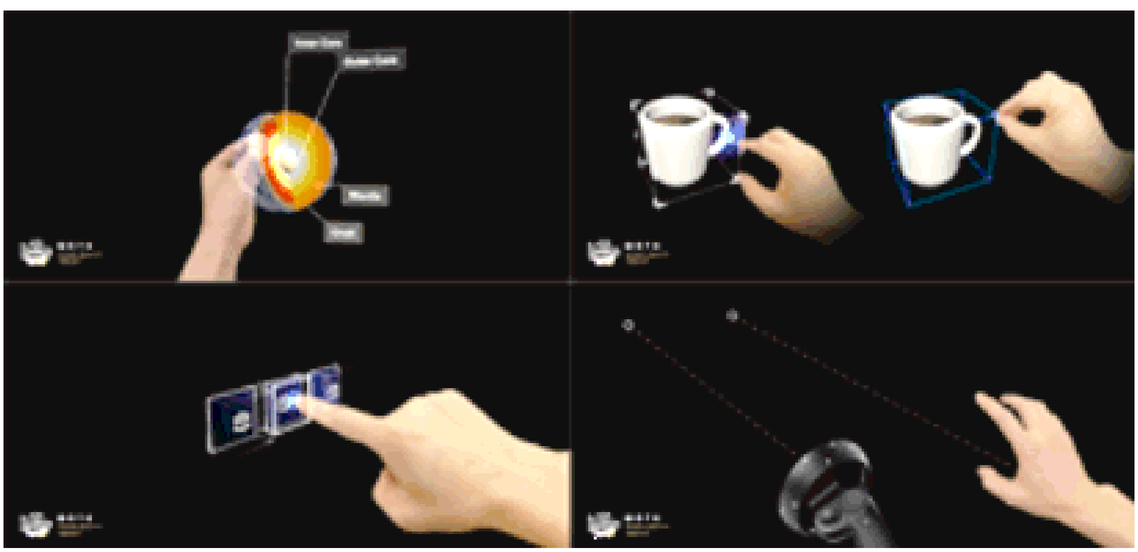

Figure 22: Object Manipulation in AR (Images copyright Park, 2019)

3.3 Soldier AR Uses

3.3.1 Access Information

See-through helmet mounted displays with AR capabilities enable a soldier to consult information while observing a real-world scene, without the need to look away from the scene to consult other devices or paper matter. Information content could include maps, operations orders, photographs of high value targets, mission plans, radio codes, etc.

Figure 23: Soldier Information Display (Image copyright ARA, 2021)

3.3.2 Planning and Briefing

The use of AR embedded entities enables AR users to collectively view mission-relevant information. The example below (Figure 24) demonstrates how a group of mission planners can view the same 3D terrain maps with situated entities. Given that the embedded entity (3D map) is software generated, planners can employ a wide range of planning tools to improve their terrain awareness (e.g. intervisibility plots from expected enemy positions) and mission timings through the use of visual simulations of alternative mission Courses of Action (COAs). The map can be manipulated to view different perspectives, or the planners can walk around the map to get different views. Entities can be annotated using drawing tools (e.g., phase lines, unit symbols) and animations can be created to support coordination planning.

Figure 24: Mission Planning with AR (Image copyright ABC NewsLive, 2020)

Airbus Defence and Space unit published a video demonstrating the capabilities of its Holographic Tactical Sandbox tool for augmented reality headsets (Figure 25). Designed to work with the Airbus Fortion TacticalC2 application (Airbus, 2021), the software enables military officers and personnel to view 3D maps of battlefield locations placed in their physical space using head-mounted displays. The 3D maps can be used for mission planning, mission rehearsal, and training exercises. Using gesture inputs, users can rotate, annotate, manipulate, and interact with the maps, allowing them to view the terrain from various perspectives and identify tactical advantages in advance of the real-world action.

Figure 25: AR Sandbox Display (Image copyright Palladino, 2019)

Collaboration does not require all AR-enabled planners to be in the same room. Figure 26 shows how both present and remote AR users can collaborate over the same map and mission plan as though they were all in the same room.

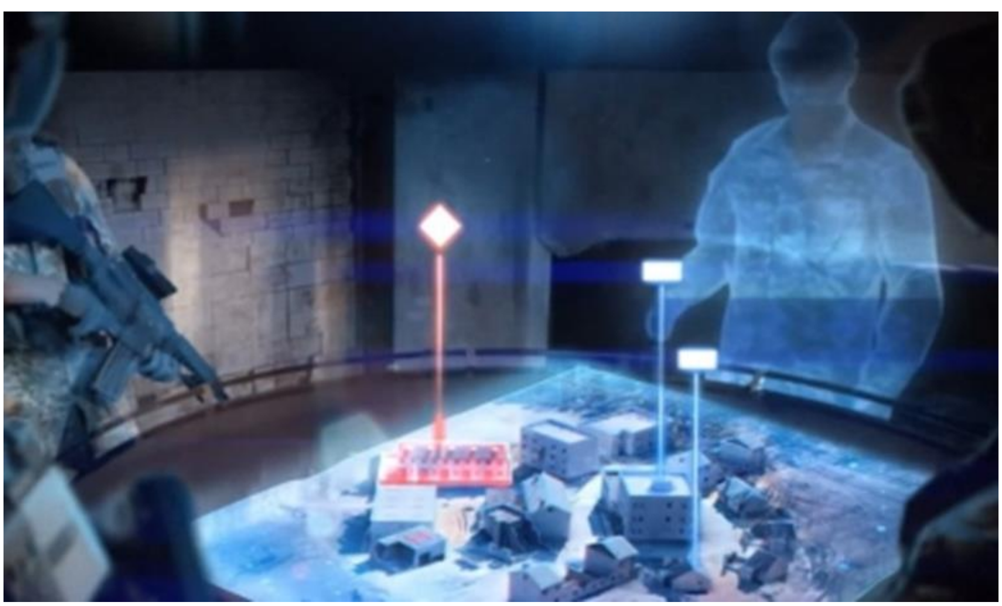

Figure 26: Remote Planning Collaboration Display (Image copyright ABC NewsLive, 2020)

3.3.3 Navigation

Navigation involves wayfinding and terrain visualization functions.

3.3.3.1 Wayfinding

In the early 2000s, Canada's Soldiers Information Requirements -Technology Demonstration (SIREQ-TD) program investigated the use of helmet-mounted displays for dismounted infantry operations. This research included both occluded and see-through AR displays. As shown in Figure 27, the technology to achieve this capability was large, bulky, and cumbersome, but it was effective at determining how displayed digital information could enhance navigation and wayfinding performance over conventional means, especially at night (Kumagai, 2005).

Testing was undertaken in both day and night conditions (Figure 27) using the same range of augmented information overlays (Figure 28) to indicate direction, and distance, to the next waypoint.

Figure 27: SIREQ Day and Night AR Testing (Image copyright Humansystems® Inc.)

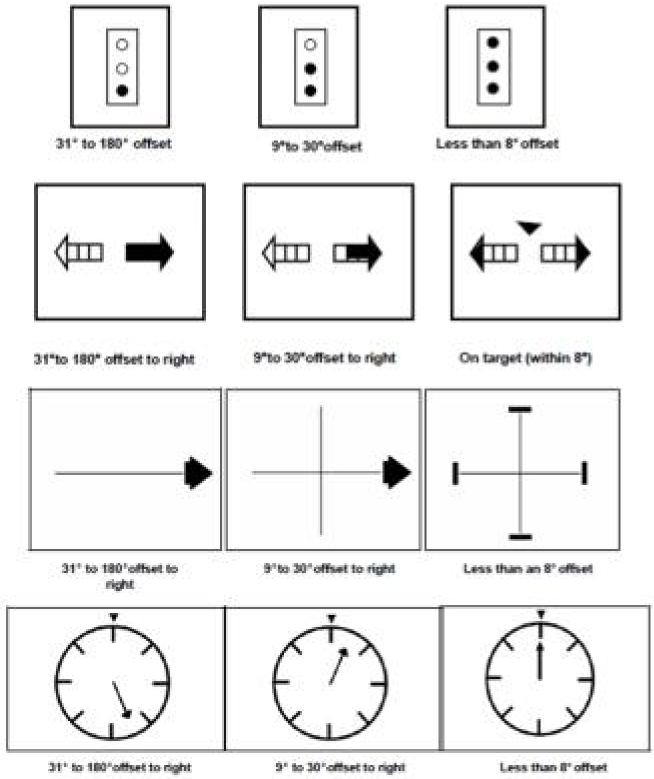

Figure 28: Directional AR Displays (Image copyright Humansystems® Inc.)

Since the early 2000's, the use of directional and distance cues in commercial and military display systems has become ubiquitous in navigation applications as the benefits have been clearly proven in terms of speed, accuracy, and error reduction (Kumagai, 2005, Colbert and Tack, 2005). Soldiers favour the see-through augmented reality displays, over handheld and look-down displays, because they can maintain their view of the real-world scene while receiving wayfinding cues in their field of view. Since soldiers typically prefer to 'shoot a line' (i.e. align their direction of travel to a distant visual cue or feature) and walk to that point without consulting their compass or wayfinding device so that they can concentrate on observing threats when moving. See-through, AR displays make this very easy to do since the direction cues are aligned with their eye, making for fast, accurate checks without unnecessary delays and distractions from having to look away from their intended path to observe their arcs and then re-align again to their intended path.

3.3.3.2 Terrain Visualization

AR systems are capable of displaying interactive 3D entities in a user's field of view. The Integrated Visual Augmentation System (IVAS) example shown in Figure 29 demonstrates a virtual 'diorama' of the terrain and features in the soldier's vicinity. The figure shows a rolling compass at the top of the display to orient the user to the ground, including the display of unit symbols at their associated relative bearing. Below the compass is a view of the real world and the 'diorama' is suspended in space showing satellite imagery of the terrain, the user's own location and facing direction relative to the tactical terrain map, and entities of interest are displayed (i.e., red diamond signifying enemy).

Figure 29: AR Terrain Model Visualization (Image copyright ABC NewsLive, 2020)

Using gestural control and virtual object manipulation, the soldier can move the tactical map around in the view, rotate the map to see the battle space from different perspectives, observe terrain features (assuming the model include DTED data for terrain and/or building structures), and zoom in or out for more or less detail. The soldier is also able to annotate and manipulate tactical icons and markers on the map and share these with other soldiers.

3.3.4 Situation Awareness

3.3.4.1 Situate Entities

Canada's Soldiers Information Requirements -Technology Demonstration (SIREQ-TD) program investigated the use of helmet-mounted displays for dismounted infantry operations, including the enhancement of situational awareness information. This research compared the effectiveness and usability of see-through AR displays with conventional map and compass, and other display modalities (i.e., audio, and tactile). The see-through AR display used a virtual retinal display technology that 'painted' the display image directly on to the retina of the wearer (Figure 30).

Figure 31 shows the AR information display developed by the SIREQ project, that was overlaid on the soldier's real-world view. After plotting a route plan, with friendly and enemy units and entities situated on the map, the soldier would use the AR information display to navigate the route and maintain situational awareness of the distance and bearing to friendly and enemy units. The display included a rolling compass (in mils) that showed the line-of-sight bearing, the bearing of the next waypoint, and arrow cues to bring the soldier on to that bearing. Other entities (friendly and enemy) were denoted by a tactical symbol that appeared when the entities were within the compass range indicated. If the soldier were to center the tactical symbol in their line of sight, then addition details about the unit would be displayed. Information about the next waypoint (name, grid reference, bearing, and distance) and the user's grid location were dynamically displayed as well.

Figure 30: SIREQ Virtual Retinal Display (Image copyright Humansystems® Inc.)

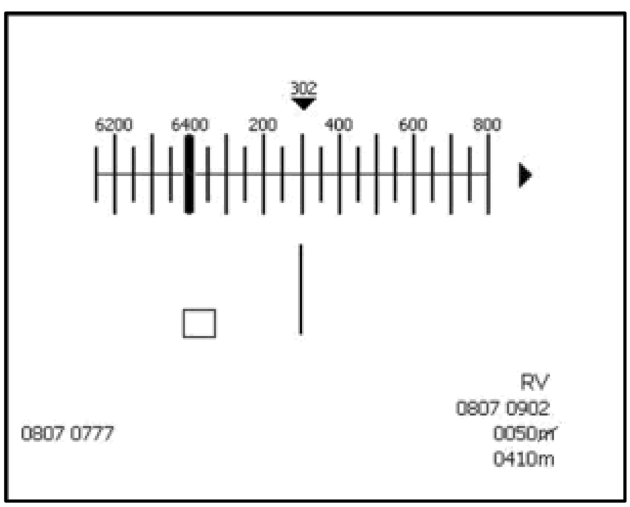

Figure 31: AR Rolling Compass Situational Awareness Display (Image copyright Humansystems® Inc.)

Through various SIREQ studies of see-through AR displays for situational awareness, the AR display was found to enable very accurate bearing and distance estimations to mission locations and key friendly/enemy entities, suggesting a more accurate and informed awareness of the battle space than with map and compass alone, as well as improving navigation performance and awareness of visual target soldiers encountered on route (Tack, 2005). Soldiers did note challenges, however; the bright sunlight conditions affected the readability of the see-through display.

AR displays for situational awareness have continued to develop, specifically under the U.S. DARPA Ultra-Vis program, as computing power, sensor capabilities, display technology, and AR tracking/registration software have advanced over the years.

As one recent example, the soldier augmented reality technology, ARC4 by Applied Research Associates (ARA), provides heads-up situational awareness to the dismounted warfighter, enabling non-line-of-sight team coordination in distributed operations (Figure 32). ARC4 combines compact head tracking sensors with pose estimation algorithms, and network management software to overlay tactical iconic information accurately on the user's real-world view. The technology supports heads-up navigation, blue-force tracking, target handoff, image sharing, and tagging of environmental features. It integrates with command-and-control (C2) software tools (e.g., Nett Warrior, Android Tactical Assault Kit) and interfaces with a wide range of daytime see-through displays and night vision goggles. Pose estimation fuses inertial data, magnetometer data, GPS, DTED, and digital imagery to determine the operator's precise orientation and position. These measurements use mountainous terrain horizon geometry, landmarks, and sun position, enabling ARC4 to achieve significant improvements in position accuracy compared to conventional INS/GPS solutions of similar size, weight, and power (Gans, Roberts, Bennett, Towles, Menozzi, Cook, and Sherrill, 2015).

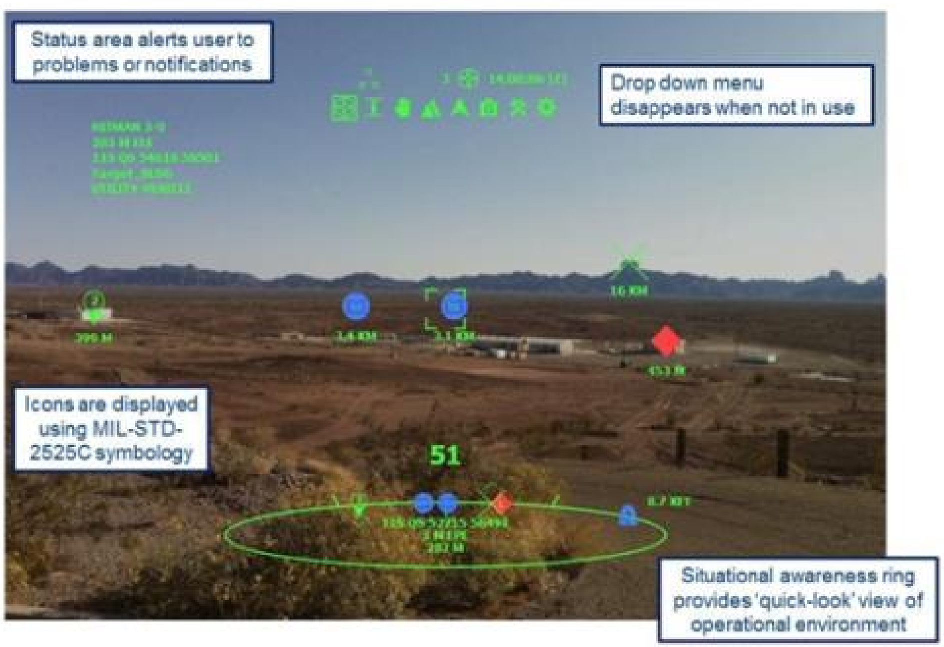

Figure 32: ARA Situational Awareness Display (Image copyright Gans, Roberts, Bennett, Towles, Menozzi, Cook, and Sherrill, 2015)

3.3.4.2 Local Mounted Awareness

The concept of a "glass" tank has been around for over for more than a decade. This concept was intended to enable soldiers inside an armoured vehicle to observe the ground around the vehicle as if the vehicle walls were transparent. Most early concepts involved the integration of a single panaspheric camera system or of multiple cameras mounted on the vehicle for display on a monitor inside the vehicle. The advent of head-mounted displays with head tracking has sought to integrate the surround video feeds and align those with the soldier's facing direction to achieve the impression of a 360-degree view just by turning their head. The U.S. Army is now using head-mounted AR systems, like IVAS, to achieve the same effect with the possibility of overlaying further geo-located situational awareness information to the remote surround view.

The U.S. IVAS program is now embarking on leveraging new and existing sensor systems on vehicles to provide the embarked soldier with both enhanced visual situational awareness as well as Command & Control (C2) awareness of the larger battle from inside the vehicle (Bacon, 2021). Figure 33 and Figure 34 show soldiers with the IVAS system and an image of the video camera sensors mounted on the vehicle's exterior.

Figure 33: Mounted Camera System (Image copyright Bacon, 2021)

Figure 34: Mounted Infantry with IVAS Goggles (Bacon, 2021)

3.3.5 Observation and Surveillance

3.3.5.1 Detection, Recognition, and Identification (DRI)

Night vision technologies have continued to advance in terms of field of view, resolution, contrast, and the fusion of different wavelengths to enhance the detection, recognition, and identification of targets and other objects in the observer's visual field. A significant development in night vision was to combine I^2 technology with infra-red (IR) thermal technology in order to provide a hybrid capability that offers the detail and image quality of I^2 with the capability to detect heat sources often obscured by low lighting levels, vegetation, or smoke. Figure 35 shows a high-resolution I^2 image on the left and a fused image (adding IR) on the right. Lighting conditions were insufficient for the viewer to detect the enemy soldier with I^2 alone, but when combined with thermal imagery of that soldier and weapon the threat is clear.

Figure 35: I^2 / IR Fusion Example (Image copyright Optics 1, 2021)

Recent developments in night vision and night vision fusion have improved the quality and reduced the size, power consumption, and cost of these devices. The fusion capabilities have also been enhanced to include a range of fusion settings to suit the ambient conditions and mission. As an example, the Enhanced Clip-On Thermal Imager (E-COTI) can attach to most I^2 night vision goggles to overlay thermal imagery and additional information. Figure 36 shows some examples. The left image shows an outline mode with edge detection, the middle image shows the normal full-thermal image and the right image shows a darker patrol mode. In each case, the varies the level and location of IR imagery overlaid on the I^2 image. The E-COTI can also overlay real-time compass and geo-referenced navigation information when wirelessly paired with an Android device.

Figure 36: E-COTI Fusion Display Options (Image copyright Optics 1, 2021)

The use of fusion technologies and information overlays can be expanded to further enhance detection, recognition, and identification for the soldier. With the ENVG-B's (Enhanced Night Vision Goggle - Binocular) capability to wirelessly connect to other optics, such as the FWS-I (Family of Weapon Sights - Individual), weapon sight information can be overlaid on the current I^2 or fused night vision scene (Figure 37). This enables soldiers to take advantage of the magnification of the weapon sight optics to inspect targets and other objects of interest, while a compass shows aiming direction to improve SA and potentially avoid fratricide. This wireless connectivity can also be used to import and overlay other data, including information from a battle management system (e.g., the US Army's Nett Warrior).

Figure 37: ENVG-B with FWS-I Display(image copyright Trevithick, 2020)

3.3.5.2 Drone Integration

Soldier-worn AR displays can overlay remote surveillance imagery, including that produced by drone cameras (Freedberg, 2019). US IVAS investigations have experimented with transmitting live surveillance video (daylight and IR) from a palmtop nano UAV (i.e., FLIR's Black Hornet PRS, Figure 38) to an operator's AR display, and to the displays of other soldiers in the squad. AI tracking algorithms have been developed that automatically identify potential targets like people and vehicles, track them as they move, and highlight them on the AR display.

Flight surveillance data (including 2D video overflight imagery) were downloaded from the nano UAV to a mini-server carried by the squad, which then converted the imagery into a 3D model. A small virtual reality terrain model was thereby created, in as little as 8 minutes. Soldiers can then upload the terrain model to an AR system, to virtually reconnoiter this battle space, inspecting potential chokepoints, overwatch positions, egress routes, high threat areas, lines of fire, and approach routes, before proceeding into the real terrain.

Figure 38: Black Hornet Nano-Drone (Image copyright Freedberg Jr., 2019)

3.3.6 Lethality

3.3.6.1 Target Engagement

Weapon-mounted cameras for off-axis or off-bore viewing (i.e., observing the weapon aimpoint through a helmet-mounted display) is not new. Major military science and technology (S&T) programs, including Canada's SIREQ and FSAR programs, were testing the effectiveness and usability of this capability since the 1990s. While the capability was achievable, the promise exceeded the technology in terms of functionality, feasibility, practicality, usability, and cost (i.e., the off-bore capability did not justify the need for a soldier-worn computer and helmet-mounted display system alone).

As night vision goggle and weapon sight technologies have advanced and AR soldier systems have progressed quickly on the backs of commercial development, like Microsoft's Hololens technology, many of these earlier technology challenges have been overcome in technological terms. While it was difficult to justify wearing a separate display for off-axis viewing alone, it is a worthwhile accessory capability if soldiers are already wearing helmet-mounted displays as part of an existing digitized soldier system.

The United States have combined their Enhanced Night Vision Goggle (ENVG) and Future Weapon Sight (FWS) programs (Freedberg, 2018) to create an enhanced, rapid target acquisition capability (Figure 39). Using a wireless connection between the weapon-mounted thermal sight and the helmet-mounted fused, night vision sight, a soldier can sight the weapon around corners while keeping safely behind cover. Alternatively, the soldier can see the crosshairs image from the weapon sight overlaid in their night vision field of view, like a virtual laser aimer. Other information can be overlaid in the ENVG display, offering more AR possibilities to the soldier.

Figure 39: Thermal Weapon Sight Overlay (Freedberg Jr, 2018)

3.3.6.2 Call for Fire

AR is also being used to improve the training realism of U.S. Marine Corps calls-for-fire. The Office of Naval Research (ONR) adapted Microsoft's commercial HoloLens AR headset for military training by pairing it with their Augmented Immersive Team Training (AITT) system. This combined system pairs portable computing with quad-copter UAVs to support call-for-fire and close-air support training for Forward Observers (Figure 40). The AR system can overlay weapon effects on the real-world scene so that the Forward Observer can see the accuracy of their calls for mortar, artillery, or aircraft fire missions (Jontz, 2017). It is not difficult to imagine that the next step in AR call-for-fire will enable the soldier to place target icons on real-world locations to designate the call-for-fire targets.

Figure 40: AR Call-for-Fire (Image copyright Jontz, 2017)

3.3.7 After-Action Review

Armed with time-synched soldier location data, weapons engagement data (when training with force-on-force systems), 2D or 3D terrain data, and AR systems, it is possible to replay training and live missions for after-action review. The use of dynamic location data of soldiers and vehicles to replay the movements of these entities post-mission distinguishes this capability from pre-mission planning. Figure 41 demonstrates soldiers wearing the IVAS AR system observing a dynamic after-action replay of an urban training mission. Soldiers are able to manipulate the dynamic terrain map, zoom in and out, and change perspective to better understand the circumstances and decisions undertaken during the mission so that lessons can be better learned, and performance improved in future missions. Using a fiducial marker, this type of virtual 'sandbox' after-action review could be undertaken in any location, in any circumstances, even to carry out mission rehearsal during transit to an insertion point.

Figure 41: AR After-Action Review (Allen, 2019)

3.3.8 Training

Dynamic, AR-embedded, holographic 'enemy' can also be used to add realism to training. Using mixed-reality AR IVAS headsets, Figure 42 demonstrates soldiers clearing a building with virtual insurgents. Realism is enhanced through a more immersive experience due to AR's use of visual occlusion of real objects, using LIDAR or camera scanning of the scene to identify real surfaces and objects. Virtual objects, in this case the insurgent enemy, will be visually occluded by real objects in the line of sight between the virtual enemy and the AR user, making situations appear more realistic. Similar to virtual battlespace simulation tools, the virtual enemy will react to the actions and spoken commands of the trainees, adding further realism to the training experience.

Figure 42: AR Training Example (Image copyright ABC NewsLive, 2020)

Future training with AR could provide soldiers with the opportunity to train different skills and small unit training actions at any time, in any environment (e.g., day or night, woodland or urban). Individual training could include a virtual shooting range with virtual targets that pop up at known or distances, with static or moving targets, and even simulate virtual enemy assaulting their position and maneuvering through the use of cover. Small unit training could involve a team of soldiers executing different phases of battle to train coordinated movement, covering fire, command & control actions, etc. against a simulated enemy/friendly/non-combatant environment.

3.3.9 Medical

Current combat medical training often involves the use of simple, static wound simulations using a wound card (attached to a human pretending to be a casualty) to moulded rubber models of injuries with fake painted blood (i.e. a moulage). These low-fidelity simulations and the time required to create, set up, manage, and execute casualty care training with these tools reduces the available training time, realism, and hands-on applicability for trainees (Taylor et al., 2018).

The U.S. Army is developing AR training tools to enhance the quality and realism of casualty care training by overlaying AR wounds on a casualty (human or mannequin) that remain properly, anatomically situated during any trainee or casualty movement (Figure 43). Wounds would also appear dynamic, with realistic blood flow and wound characteristics, and responses to treatment. Their Combat Casualty Care Augmented Reality Intelligent Training System (C3ARESYS) concept would monitor the trainee's treatment steps relative to the wound/casualty condition, and the instructor could view the process from the trainee's viewpoint (Taylor et al., 2018).

Figure 43: C3ARESYS Concept (Image copyright Taylor, Deschamps, Tanaka, Nicholson, Bruder, Welch and Guido-Sanz, 2018)

Augmented reality can be used for visualizing anatomy (e.g., critical blood vessels) and treatment steps/procedures, integrated with medical sensors (e.g., ultrasound) to visualize the inside of the body relative to the surface (Figure 44), and can even be used for collaborative AR-assisted surgeries with participation of remote surgeons (Mehdi and Lemieux, 2014).

HSI HUMANSYSTEMS INCORPORATED

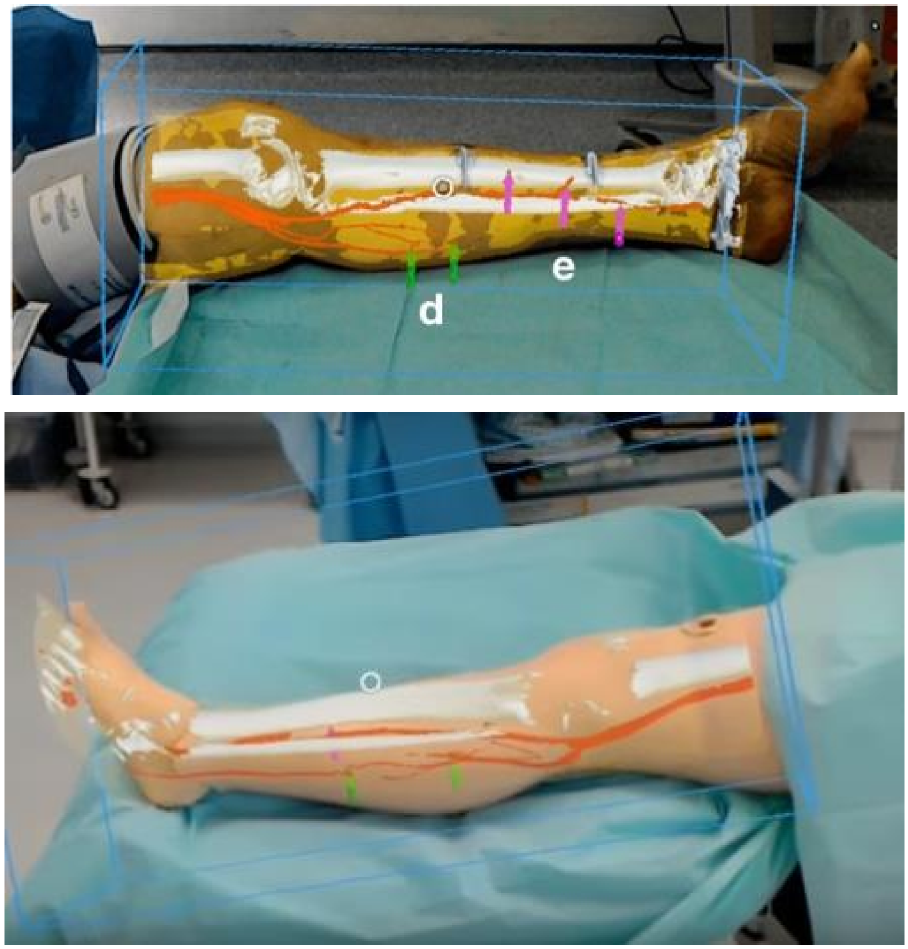

Figure 44: Human Anatomy Overlay (Images copyright Pratt and Kinross, 2018)

The U.S. Army is investigating the use of AR technologies to provide military first responders offering casualty care in the field with remote, real-time guidance from medical care centers.

The British Army is developing an AR system for battlefield medics, , to enable remote surgeons and medical specialists to observe and advise trauma treatments in real time and provide supporting information in the AR display (Project Lara).

3.3.10 Maintenance

Military systems maintenance still relies on paper and PDF manuals, schematics, and drawings. Use of AR technologies to support maintenance functions is one of the more prolific commercial uses of augmented reality. Using AR, maintainers can view referential information, instructional videos, and status data while also observing the equipment undergoing maintenance (as described in section 3.2.2). Situated visualization also aligns the virtual information overlay on the physical equipment to be repaired, providing specific, object-linked information (Figure 45).

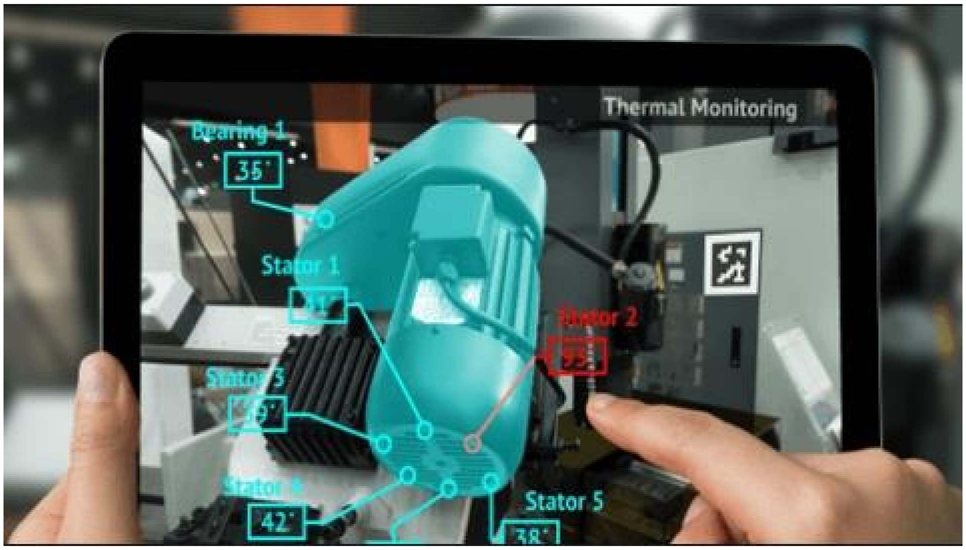

Figure 45: AR Maintenance Example (Image copyright Coon, 2018)

Figure 46 shows an example of an AR system for maintenance tasks inside a LAV-25A1 armoured personnel carrier. A study showed that these maintenance tasks could be performed significantly faster with greater accuracy than without the AR enhancement (Henderson and Feiner, 2011).

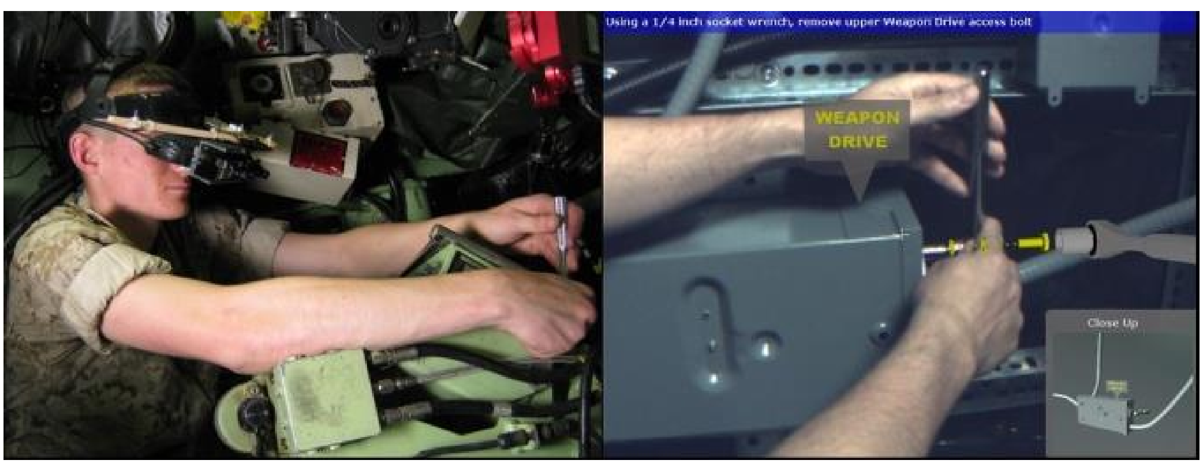

Figure 46: AR Vehicle Maintenance (Image copyright Henderson and Feiner, 2011)

Military organizations are looking to AR for improved vehicle maintenance capabilities, but they are also looking at leveraging AR technologies to keep more weapons and equipment in the fight and reduce any associated down time. More first-line and field maintenance capability could be achieved with AR systems, particularly if these are supported by expert guidance through remote, collaborative troubleshooting from higher centers of maintenance expertise. This maintenance method could provide a safer operating environment, reduce the loss of equipment, shorten the training time of support personnel, and save manpower and material resources while advancing the combat effectiveness of the army (Wang, 2020).

3.4 Military AR Programs

The section describes a number of past and present AR developments for Army applications. While many nations have examined the use of AR applications for soldiers, few have consistently invested in the design and development of a mobile soldier AR capability as the United States has, for over two decades. Other nations that have developed soldier AR applications have typically leveraged commercial, sometimes domestic, technologies. This section provides a brief summary of some of these programs, first considering Canada's SIREQ program before describing international activities.

3.4.1 Soldier Information Requirements Technology Demonstration (SIREQ-TDP)

Canada:

Defence Research and Development Canada - Toronto Research Centre (DRDC-TRC) undertook a six-year program of experimentation, development, and testing with soldiers in the laboratory and field to investigate emerging and future information technologies intended to enhance situational awareness, lethality, survivability, C4I, planning, navigation, surveillance, distributed order, mission rehearsal, and terrain visualization.

Included in this effort were investigations of AR for soldier navigation and situational awareness (Figure 47), which found that AR displays significantly improved navigation performance, target detection, and battlefield situation awareness, as compared to conventional map and compass navigation.

Figure 47: AR display used in SIREQ Studies (Image copyright Humansystems® Inc.)

3.4.2 Tactical Augmented Reality (TAR)

United States:

Following on from studies using earlier helmet-mounted displays, the U.S. soldier situational awareness programs (i.e. Land Warrior and Nett Warrior programs), stood up their Tactical Augmented Reality (TAR) program to broadly develop AR helmet-mounted display systems for ground soldiers. DARPA began developing an augmented reality system that overlays critical information into a soldier's field of vision. The goals of the program were to increase soldier situational awareness, share data quickly with other soldiers and higher headquarters, and employ a remote weapon-mounted thermal sight so a soldier could observe and engage targets without having their eye behind the sight. Their TAR package wirelessly combined a 1-inch by 1-inch eyepiece with a tablet and weapon-mounted thermal night vision sight to enable soldiers to see in the dark, view the location of geo-tagged enemies in 3D space, receive video feeds from surveillance platforms, and observe targets from behind obstacles (Figure 48).

Figure 48: Example TAR System (Image copyright Gallagher, 2017)

3.4.3 Urban, Leader, Tactical, Response, Awareness - Visualization (ULTRA-VIS)

United States:

The Urban, Leader, Tactical, Response, Awareness - Visualization (ULTRA-VIS) DARPA program was an early (2012-14), post Nett Warrior, wearable display that employed a holographic waveguide technology (BAE's Q-Sight technology) to provide AR overlays (Figure 49). According to DARPA, the program developed and integrated a lightweight, low-power holographic see-through display with a camera (vision-enabled) position, location (GPS), and orientation head-tracking system (inertial sensors, gyroscopes, magnetometers, and accelerometers). The system also uses camera vision methods to improve the estimation of location, azimuth, and attitude through horizon matching by comparing the camera image to digital terrain elevation data (DTED) from a world DTED database (Madrigal, 2014).

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Figure 49: Ultra-Vis System (Image copyright Roston, 2014)

The situational awareness software developed in the ULTRA-VIS program was called ARC4, which was later commercialized into the ARC4 AR system. ARC4 overlays geo-registered icons representing blue-force units, enemy units, mission-critical locations, and other entities on the soldier's real-world view (Figure 50).

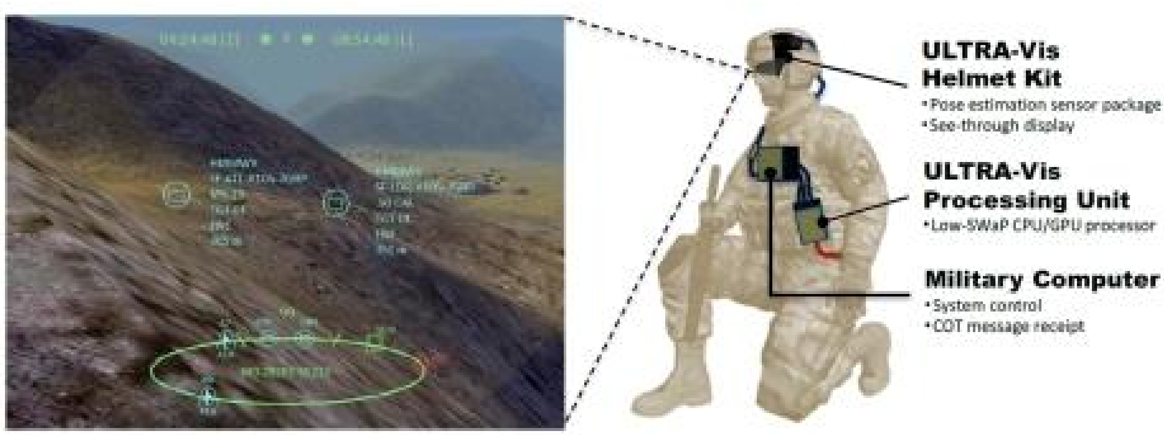


Figure 50: Ultra-Vis Components and Display (Image copyright Robert, Volpe, Clipp, and Argenta, 2012)

3.4.4 Heads-Up Navigation, Tracking, and Reporting (HUNTR)

United States:

Heads-Up Navigation, Tracking, and Reporting (HUNTR) was an expansion of ULTRA-VIS capabilities. The purpose of the 2015-16 HUNTR program was to "demonstrate augmented reality for day and night tactical applications to provide networked heads-up situational awareness to reduce fratricide, and increase lethality, survivability, and maneuverability" (CERDEC, 2015). The HUNTR program leveraged the ARC4 situation awareness software from the ULTRA-VIS program as an extension to the Nett Warrior day display and night vision display (ENVG-II) and integrated these with a custom head tracking and video processing system attached to the side of the helmet. HUNTR provided the wearer with tactical, geo-registered information for real-time situational awareness.

The HUNTR program employed the Android port of the ARC4 package, GPS data, helmet/camera data, and inertial sensors to geo-register the soldier's field of view with the real world (Gallagher, 2017) - see Figure 51 and Figure 52.

Figure 51: HUNTR Ultra-Vis Display (Cerdec, 2015)

Figure 52: HUNTR Visual Display Device (U.S. Army Photo)

3.4.5 Integrated Visual Augmentation System (IVAS)

United States:

All of the previously mentioned U.S. Army AR development programs have led to this one. In late 2018, Microsoft Corporation was awarded a $480 million (USD) contract to begin development in 2019 of the Integrated Visual Augmentation System (IVAS), using its Hololens augmented reality product, in 24 months. The ultimate goal of IVAS was to increase soldier lethality, mobility, and situational awareness (U.S. Procurement Statement of Objectives).

The program included a stepwise development effort consisting of four sequential capability sets that build on the earlier U.S. Heads Up Display (HUD 3.0) and Synthetic Training Environment (STE) squad capability programs. Each capability set development was followed by a Soldier Touch Point (STP) field evaluation by soldiers that provided feedback to the engineers and designers, with the aim of continuously optimizing and improving IVAS from one capability set to the next.

According to its Statement of Objectives, IVAS will include the following features:

- Head Borne Vision System (no helmet mount assembly; low profile, conformal goggle/visor system providing 24/7 squad situational awareness in all operating environments; see thru, wide field of view binocular 3D display; dual high resolution digital color sensors, integral ballistic, laser and hearing protections with 3D sound field); provides a natural field of view for the user similar to current types of eye protection.
- Day/Night Rapid Target Acquisition (RTA) from Family of Weapon Sights-Individual (FWS-I) and remote viewing from Family of Weapon Sights–Crew Served (FWS-CS)
- Machine Learning Capabilities/Artificial Intelligence (AI)
- Synthetic Training Environment (STE) Squad Capability (One World Terrain, Training Simulation Software, Training Management Tools, and associated integration hardware)

- An Adaptive Squad Operating System
- Nett Warrior 3.0/Tactical Assault Kit (TAK) Connectivity (operating on Secure-But-Unclassified (SBU) portion of the Integrated Tactical Network (ITN) using current military radios; operation in open, contested, and denied environments with minimum capability to see/shoot/move/navigate)
- Fused Day/Night Vision Capabilities for multiple sensor/imaging feeds
- Intra-Soldier Wireless (ISW) Connectivity (multi-point wireless) for on-body Soldier devices
- Squad Lethality Ratings/Metrics (real-time measure of squad & soldier performance; physiological feedback to include but not limited to concussions, heart rate, breathing rate, readiness)
- Mixed/Live Reality for Combat Training and Rehearsals including Navigation, Targeting, Phase Line (Symbology)
- Automatic or Aided Target Recognition (ATR) for relevant threats
- Government-Owned Soldier/Squad Architecture (collaboratively developed by US Government and industry over 24 months with key interfaces across squad identified, developed, validated, and implemented; tactical power architecture and management system)
- Modular open-source data, unclassified or perishable Position, Location, Information (PLI) and stored in the Cloud.

Figure 53 provides an image of IVAS Capability Set 3. As of this writing, the U.S. Government had just awarded Microsoft a ten-year, $22 Billion (USD) contract to produce and supply the IVAS system to the U.S. Army.

Figure 53: IVAS System (Cox, 2020)

3.4.6 LimpidArmor

Ukraine:

Developed by a Ukrainian defence contractor, LimpidArmor, the Circular Review System headset integrates a protective helmet with the Microsoft Hololens AR headset. Wearing this system affords tank commanders a 360-degree view of the battlefield (Figure 54).

While camera feeds can be used to provide moveable 2D imagery to a flat display, a unified 360-degree perspective is more versatile and can be used to overlay much more information to the wearer if required.

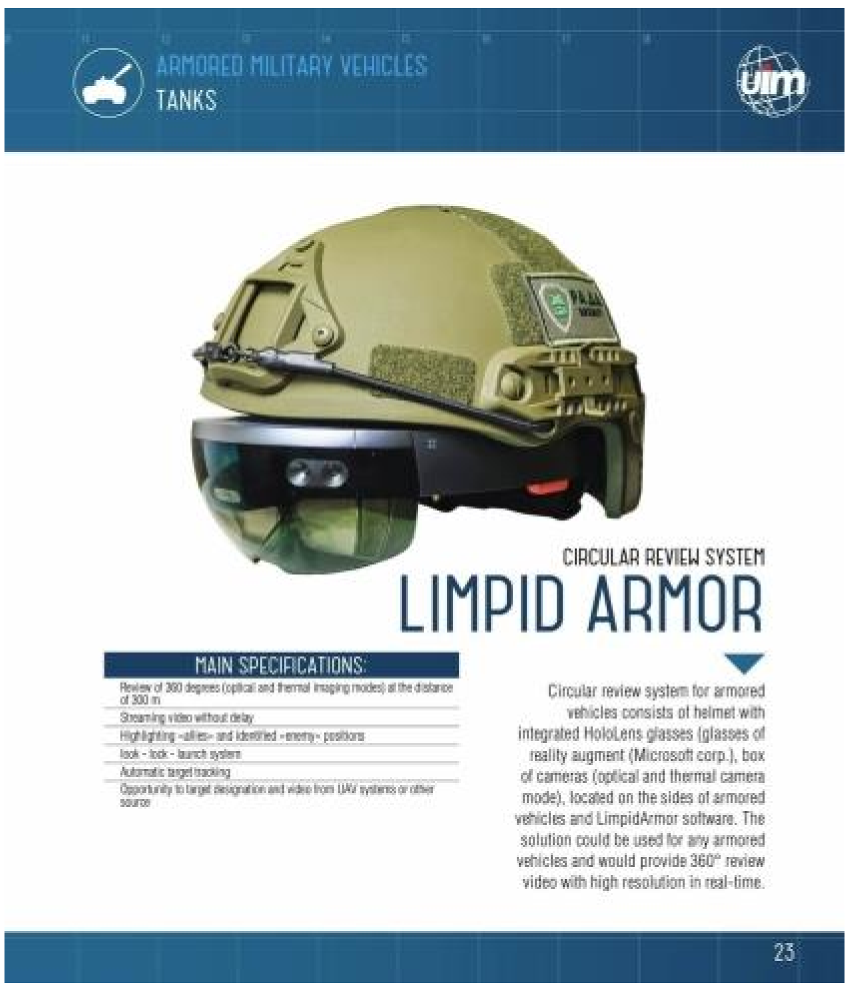


Figure 54: Limpid Armor System (Image copyright Martindale, 2016)

3.4.7 Army Individual Eco-Lightweight Equipment (ARIELE)

Singapore:

Singapore's Army Individual Eco-Lightweight Equipment (ARIELE) soldier system ensemble employs a see-thru helmet mounted display (Shielded Advanced Eyewear System - SHADES) to provide enhanced situational awareness (Figure 55). SHADES is described by the developer, ST Kinetics, as an intelligent Head-Up Display (HUD) system providing real-time AR information to the soldier for improved situational awareness, wireless command and control over unmanned systems and weapon stations, intuitive communication and coordination, navigation, as well as identification and tracking of both friendly and enemy forces.

Figure 55: Singapore's Ariele System (Image copyright Asian Military Review, 2019)

3.4.8 AR for Canines

United States:

There is a U.S. Army Research Laboratory initiative to investigate the effectiveness of providing military working dogs with AR capabilities in order to assist their handlers in rescue operations and to scout for hazards and explosives while the handler remains at a safe distance (Popular Mechanics, 2020). The goggle system is developed by Command Sight.

The goggles enable Army dog handlers to see what the dog sees via a camera mounted in the dog's goggles (Figure 56) and to identify points of interest within a dog's field of view without exposing the handler to hostile fire. Inside the goggles, the dogs can see a visual indicator that they can be trained to follow, directing them to a specific spot, such as the location of a possible explosives cache or enemy troops.

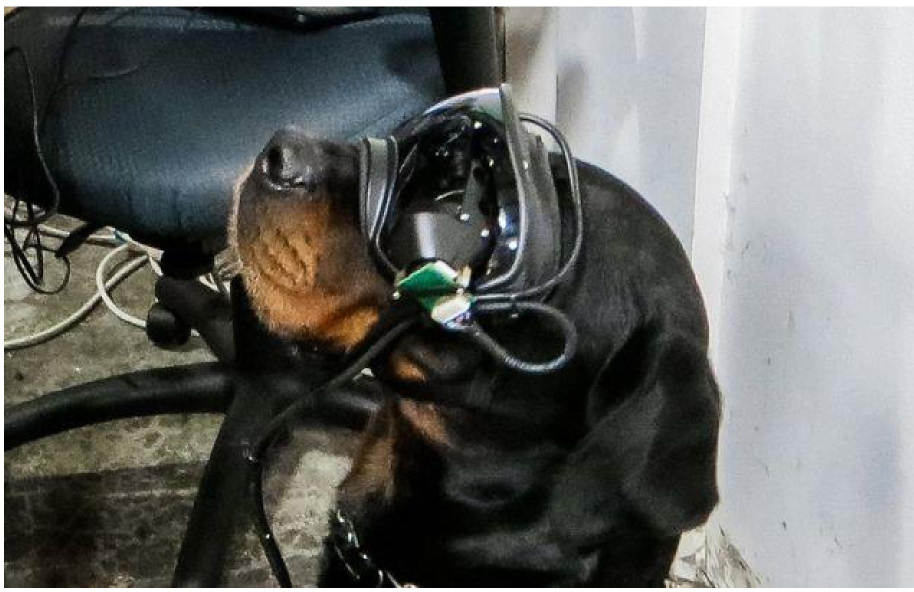


Figure 56: AR for Canines (Image copyright Popular Mechanics, 2020)

3.4.9   XACTse HUD

Germany:

The German system XACTse HUD shows tactical information in the soldier's field of vision (Figure 57). Navigation and orientation data, including own position, north, bearing and line of sight, are displayed in the XACTse HUD (Figure 58). Paratroopers can view information about their own position as well as the distance and location to a target during approach. Own forces are displayed with distance information through tactical symbols in the field of view, including Blue Force Tracking (friend-or-foe detection). The XACTse HUD can be used as a stand-alone device during the day or in combination with night vision goggles for night operations.

Figure 57: XACTse System (Image copyright Elbit Systems, 2018)

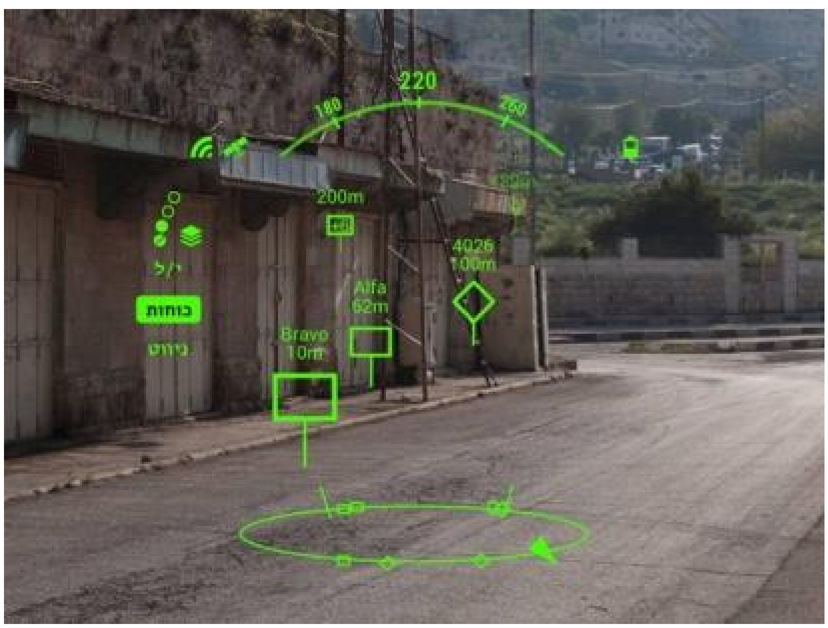


Figure 58: XACTse AR Display (Image copyright Elbit Systems, 2018)

3.4.10 Tactical Reconfigurable Artificial Combat Enhanced Reality (TRACER)

United States:

The Tactical Reconfigurable Artificial Combat Enhanced Reality (TRACER) system consists of a virtual-reality (VR) headset, a backpack processor, a simulated weapon designed to deliver realistic recoil, and a software package that creates different simulation scenarios for security personnel to experience (Figure 59). TRACER leverages software developed by Magic Leap Horizons as part of the U.S. Army's Augmented Reality Dismounted Soldier Training (ARDST) project.

These technologies combine to provide extremely accurate weapon and movement tracking capabilities as well as highly immersive simulation visual, auditory, and haptic feedback. The system is built mostly from commercial, off-the-shelf products.

Figure 59: TRACER Goggles (Image copyright Photonis, 2019)

Hologram entities respond to Marine instructions and behaviours making the training experience more interactive and realistic (Figure 60).

Figure 60: TRACER Enemy Holograms (Image copyright Photonis, 2019)

After-action review provides playback from any viewpoint and can be compared between training missions to identify issues and rate of progress (Figure 61).

Figure 61: TRACER After-Action-Review (Image copyright Photonis, 2019)

3.5 AR Technology Review

The hardware, displays, and software technologies within the worlds of VR, AR, MR, and XR are expanding at a rapid pace (Karanjia et al., 2019). As of this report, AR has since graduated from Gartner's Hype Cycle, Figure 62, as the technology is maturing into wide and mainstream adoption across multiple industries.

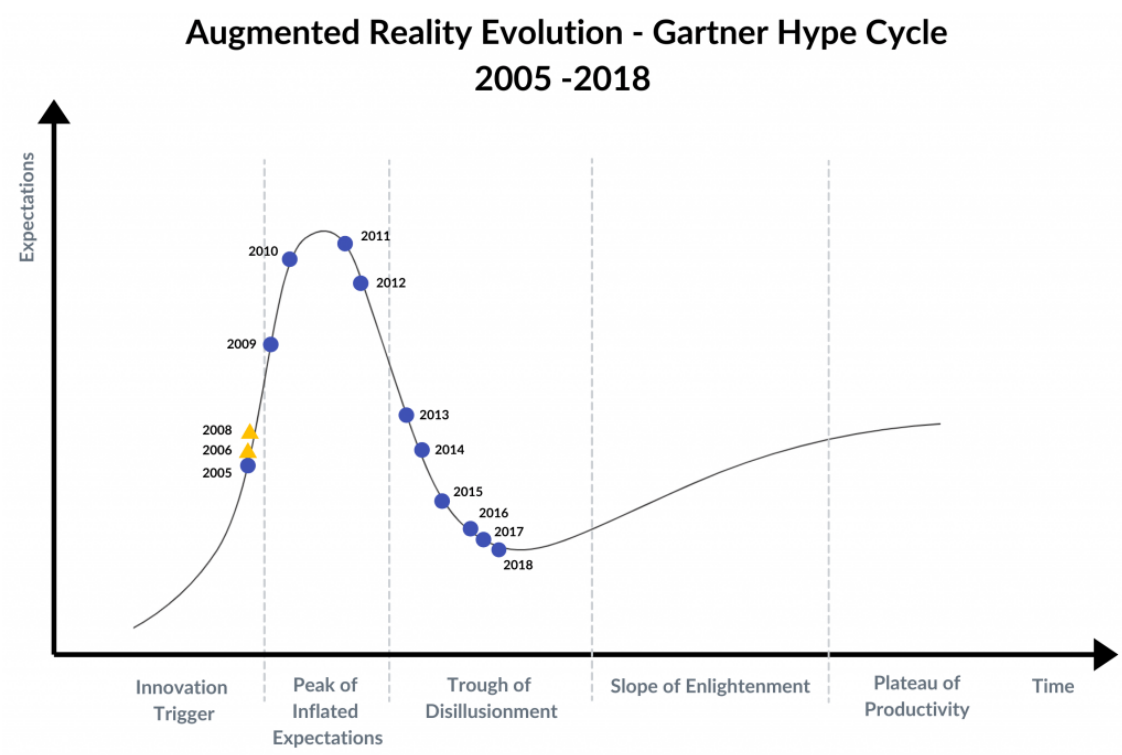


Figure 62: AR Gartner Life Cycle (Image copyright Herdina, 2020)

This current AR landscape is driven by recent advancements in computing, processing, networking, battery, tracking, and miniaturization of sensor and display technologies (Karlsson, 2015). The major technology players (e.g., Apple, Facebook, Microsoft, HTC, Toshiba, and Epson) have developed AR hardware and software (Karanjia et al., 2019). There are also hundreds of other start-up or less 'consumer-familiar' organizations that have also done hardware and software development for AR, raising significant funding throughout 2020: Spatial, $14M; Mad Gaze, $19M; Librestream, $24M; Nreal, $40M; Envisics, $50M; Mojo Vision, $51M ($151M in three years); and Magic Leap $350M (Envisics, 2020; Karanjia et al., 2019; Langley, 2020; Liao, 2020; LibreStream, 2020; Mast, n.d.; Palladino, 2020; Peddie, 2017)

Augmented reality devices have advantages over virtual devices in that the user is able to see both the real and augmented world (Mixed Reality). At a high level, AR devices include the following technologies: displays, sensors, processors, inputs, & networking (Figure 63) As an indication of the complexity of AR devices, Figure 63 provides a structured breakdown of the many different categories and types technologies necessary to achieve an AR display.

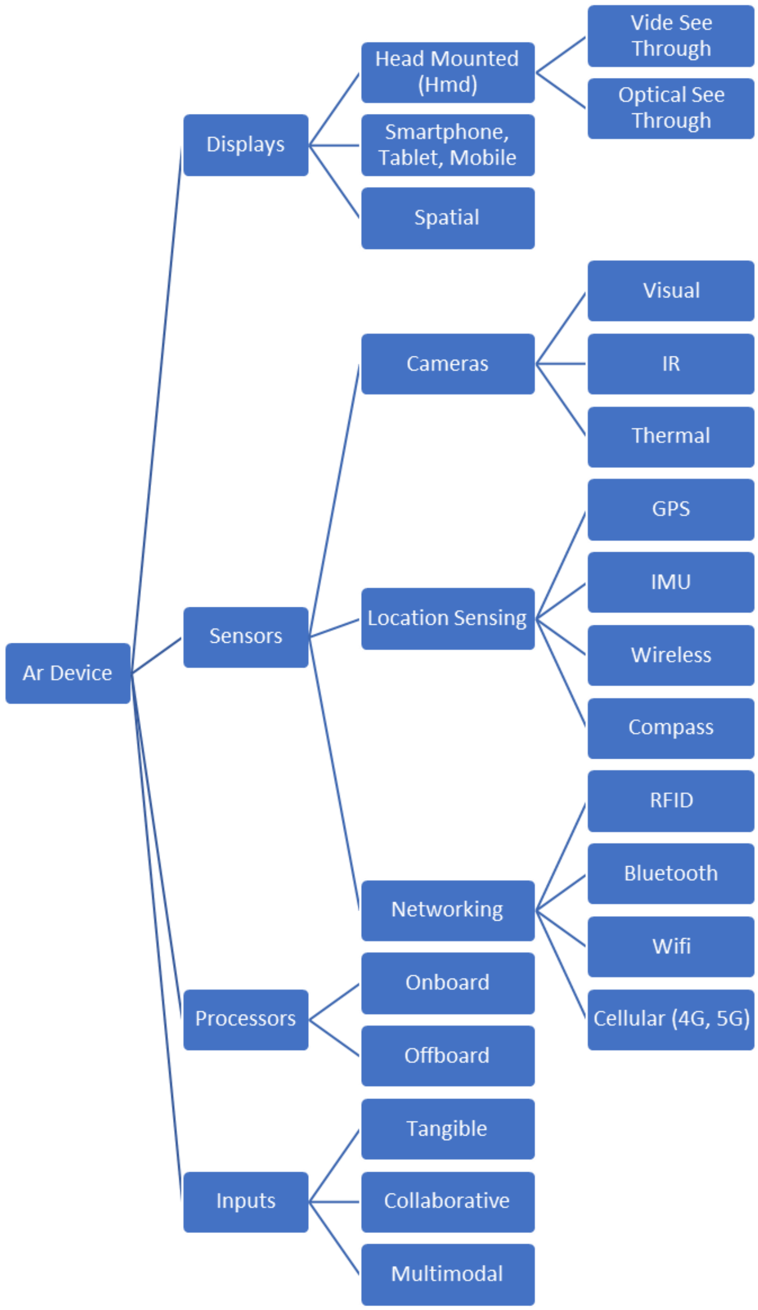


Figure 63: AR Device Technologies

Displays show information to the user (e.g. handheld, head-mounted, etc.). Sensors are generally MEMS (micro-electro-mechanical sensors) that aid in the tracking of the desired targets or information. Processors can be on-board or off-board the specific AR device; they analyze the visual inputs for the desired targeting or marker tracking. Lastly, inputs are the interactions between the user and the AR world – for example gestures, audio commands, tactile or haptic buttons, or any other number of collaborative commands. These are generally categorized as tangible, collaborative, or multi-modal. A tangible interface input may include a secondary device such as a sensing glove (Figure 64). A collaborative input involves other users sending information or sharing virtual objects across a network. Lastly, multimodal interface inputs, such as those found on the HoloLens 2, may include eye-tracked gestures such as blinking, hand-tracked gestures, or speech input (Sicaru et al., 2017).

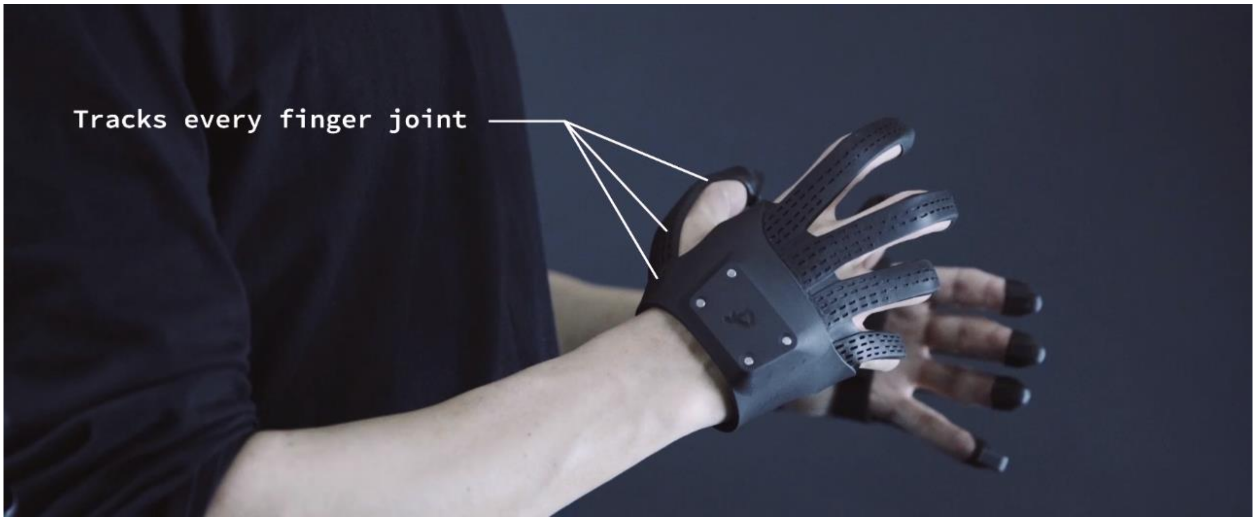


Figure 64: Augmented Reality Glove (Image copyright Melnick, 2018)

3.6 Augmented Reality Criteria Descriptions

Before diving into the most recent devices on the market, an overview of relevant criteria is needed to have a greater understanding of the technologies available. Each criteria descriptor below could warrant its own detailed discussion; however, the aim is to prime the reader to the pertinent knowledge required for a basic understanding of the various AR devices in use today and where AR devices may be headed in the future.

3.6.1 Eye Related Criteria

3.6.1.1 Field of View

Field of View (FOV) is the total angular range visible to both eyes and is expressed in degrees. The average healthy adult has a horizontal FOV of approximately 200 degrees including two peripheral areas and the area of binocular overlap. Binocular overlap is that part of the FOV where the two visual fields overlap allowing stereopsis – this is important for depth perception. The vertical FOV is 130 degrees. The monocular visual field is approximately 150 degrees wide, with HMDs and AR displays using only a portion of that (Figure 66).

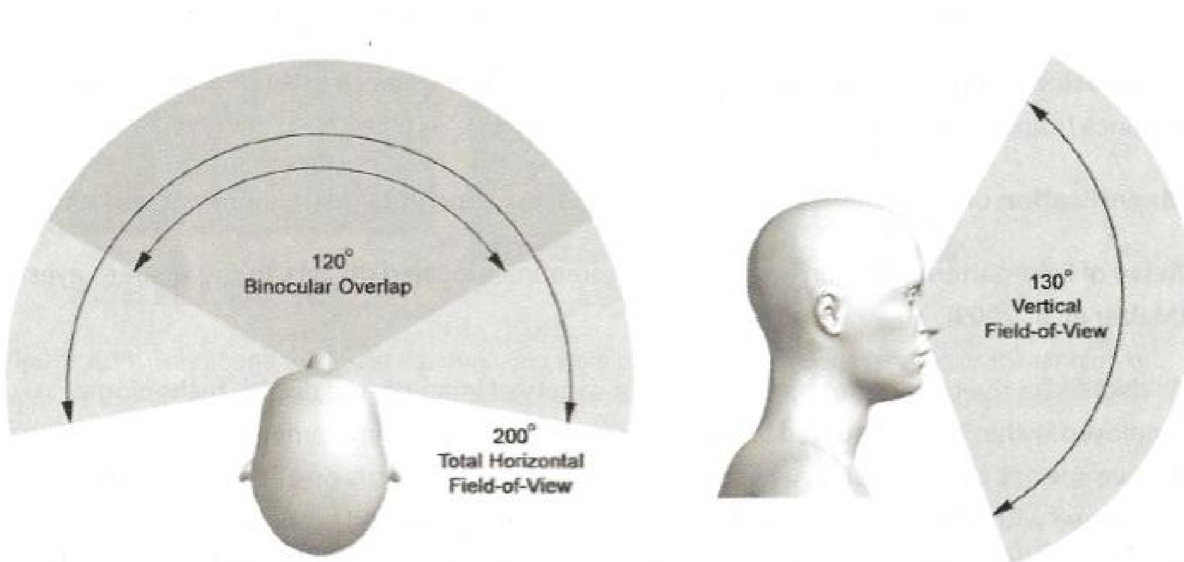


Figure 65: Human FOV (Aukstakalnis, 2017)

In general, manufacturers are striving to create devices with larger and larger FOV. In general, the FOV of most AR devices cover only a small portion of the human visual field. The following figures shows the relationship between the human visual field, and typical FOVs for VR and AR devices. For example, the Hololens 2 claims a 52-degree FOV measured diagonally (approx. 43 x 29 degrees) whereas human vision is ~200x130 degrees (Figure 67).

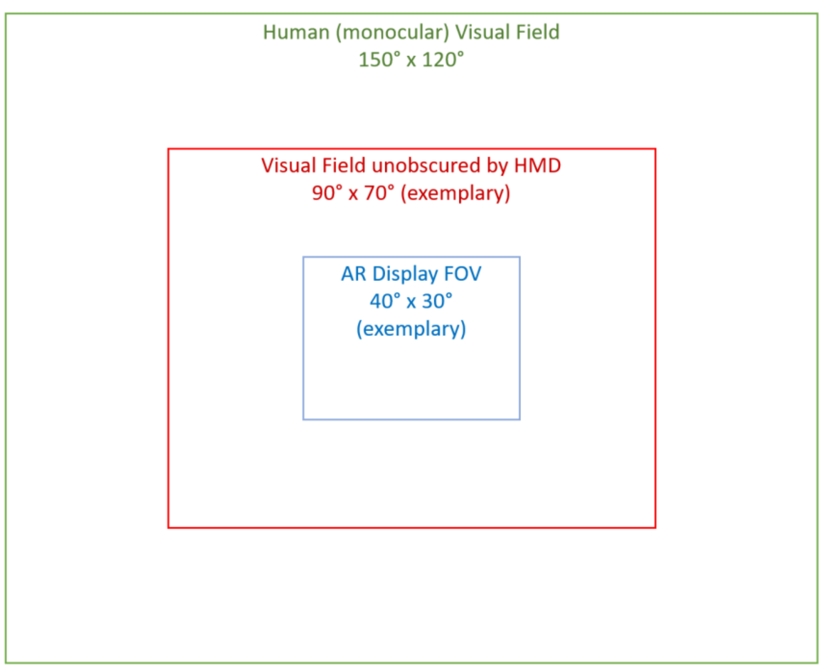


Figure 66: FOV of typical AR and VR devices (Wagner, 2019)(Kress, 2019).

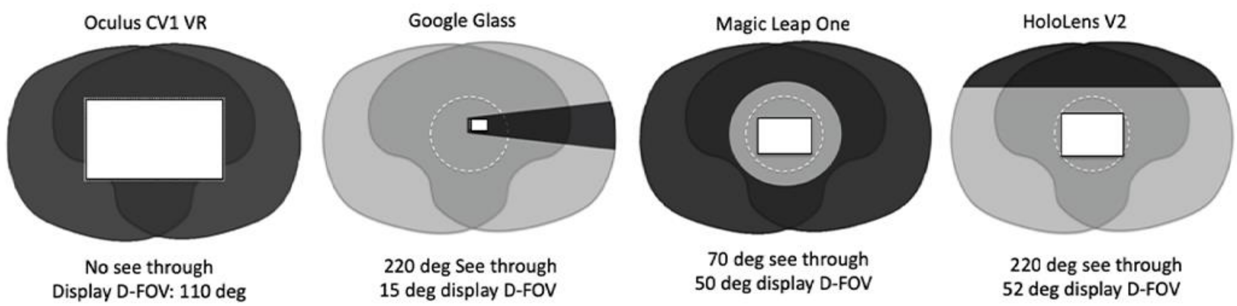


Figure 67: FOV of typical AR and VR devices (Wagner, 2019)(Kress, 2019).

3.6.1.2 Interpupillary Distance (IPD)

Interpupillary Distance (IPD) is the distance between the center of each pupil. Proper lens and projection alignment is key to ensure adequate tracking of images and representation to the user. Mean Adult IPD is approximately 63 mm with a range between 50 and 75 mm (Dodgson, 2004). Understanding and accounting for this distance will be key for future AR devices that employ pupil and gaze tracking to change the location of the highest resolution points of the display on the AR Head-Mounted Device.

3.6.1.3 Eye Relief

Eye Relief, Figure 68**,** is the distance from the cornea to the surface of the first optical element in the device. For exam, typical eyewear is ~12mm from eye to the first optical element.

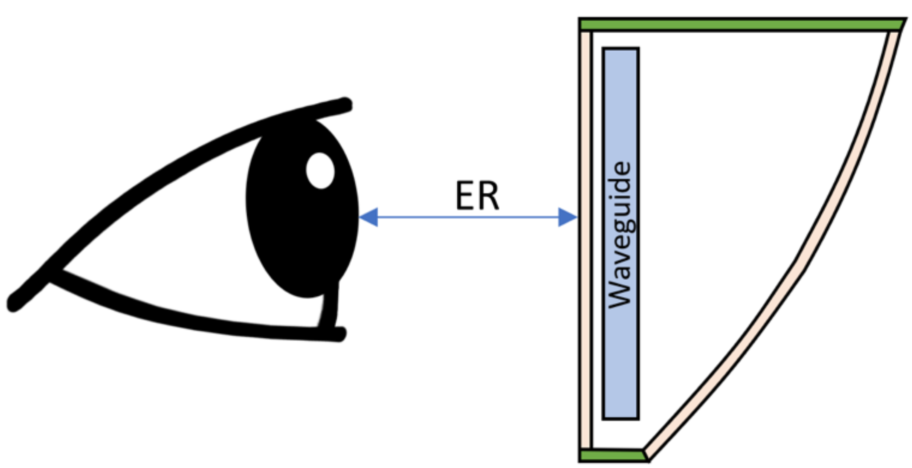
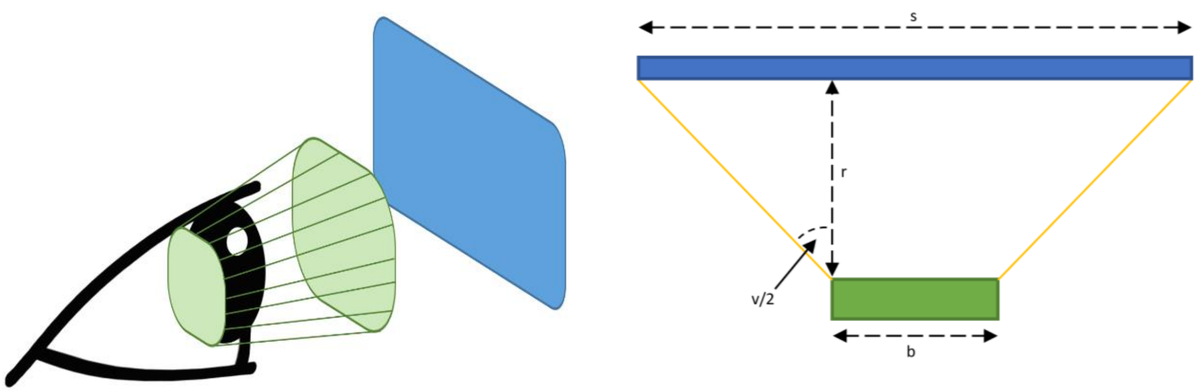


Figure 68: Eye Relief Visual (Wagner, 2019)

3.6.1.4 Eye Box

Eye Box (or Exit Pupil), Figure 69, is the volume where users can properly see display content. Outside of this eye box, content may be distorted or blurred. A small eye box requires a stationary pupil but increases the light efficiency transferred to the eye, which is a desirable feature for binoculars, telescopes, and microscopes. However, the FOV is limited when the eye box is small. In the AR world, a larger eye box is desired since the pupils are not fixed as the user observes their environment. A small eye box requires more head movement and less eye movement. AR manufacturers must also increase the eye box to account for variance in IPD. However, increasing the eye box requires a much larger display in front of the user (waveguide – see Section 3.6.2.3.1). Unfortunately, based on the relationship between eye box, eye relief, and the optical surface, this becomes difficult at larger desired FOVs.



$$s = b + 2\,r\,tan(v/2)$$

S = optical surface (e.g., waveguide) width

b = eye box size

r = eye relief

v = field of view

Figure 69: Eye Box & relationship to display (waveguide) size (Wagner, 2019)

Using the formula in Figure 69, an FOV of 40, 90, or 150 degrees would result in an optical surface size of 35, 60, or 135 mm, respectively (Figure 70). The 135 mm condition induces a large region of binocular overlap and therefore drastically increases the complexity of the display surface and display of visual information. Investigations are on-going to determine the practical use of curved waveguides and alternative projection systems.

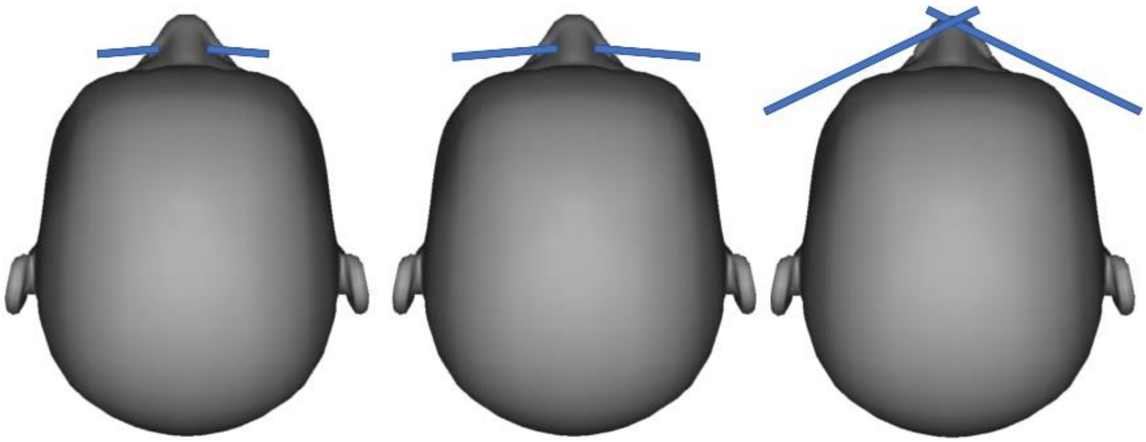


Figure 70: Waveguide sizes example (Wagner, 2019)

3.6.2 Display

There are multiple ways to categorize AR devices (Aukstakalnis, 2017; Peddie, 2017; Schmalstieg & Hollerer, 2016), including:

- Application (Industry, Sector)
- Display Type (e.g., Handheld, Video-See Through)
- Mobility (e.g., Wearable / Non-wearable)
- Tracking Method (e.g., marker-based, location-based)

Display technology is the most common way to categorize AR devices as it is one of the main differentiating factors. Displays are the means of transferring either real or augmented world data from the device to the user's eyes.

There is overlap between some wearable based systems, namely smart glasses and helmet/helmet-mounted-displays (HMD), and they are used interchangeably by some manufacturers. Categorizing AR Systems by displays returns the following four display types: 1) Fully Immersive, 2) Video-See Through, 3) Optical See-Through and 4) Spatial / Projector (Figure 71):

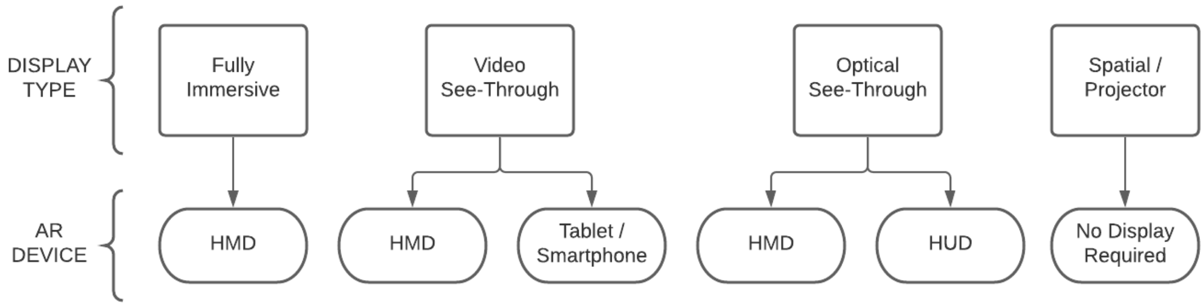


Figure 71: Classification of AR Devices by Display

3.6.2.1 Fully Immersive

Fully Immersive displays block the user's view of the real world and provide a fully computer-generated environment for user immersion. Fully immersive displays are always head-mounted. Sensors tracking head positions and orientation provide the sensation of presence within that world. These include simple displays such as Google Cardboard or more complex VR HMDs like the Oculus Rift (Figure 72). Fully immersive displays tend to have more instances of visual fatigue than non-immersive displays.

Figure 72: Fully Immersive Display Example (Oculus, 2021)

3.6.2.2 Video See-Through

Video See-Through displays are similar to fully immersive displays, but the content is from either a forward-facing camera on the device itself or from a remote environment (Figure 73). These video signals can be augmented with computer-generated images or situational information. Immersion can be greater in these devices since it is possible to adjust the image in various ways (brightness, contrast, filtering, etc.) before presenting it to the user (Karlsson, 2015). Some manufacturers call these devices Mixed Reality since the devices can show a virtual environment (VR) or an augmented real world (AR). LCD, OLED, & LED displays are commonly used. While the screens are generally flat and two-dimensional, lenses can be used to create a 3D effect. Since the entire video is processed prior to being displayed to the user, there is the potential for display lag depending on the processing steps prior to displaying the altered image. Video See-Through AR HMDs (Figure 74) are not nearly as common as Video-based VR. In general, this type of technology is found in medicine/surgical applications where the user has a Fully-Enclosed display with a camera being used to display the inside of the patient's body (Keutel, 2020). Video see-through AR can also be implemented on other display formats, including tablet or mobile devices (Figure 75). This type of AR is general monoscopic (one camera, 2D view of 3D content – i.e., smartphone) and is the most common form of AR since all that is required is a smartphone or tablet and an AR application.

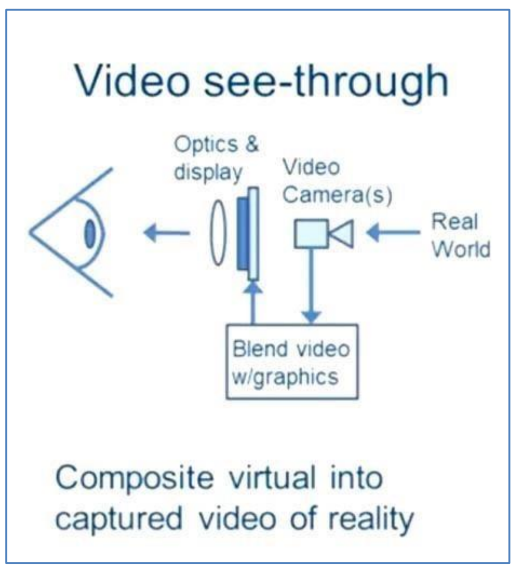


Figure 73: Video See-Through Display (Strange, 2018)

Figure 74: Video See-Through HMD example (Keutel, 2020)

Figure 75: Video See-Through Display - Table/Smartphone (Kossobokova, 2019)

3.6.2.3 Optical See-Through

Optical See-Through displays (Figure 76) allow the user to see the real world with overlapped computer-generated information. This is the most common type of display for AR as fully immersive and video-see through are typically associated with VR and MR, respectively. The majority of AR HMD manufacturers are trending towards Optical See-Through technologies. With Optical See-Through the devices can be categorized as a Heads-Up Display (HUD) and Head-Mounted Display (HMD) / Smart Glasses (Figure 79). For more information on these devices please refer to Section 3.9. These displays provide an unobstructed view of the real world and generally produce a parallax-free, real-world image as compared to their video see-through counterparts. The user can see the real-world surroundings even with a power failure. Optical displays are inherently more complex than a see-through display, as a virtual or augmented image is overlaid on the real-world environment using a transparent screen (see-through). To accomplish the transparency, an optical combiner (Figure 78) or waveguide is used to transfer the image from the source to the user and overlay the virtual imagery on the real world.

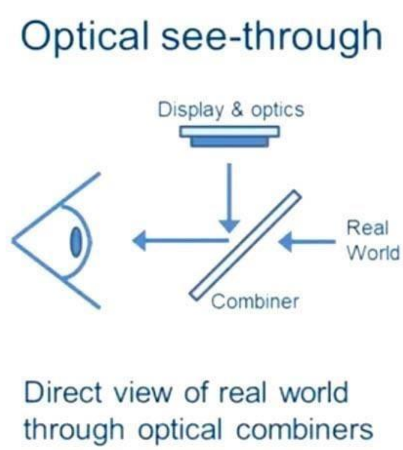


Figure 76: Optical-See Through Display (Strange, 2018)

3.6.2.3.1 Waveguides

Waveguides, introduced earlier in Section 3.2.1, are found in advanced optical see-through AR devices and they are proprietary and specific to the device. Waveguide technology is portrayed in Figure 77. The image is projected from a MicroOLED or similar display device and routed passively to the user's eye via the waveguide which can be holographic, polarized, diffractive, or reflective (Aukstakalnis, 2017; Peddie, 2017). Holographic waveguides are less than 2 mm in thickness. Manufacturers include TruLife Optics, Wave Optics, Akonia Holographics, and DigiLens. Optical waveguides reduce the size and weight of HMDs compared to conventional optical lenses and are deployed on all modern AR Optical See-Through Systems (Cameron, 2012).

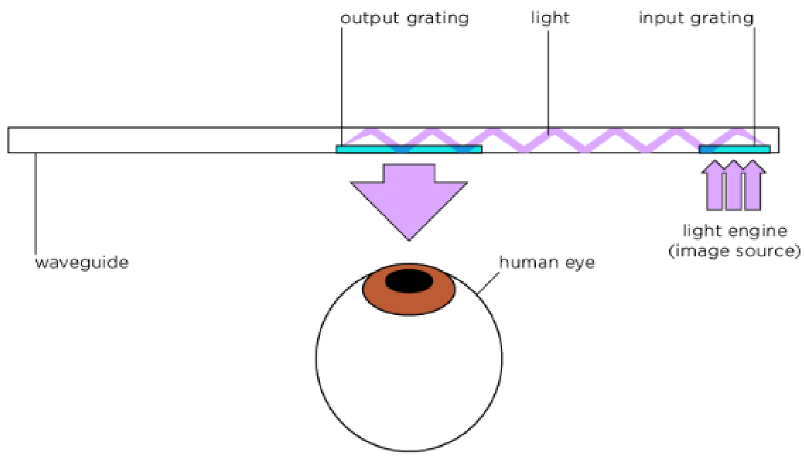


Figure 77: Optical waveguide technology (Grayson, 2019)AR

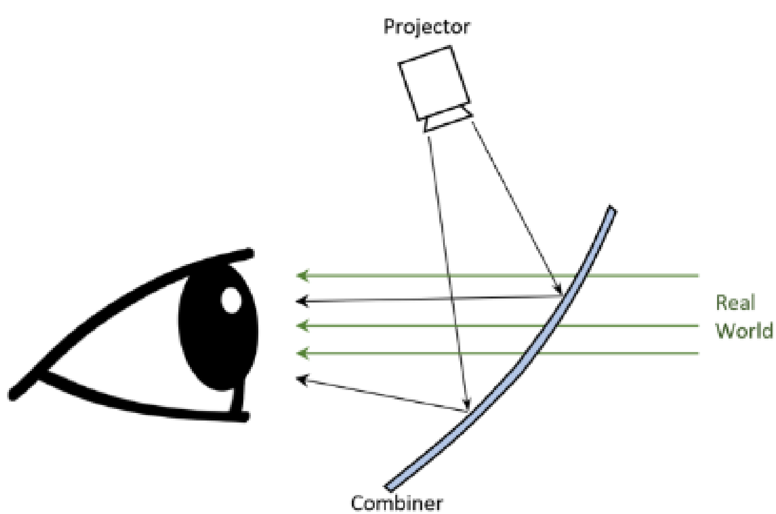


Figure 78: Optical Combiner (Wagner, 2019)

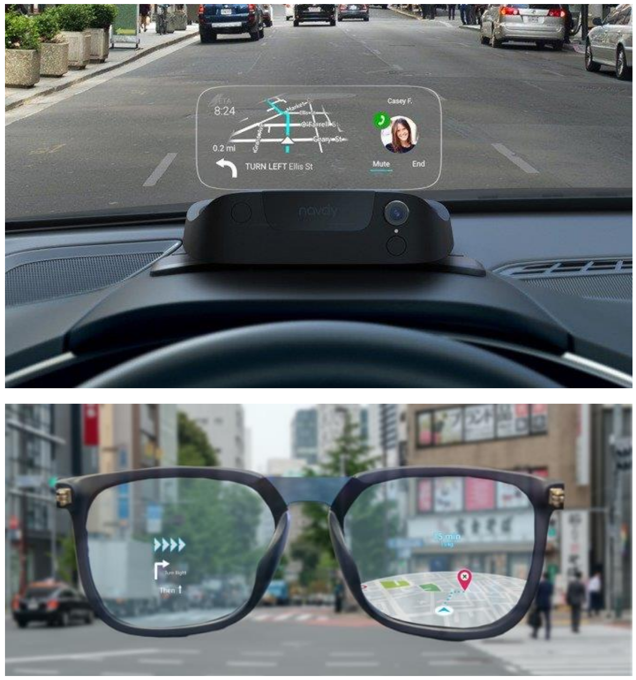


Figure 79: Optical See-Through Examples (Fruci, 2019)

3.6.2.4 Spatial / Projector

Spatial / Projector displays (Figure 80) project an image onto a surface or real-world object requiring no user-worn devices to view the augmented or virtual projection. Spatial augmented reality displays allow projections onto surfaces that are curved or warped and when coupled with user location tracking, enable the users to see the projection in three dimensions (Figure 81) (Peddie, 2017). The addition of HMD can supplement the projection to add additional immersion-quality or information presented to the user. Examples such as Hololamp and AR Sandbox (Figure 82) are discussed later.

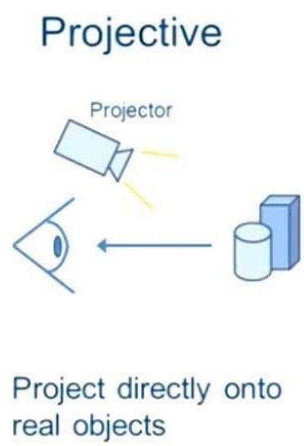


Figure 80: Spatial / Projector Display (Strange, 2018)

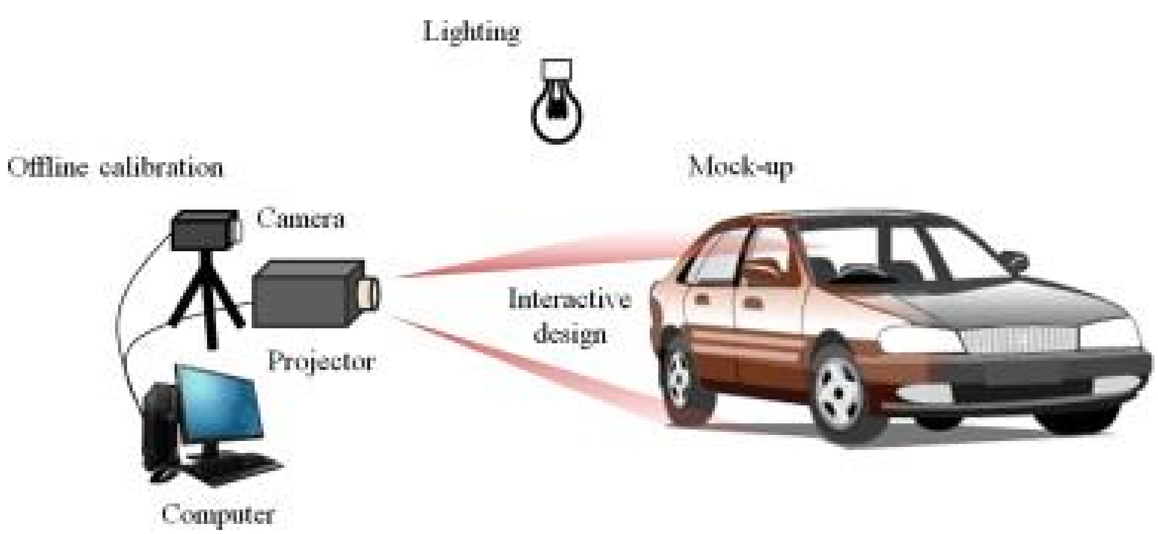


Figure 81: Spatial / Projector Display Example

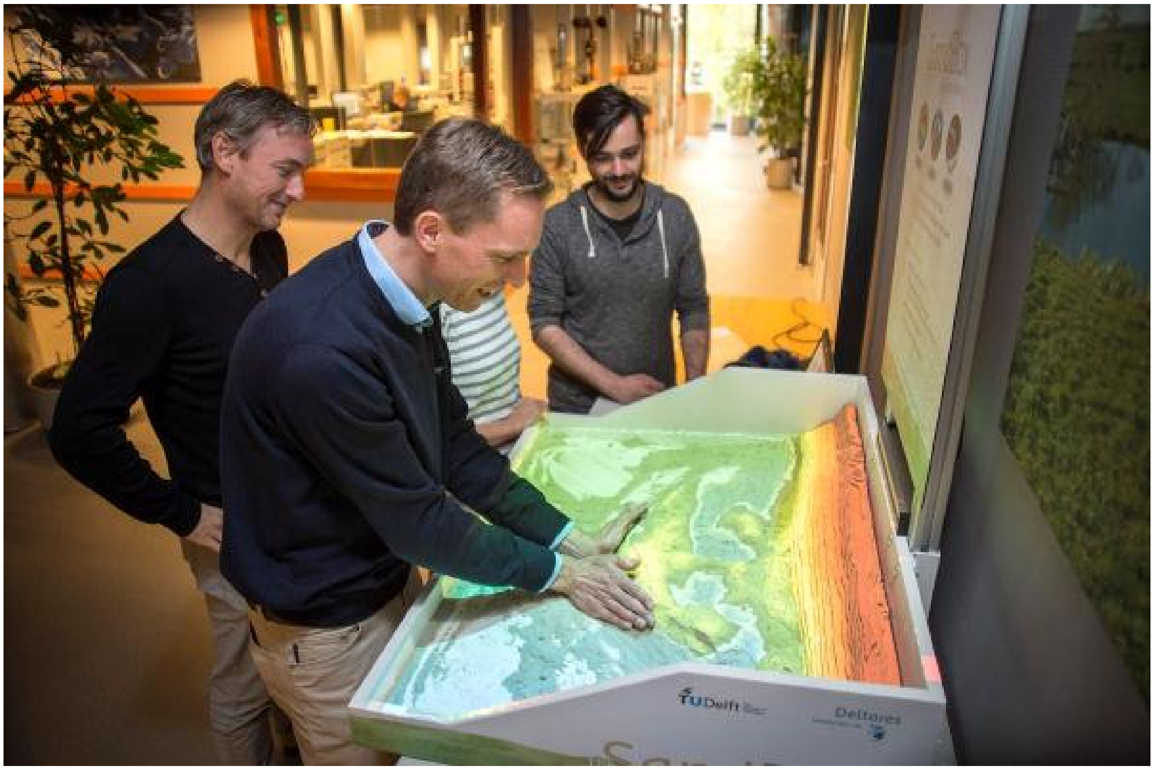


Figure 82: AR Sandbox Protection AR (Deltares, n.d.)

3.6.3 Resolution

Resolution is more complex with near-eye displays, as compared to the traditional flat screen. The goal of AR and VR devices is to achieve near retinal-level resolution matched with our eyes field of view. The acuity of a person with 20/20 vision is about 1 arcmin, ~60 pixels per degree (ppd) within the central fovea region (clearest vision point on the retina) and lower within the peripheral region (Tan et al., 2018). However, there is a tradeoff between high angular resolution and a wide field of view. In order to obtain 100-degree FOV with 60 ppd, a resolution of approximately 6K would be required per eye (Figure 83). In contrast, the original Hololens had 720 vertical pixels spread across 17.5 degrees vertical FOV. This results in approximately 41 ppd over a much smaller FOV (Guttag, 2020). There is ongoing research to create a multi-resolution, foveated display with a wide FOV (low resolution for peripheral and low FOV and high resolution for the foveated region) (Tan et al., 2018). Some devices are already announcing this type of technology (Varjo VR & XR as an example).

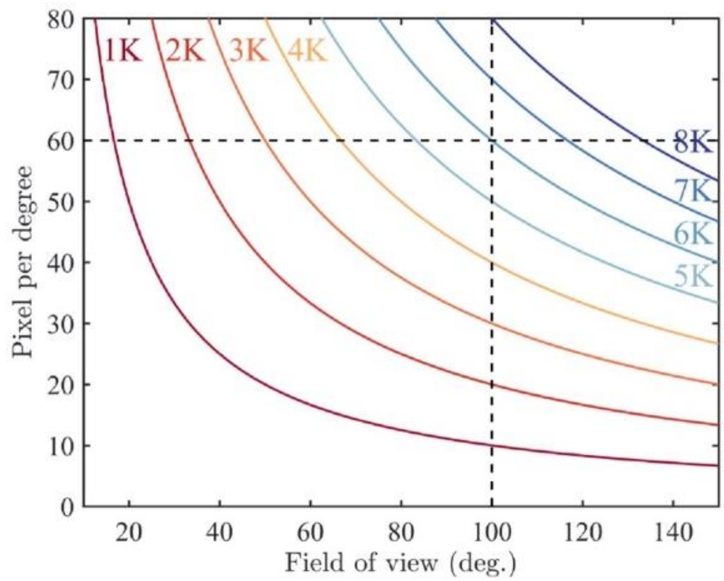


Figure 83: Relationship between Pixels per degree (resolution) and FOV (Tan et al., 2018)

3.6.4 Latency

Latency occurs when an image or information (e.g. user movement or tracked information / edges) processed through the AR device is not displayed immediately to the user. Since the AR image is processed through multiple steps, there will always be some latency with both video and optical see-through devices (Schmalstieg & Hollerer, 2016). This latency is caused by:

- Physical measurement of the sensor
- Sending of information to the computing device
- Processing and measuring by the computing device
- Image generation by the graphics device
- Video synchronization between graphics device and display
- Internal delay in the display until the image is finally shown

Users wearing HMDs can also induce increased latency. For example, moving a HMD at 50 degrees per second can lead to registration errors of up to 20-60 mm in registration of a tracked object. This phenomenon is commonly referred to as "image swimming" where the display lags behind the movement of the user. Latency can be reduced in video see-through displays by inducing a matched delay to the entire video shown to the user. In the Video See-Through devices, this end-to-end latency should be below 40 ms total. In Optical See-Through devices, where the overlay is based on the users current sight of the real world, the latency tolerances should be even tighter at ~10 ms since the augmented image must match the speed of reality to ensure proper alignment (Peddie, 2017). Predictive algorithms on object movements can help to reduce the latency produced by optical see-through devices.

3.6.5 Refresh Rate

The refresh rate is also referred to as frame rate (FPS – frames per second) which is the number of times that the image generating device produces an image. The human eye observes 12 FPS as distinct and separate images, 20 FPS as flickering images, and 24 FPS as the minimum video standard. The refresh rate is sometimes measured in Hz, which is useful when characterizing the refresh rate of coloured displays. For example, HoloLens has a 240 Hz refresh rate which equals 60 Hz for four separate colour fields equating to a 60 FPS user experience. Higher frame rates can also minimize the latency, blurring or jittering experience with fast moving objects or a fast moving user (head-rotation) (Peddie, 2017). In most cases it is desirable to have an FPS > 60 for both AR and VR devices. This equates to a new image every 16.6 ms (Microsoft, 2020).

3.6.6 Brightness & Contrast

Brightness is the perceived intensity of light emitted from a screen. Contrast is the ratio of the brightest spot to the darkest spot within an image. High contrast ratios allow users to depict images more clearly compared to low contrast images (Figure 84). Video See-Through devices can manipulate the image presented to the user by artificially enhancing brightness and contrast; however, one is limited by the camera's specifications such as megapixels, FOV, aperture, focus and zoom. Optical See-Through devices need to provide enough brightness and contrast to ensure users can properly see the projected display with respect to the outside world. Since the display is transparent, real-word objects are potentially visible behind the augmented image presented. High real-world brightness levels can make it more difficult to see the augmented overlay. To account for this, the manufacturers of Optical See-Through devices artificially dim the real world view with lens filters or recommend that devices are used only in shaded or indoor areas (Schmalstieg & Hollerer, 2016).

Figure 84: Low contrast (left) and high contrast (right) examples. (Nelson, 2020)

3.6.7 Weight, Balance, & Size

The weight, balance, and size of HMDs or Smart Glasses are key design elements that affect their comfort and wearability, because they affect physical loads and head movements within the user's environment. One study (Ito et al., 2019) used an Oculus Rift with varying weights and center of mass (CoM) conditions. Their findings indicate that subjective fatigue increased with weight and with a CoM anterior to the standard location (Ito et al., 2019).

3.6.8 Sensors

Augmented Reality requires more complex sensing, as compared to VR. This section discusses the major sensors (Figure 85) found on most AR devices: Cameras, motion tracking sensors, and gaze tracking sensors.

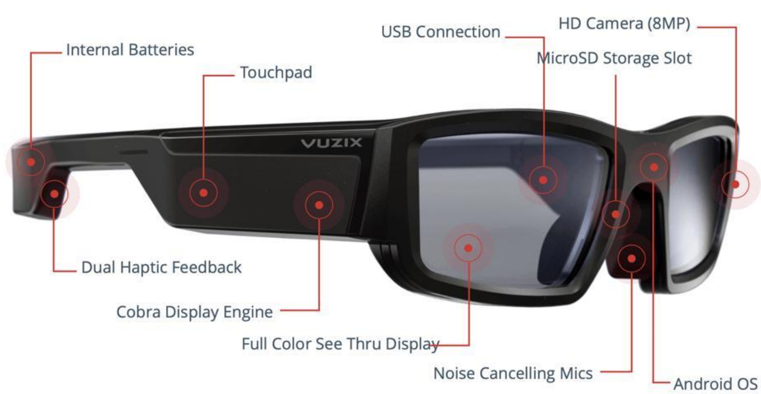


Figure 85: Illustration of sensors on an augmented reality device (Koetsier, 2020)

3.6.8.1 Cameras

AR systems generally have at least one camera in the visible light spectrum and 1-2+ for depth sensing. Infrared cameras and thermal sensors may also be present for heat mapping and to measure depth. IR cameras project a pattern of light and analyze the pixel data between the projected and returned pattern of light to determine surfaces and depths (Rienduea, 2017). Utilizing multiple depth sensors increased processing demand but also accuracy and depth performance (Rienduea, 2017).

Additionally, the processing of video from these images must be capable of mitigating distortions, vibrations, latency, and jitter. Cameras vary drastically in resolution, color-sensing, size, weight, and pixel density; therefore, no single camera sensor can provide all information an AR device would require (Figure 86).

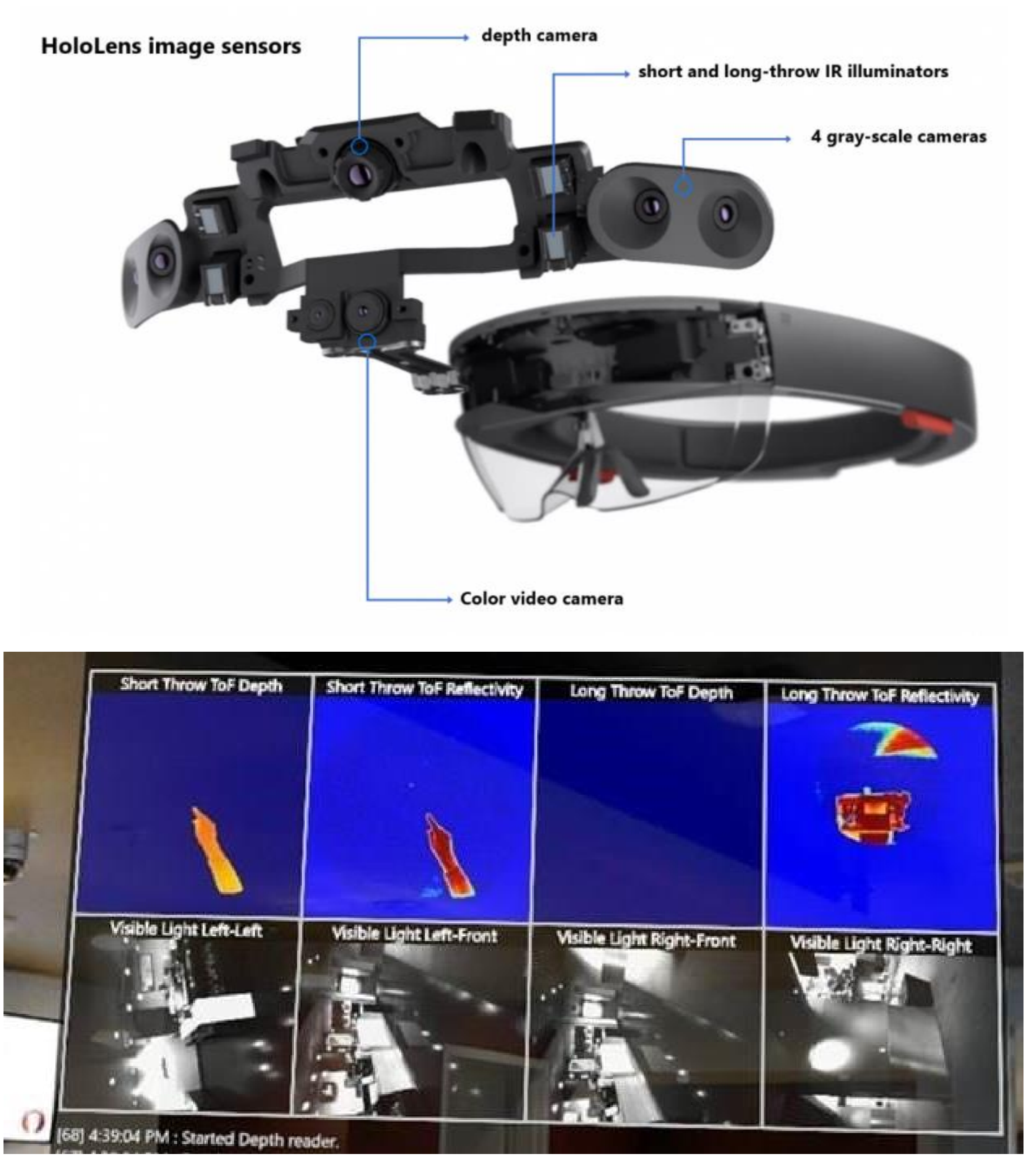


Figure 86: Hololens 2 cameras and resulting images (Davies, 2018)

3.6.8.2 Motion Tracking Sensors

Tracking the camera in relation to user head position is also extremely important. Most AR devices utilize 6-degrees-of-freedom (6DOF) to track the cameras movements. Inertial Sensors (gyroscope, accelerometer) or location based (GPS, compass, magnetometer) or network signal-strength based sensors can all feed into tracking the 6DOF of the user and camera positioning (Figure 87).

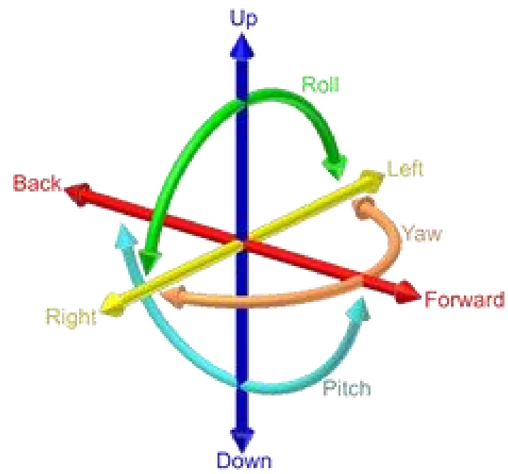


***Figure 87: Motion Tracking Sensor degrees of freedom/measurement* (Weis, 2018)**

3.6.8.2.1 Inertial Measurement Unit (IMU)

IMUs are the most common measuring device to track relative location and motion or movement of the user's head when utilizing an HMD. IMUs utilize gyroscopes, accelerometers, and magnetometers in one combined micro-electromechanical system (MEMS). Each of these measures the acceleration, rotation, and relative direction (compared to the earth's magnetic field) in combination, with the output being location, orientation, and direction (Figure 88) (Rienduea, 2017; Schmalstieg & Hollerer, 2016).

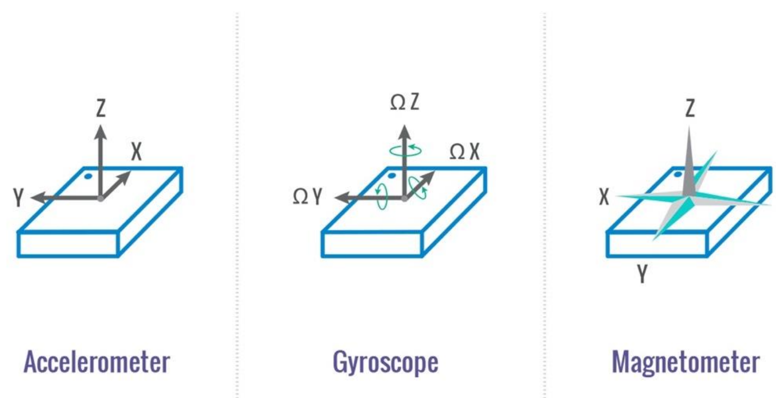


Figure 88: Typical IMU sensors(Weis, 2018)

3.6.8.2.2 Gyroscopes

Gyroscopes use the rate of rotation around the three axis of the user's head movements with respect to gravity to determine orientation (Figure 89).

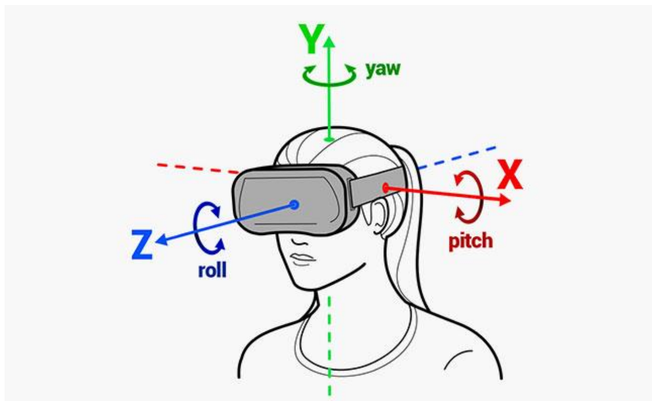


Figure 89: Gyroscope pitch, yaw, and roll illustrations (Veative Labs, 2019)

3.6.8.2.3 Accelerometers

Accelerometers measure the acceleration (the rate of change of velocity) acted upon a specific axis. Most devices utilize three-axis accelerometers.

3.6.8.2.4 Magnetometers

Magnetometers are an electronic compass that measure the direction of the earth's magnetic field using magneto-resistance (Hall Effect). These allow for global orientation; however they are subject to distortion from local magnetic fields (Schmalstieg & Hollerer, 2016).

3.6.8.2.5 Global Positioning Systems (GPS)

Another method of measuring motion and position is through the use of GPS and Assisted-GPS (A-GPS). GPS utilizes time-of-flight coded radio signals from satellites in Earth's orbit. If the signals from four or more satellites are available, the location can be measured. The more satellites visible by the GPS the greater the accuracy (i.e., between ~1 to 100m in urban canyons and 0.5 – 5 m in open areas) (Schmalstieg & Hollerer, 2016). Unfortunately, this method rarely considers height/elevation due to inherent errors and the signal loss indoors provides unreliable data. A-GPS utilizes cellular towers to assist in the geolocating of the receiving element. Accuracy is greatly improved in urban areas with cellular reception by measuring signal strength to known tower locations or base stations. Bluetooth sensors can also track locations based on signal strength relative to Bluetooth beacon emitters; however, range is less than other methods (20-150m).

3.6.8.3 Pupil & Gaze Tracking

Eye tracking involves either locating pupil orientation or gaze (relative direction of eye motion to the head). SensoMotoric (SMI) was one of the first organizations to debut Eye Tracking for AR in 2016 using Epson Moverio BT-200. SMI have since been acquired by Apple in anticipation of their first AR device for release in 2022. Eye tracking can be utilized to open screen menus based on gaze direction and duration or to improve the visual output of display devices by providing higher resolution at pupil locations.

As discussed previously there exists a trade-off between field of view and display resolution. To accommodate this, some manufacturers are recently introducing foveated rendering displays. Foveated rendering is a display technique where digital manipulations or slight movements in the display projections match the user's gaze or pupil location based on eye tracking (Figure 90). This allows for a high-definition image to be presented to the foveal range (center of our field of vision responsible for visual acuity), while lowering the resolution within the peripheral range (Kuerzel, 2017). This can reduce the computer processing requirements and power consumption of the device, allowing for improved processing of other aspects (i.e., increasing frame rate). NVIDEA has already published data on eye tracking connected to a mechano-sensor that locates the HD display portion center to the foveated region (J. Kim et al., 2019). The tracked eye movements will also allow for responses to eye movements within the AR experience not just gestures and head/hand/finger movements. This can improve the graphical user interface by eliminating or consolidating information accessed by eye movements only.

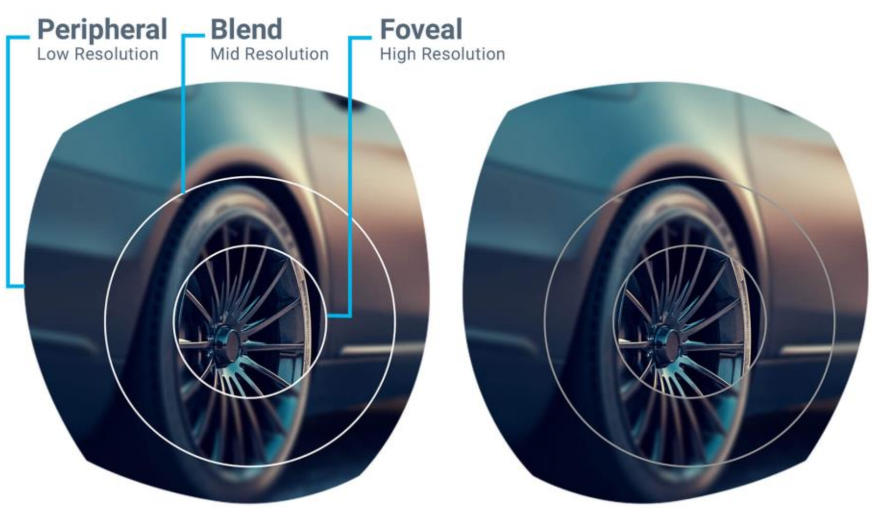


Figure 90: Foveated Rendering examples (HTC Vive, 2021)

3.6.8.4 Bio-Sensors

Commonly found on mobile phones, smart watches, and fitness trackers, biosensors will eventually become mainstream on AR devices using HMDs or integrated on other wearables reporting to the HMD processors. Heart rate, blood oxygen level, respiration rate data can be used to determine as the user's stress, cognitive load, fatigue, and effort levels while interacting with augmented reality and virtual reality.

3.6.8.5 Ambient Light

The surrounding real-world light conditions can affect the visibility of the augmented projection. Therefore, some devices include ambient light sensors to increase the brightness of augmented elements within the projected view and decrease brightness during darker conditions. The goal is to mimic the surrounding world conditions to help increase the immersive quality of the device (Peddie, 2017).

3.6.8.6 Wireless

As mentioned, the existing network infrastructure (i.e. WiFi, Bluetooth, mobile phone networks) can determine position based on signal strength. The wireless sensors are also required to relay data (including communications, situational awareness data, terrain data, etc.) to and from other users in collaborative environments or to potential base stations that aid in processing data. Base stations with wireless networking capabilities can use unique identifiers on the mobile AR units to determine location within the greater environment (Schmalstieg & Hollerer, 2016). With the adoption of 5G, many devices are exploring or utilizing the benefits of cloud-based augmented reality processing which alleviates the weight and complexity of the augmented reality devices. Depending on networked speeds, however, this does add to the end-to-end latency as discussed in Section 3.6.4.

3.6.9 Computing & Processing

Augmented reality devices can utilize on-board or on-device processing systems or offboard systems. As an example, the Hololens 2 has on-board processing of all sensor related data including the ability to track real world objects and subsequently display them on the holographic waveguide to the user's eyes (Microsoft Hololens, 2021). This process is more complex than a remote off-board processor as it requires on-board batteries and significant computing power on fit within a headset. Increasing the hardware elements to an HMD has a negative effect on the weight and balance. Lightweight AR HMDs, such as the Epson BT-35E require a wired or wireless (Bluetooth, wifi, cellular) connection to a Controller (running an OS such as Android), smartphone, or to a separate CPU for off-board processing of data (Figure 91). Augmented images are then returned to the device via the same method. These devices have the benefit of decreased weight, increased memory (off-board on a computer), however they are more cumbersome with trailing cables and body-worn devices, as compared to the full stand-alone HMDs. The processing and memory capabilities of these devices vary according to the devices they are connected to (generally via USB-C).

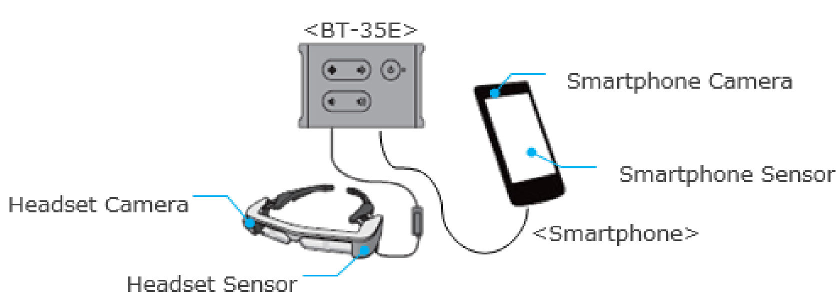


Figure 91: Hardwired HMD example (Epson BT-35 E, 2021)

3.6.10 Operating System / User Interface

Information overload can happen when the information presented to a user is greater than their ability to make decisions effectively or adapt to the presented content. This can cause mental strain, visual fatigue, and increase the chances of making mistakes (Karlsson, 2015). The User Interface (UI) is one of the most important aspects of design - displaying the right information, at the right time, in the right way. AR Developers are investigating ways to filter information adaptively based on individual users. By following hierarchical UI design standards (e.g., Shneiderman's Rules of Interface Design, Norman's Six Principles, Smith & Mosier Functional Areas of UI Software), developers can begin to adequately categorize information and tailor to individual user needs. Adaptive information filtering can track a user's preferences or attention level to specific situational awareness information and minimize or enhance as needed based on eye-tracking (You et al., 2018).

3.6.11 Power

Augmented Reality devices, especially those classified as wearables, require unique power setups. If tethered, power can be drawn from a local source such as the phone or computer it is connected to. However, most AR devices utilize some form of on-board or external battery pack. Battery life is an on-going problem for AR devices, particularly HMDs, and is highly dependent upon the information presented, the brightness of the display, the complexity of information shown, the operating temperature of the device, the number of active sensors, etc. Battery life has been identified as one of the greatest limiting factors of expansive growth for AR (MarketsandMarkets, 2019).

3.6.11.1 Battery Life, Power Consumption, Battery Type

The standard battery on most consumer HMDs is a rechargeable lithium-ion configuration that lasts 2 to 4 hours. Those HMDs with lower processing capacity or off-board processing units have run times of 6 to 12 hours. Some allow for quick-swap batteries (such as Vizux) which lets their HMD operate for 1-3 minutes on a small internal power source while the main battery is switched. Vuzix specifies a 2-to-5-hour battery life with external packs ranging from 2-5 hours and an extended external pack (attached to the user) providing 8 to 10 hours. Highly customizable and developer editions, especially MOTS devices, have external battery supply and power hookups to portable battery banks. The power draw depends on the number of sensors, information displayed, networking utilization, and many other factors.

3.6.12 Communications Interfaces

Most AR devices, especially HMDs, have some form of integrated communications device that is either button or voice activated. Gesture-controlled devices can also initiate the voice activation features depending on how the device is programmed.

3.6.12.1 Gesture / Hand Tracking

Gestures or motions conducted by the AR user can be tracked through a wearable or through virtual hand tracking. For a HMD, the primary tracking is on the user's hands and fingers in order to navigate menus, and manipulate onscreen content (rotate, drag, select, etc.) (Peddie, 2017). Early work used static postures, but with increasing computational power more dynamic and complex movements can be analyzed and stored in a recognition database (Schmalstieg & Hollerer, 2016). The gestures recognized vary across systems and there is currently no set standard. Additionally, the processing and sensing of hand movements may need to handle high speeds of up to 8 m/s and 300 deg/s (Erol et al., 2007; Varga et al., 2004).

3.6.13 Audio

As AR systems become more immersive, their audio systems should be able to produce a fidelity that properly mimics the environments the users are experiencing. This is very important in VR devices to improve immersion but is also a key in developing realistic AR experiences. For example, binaural or spatial audio in AR headsets can help users quickly locate the device or individual producing that sound – i.e. the sound comes from the location of the visual stimuli and moves in the same direction as the visual stimuli (Gallagher, 2020). Headphones can be built into HMDs to reflect both real world and augmented reality audio as well as communications systems. Additionally, some HMDs (smart glasses in particular) are utilizing bone conduction speakers versus traditional audio devices. Bone conduction produces vibrations within the individual's jaw or skull. The result is audio heard only by the user. Additionally, this allows the ears to be open to the ambient environment and therefore can improve the realism of an augmented experience (Peddie, 2017).

3.6.14 Price

The costs associated with AR go beyond the specific hardware device (e.g., HMD or smart glasses) which range from a few hundred to $20,000+ USD as COTS or MOTS. Full enterprise developed models for specific use cases can eclipse $100,000 USD or more depending on capabilities, sensors, and networking. Additional costs include the applications which are responsible for image recognition, flat surface and world recognition, customized user experience designs, optimization of sensing elements, iterative testing, ruggedization, integration with external devices like battery-packs, user experience testing, human factors and in-field testing, etc. All of these costs can involve thousands if not hundreds of thousands of hours of development for specific use-cases. For example, Facebook has a Reality Labs division with almost 10,000 employees responsible for developing both augmented and virtual reality devices. A key element in driving down costs of MOTS devices for non-consumer use will be the adoption of Smart Glasses at the consumer level. As these AR devices become more mainstream, the increased investments into their capabilities will drive costs down, increase their capabilities, and therefore feedback into increased adoption (Figure 92). Additionally, improved usability and increased adoption of these devices will help to attract more funding and research dollars.

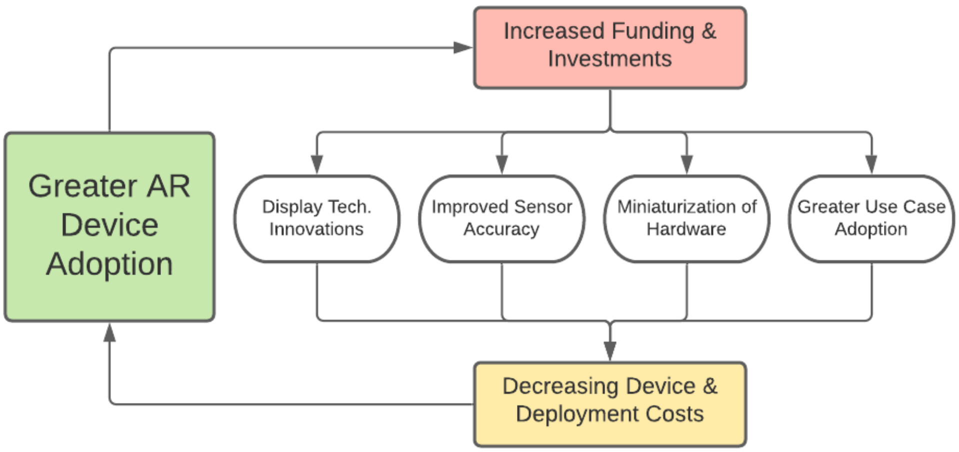


Figure 92: Device Adoption Feedback Loop

3.6.15 Compatibility

3.6.15.1 Mounts & Helmets

Within the HMD category, the majority of COTS devices are standalone HMDs that use smart glasses to present imagery. However, some are specifically compatible with existing eyewear, night-vision goggles, and helmets. All the fully-immersive, video see-through, and binocular-based optical see-through devices are based on a smart glass binocular immersion experience, and specific compatibility with different helmets and military gear would need to be investigated. Monocular optical see-through devices (eg. YoungOptics, Vuzix, BAE Systems Battleview 360, RAECON ARC4, and HUNTR) clip onto existing devices, HMDs, or other equipment. Figure 93 shows some examples (a Vuzix hardhat mount, an Elbit Systems Weapons Sights mount, and a clip-on ARC4 unit).

Figure 93: Examples of mounting options (ElbitSystems, 2021; Vuzix, 2021)

3.7 Software

As previously discussed, augmented reality systems require inputs and sensors to relate real and augmented data to the user. These inputs and sensors communicate to a device driver which is a specific type of software that determines how software interacts with hardware (e.g., sensors). This information is relayed to the specific application created by developers for the specific AR use case. The application, interface, and device driver run on a specific operating system developed for AR. A very simplified information pathway is presented in Figure 94 (Peddie, 2017). This basic pathway allows the AR device to run through its four essential processes (Hořejší, 2015):

1. Capture the Scene, User FOV
2. Identify the Scene (moving objects, stationary environment, etc.)
3. Process the Scene with Desired AR Overlay,
4. Display the AR to the User.

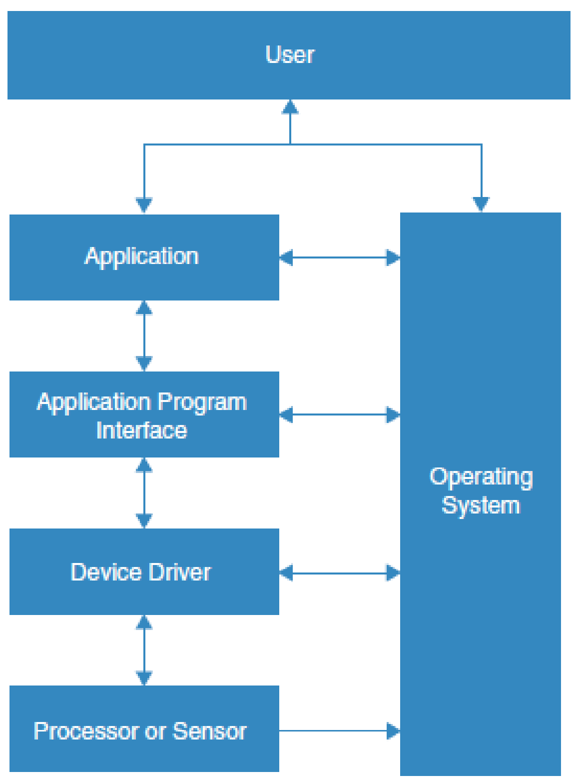


Figure 94: Information flow from processor to user (Peddie, 2017)

The software applications used by AR devices are specific to the individual device, as each has unique technologies, sensors, use-cases, desired outputs, working environment, display devices, and so on. Software Development Kits (SDK) for Augmented Reality allow developers to customize the applications to build their own specific AR environments and information overlays.

3.7.1 AR Visualization & Tracking

As discussed in Section 3.6.8, real-time, accurate information presentation from sensors and cameras is important for the AR experience. It is even more important for the military domain. Having accurate orientation, location, and situational awareness data in real time is required.

Tracking in AR technology refers to dynamic sensing and measurement of spatial properties. It involves the visualization of objects and their coordinate system relative to the world, the camera and user position coordinates, and correctly overlaying the virtual objects in a dynamic way (Figure 95). Tracking can be outside-in (sensors or cameras not located on the device are used to track its position and orientation) or inside-out (sensors on the device track position and orientation). In the latter case, there is no need for cabling, base stations, or off-board CPUs.

The tracking of visual objects that are not sensors (real world static, moving elements, blue-force, enemies, etc.) requires some form of image-based tracking utilizing visual, thermal, infrared or any other spectrum of visual data collection. The first step is to use feature detection or other image processing techniques to determine relevant objects in camera images including corner detection, blob detection, or edge detection (Sicaru et al., 2017; Wang et al., 2020).

In most AR cases, the scene has multiple unknown elements and therefore a technique called Simultaneous Localization and Mapping (SLAM) is used. Here, both image data and mathematical models are used to calculate what the real world "looks" like to the AR device. After recognizing the SLAM image markers, digital information can be overlaid on them (Vaniukov, 2020). This 3D registration is the key to AR technology, providing precise calibration to the real world.

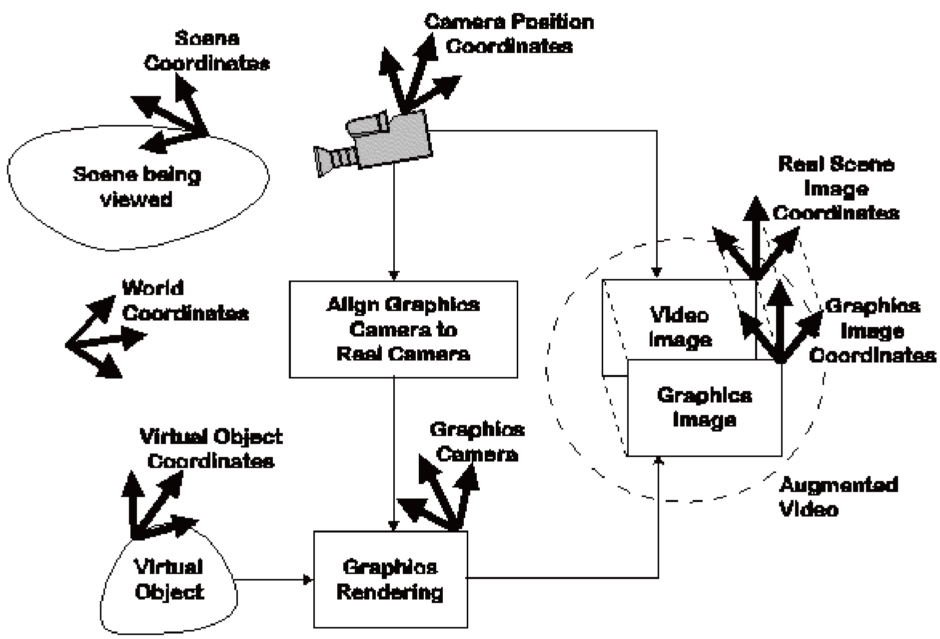


Figure 95: Coordinate Systems in AR Tracking (Vallino, 2002)

3.7.2 AR SDKs

A Software Development Kit (SDK) allows developers to create their 3D object tracking methods, image recognition, and SLAM (Simultaneous Localization and Mapping) for mobile applications, CAD platforms, Graphical User Interfaces, and other backend tracking processes. These SDKs are specific to the application type (augmented reality, virtual reality, etc.) for a given operating system. For example, , a Java SDK is needed for Android. For Windows OS, a .NET Framework SDK is required. The future success and speed of adoption with AR depends on the availability of SDKs that developers can use (Bottani & Vignali, 2019). In many instances there are free SDKs which may have limited features but can drastically decrease development costs on early iterations. Utilizing Cloud-Based or Off-Device SDKs can decrease the amount of memory taken up by the onboard system, at the cost of increasing latency in the processing and recognition of images and markers.

Some popular SDKs currently available include (Vaniukov, 2020):

- **ARCore** https://developers.google.com/ar/
    - Created by Google for Android
    - Integrate real and virtual worlds through a cell phone camera using:
        - Motion tracking
        - Light estimation
        - Environmental understanding
- **ARKit** https://developer.apple.com/augmented-reality/
    - Create augmented reality experience for iPhone and iPad (iOS 11)
    - 2D image detection, 2D image tracking Ikea Place, Overstock (US retailer), Housecraft, Giphy World
    - Recognize 3D objects and spaces/voids, differentiate between real and virtual, place virtual objects on surfaces
- **Vuforia Engine** - https://www.ptc.com/en/products/vuforia/vuforia-engine
    - Recognizes different types of visual objects (box, plane, cylinder, texts, environments) – VuMark
    - Vuforia Object Scanner - can create and scan object targets
- **HP Reveal** - https://www8.hp.com/us/en/printers/reveal.html
- **ZapWorks** - https://zap.works/pricing/
- **Amazon Sumerian**: https://aws.amazon.com/sumerian/
    - Integrated with AWS
    - Creates engaging 3D experiences
    - Easy access to machine learning, chatbots, code execution
    - Web-based platform can run AR & VR

- **Streem** - https://www.streem.com/products
- **Augment** - https://www.augment.com/
- **AR SDK** - https://www.kudan.io/sdk
- **AR.js** - https://ar-js-org.github.io/AR.js-Docs/
    - Lightweight library, JavaScript powered for web
    - Free, open source
    - Works on every mobile device with web GL and WebRTC (Web Real-Time Communication)
- **NREAL**
- **Wikitude** - https://www.wikitude.com/external/doc/documentation/latest/uwpnative/
    - Favoured by professional developers
    - Features:
        - Scene recognition
        - Extended tracking and recording of object
        - Instant targets
        - Windows support
    - Can create markerless AR apps for both iOS and Android - compared to ARKit and ARCore

3.7.3 Android Team Awareness Kit (ATAK)

Android Team Awareness Kit (ATAK) is an app-based GPS technology that is designed to improve situational awareness using both blue and red force tracking (Pruitt, 2020) (Figure 96).

Figure 96: ATAK Example (Department of Homeland Security, 2017)

Users are able to orient themselves more quickly, avoid threats and complete missions increased success rates (Directorate DHS Science and Technology, 2017). In military settings, ATAK refers to Android Tactical Assault Kit (Air Force Research Laboratory, 2021). This technology has fundamentally changed information exchange during missions by allowing instantaneous sharing of GPS coordinates, photos, videos, text messages, and other files. Employing ATAK in pre-mission planning allows organizers to consider elements of the terrain in advance, such as elevation, open space, and other potential hazards (Directorate DHS Science and Technology, 2017). Additionally, users can drop icons onto the 2D map to indicate points of interest such as planned routes and locations of vehicles. Where relationships exist, agencies can access live camera feeds from nearby street cameras or platforms (e.g., partner helicopters). The developments in ATAK technologies have enabled the sharing of information between organizations, which can improve the coordination and effectiveness of missions that involve multiple agencies (Air Force Research Laboratory, 2021). Until the introduction of ATAK, missions frequently relied on antiquated methods such as voice communications via radio for location sharing. Encrypted data can now be shared from user-to-user, user-to-team, user-to-command and user-to-entire team (Pruitt, 2020). ATAK can be downloaded onto smartphones, tablets and other handheld devices, enabling its use in multiple settings such as multiple viewers in a conference room or hands-free use by strapping the device to a user's body (Directorate DHS Science and Technology, 2017). Finally, ATAK can be integrated with a wide range of AR technologies, including the Enhanced Clip-On Thermal Viewer (ECOTI) and Enhanced Clip-On SWIR Imager (discussed in Section 4).

3.8 Military Considerations for Augmented Reality

The utilization of AR in the military sector is more challenging than typical consumer-based AR environments. Therefore, modified COTS systems are required specific to military applications with highly customizable and adaptable software and SDKs, as well as improved ruggedization, battery life, security, connectivity, protection, and a host of other requirements. You et al. (2018) identified a number of AR system challenges within the military environments including:

a) Keeping the system stable (reduce latency, jittering, etc.) during fast movements and quick head position changes

b) Robust registration during poor visibility (smoky, night, electromagnetic interference)

c) Improving computing processing and efficiency to maximize portability

d) Improved battery life compared to COTS

e) Recognizing increased cognitive demand during military exercises

A representation of the information required for an AR system utilized in a military environment is illustrated below in Figure 97:

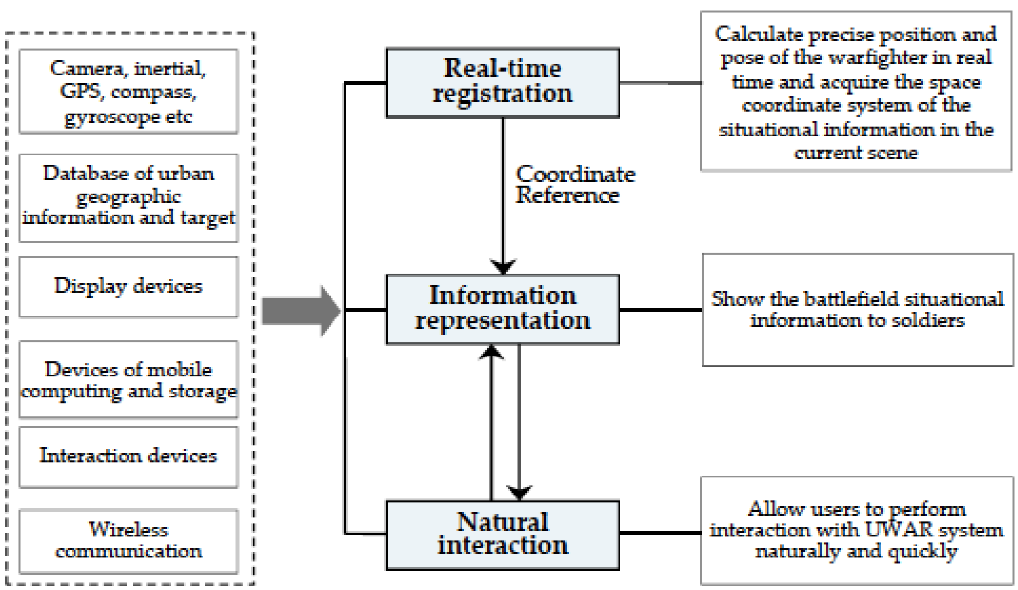


Figure 97: Information input examples required for a military-use AR system (You et al., 2018)

COTS devices as they exist today do not meet these requirements. For example, the typical battery life for the Hololens is 2-3 hours of continuous use, which is inadequate for long-term military operations (Wang et al., 2020). Many of the MOTS are based on consumer models or use their own customized hardware, waveguides, sensors, protection, power, and software systems.

3.9 AR Devices

As described, AR Devices can be categorized into Heads Up Displays (HUD), Head-Mounted Display / Smart Glasses (HMD), Tablet / Smartphones, and Spatial / Projection (Figure 98).

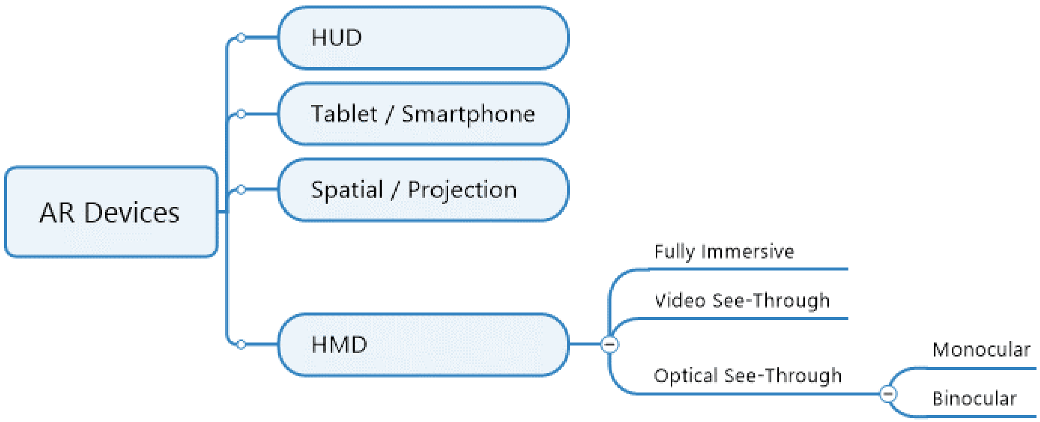


Figure 98: AR Device classification

3.9.1 Heads-Up Display (HUD)

HUD devices are commonplace in automotive and commercial/military aircraft, where the windscreen or a separate pane of glass is used as a projection surface, in order to enhance situational awareness (G.-H. Kim et al., 2008). WayRay introduced their HUD that utilizes augmented reality within the windshield (Figure 99). Panasonic is also developing their own Augmented Reality HUD that utilized artificial intelligence to recognize objects as well as driver gaze to alert for potential dangers. This AR HUD from Panasonic (Figure 100), is slated to be in vehicles by 2024 (Baldwin, 2021).

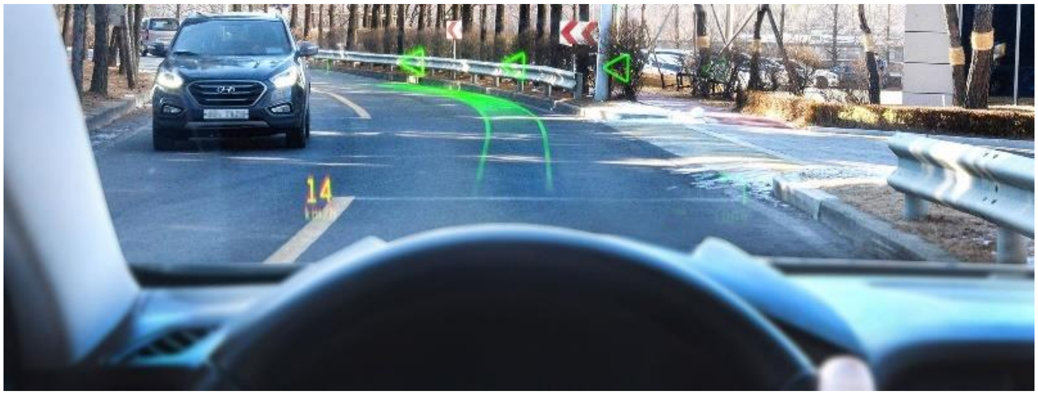


Figure 99: WayRay HUD built into the windshield (waveguide technology) (WayRay, 2020)

Figure 100: Panasonic HUD example (Baldwin, 2021)

3.9.2 Tablet/Smart Phone

Handheld devices like tablets and smartphones are the most common AR device on the market today. There are many free AR programs available on Android and Apple Platforms. These devices have both back and front-facing cameras and can access remote visuals to combine into an augmented image. The most popular handheld AR systems are commercial in nature including: IKEA Place (furniture placement), MeasureKit (measuring tool), Snapchat, Instagram, and Google Translate. From a modified COTS perspective, utilizing Tablet, Smartphone, or Smart Watch displays provide multiple opportunities to support military operations and combat missions.

3.9.3 Spatial / Projection

Spatial Projection-based AR devices do not require any optical device to view content. Three examples of this technology include Hololamp (Figure 101) and AR Sandbox (Figure 102). The Hololamp projects an image using a short-throw projector and includes tracking sensors to observe user gestures. The application of Hololamp below showcases a menu with a projected 3D view of the food available and allows for users to select and order.

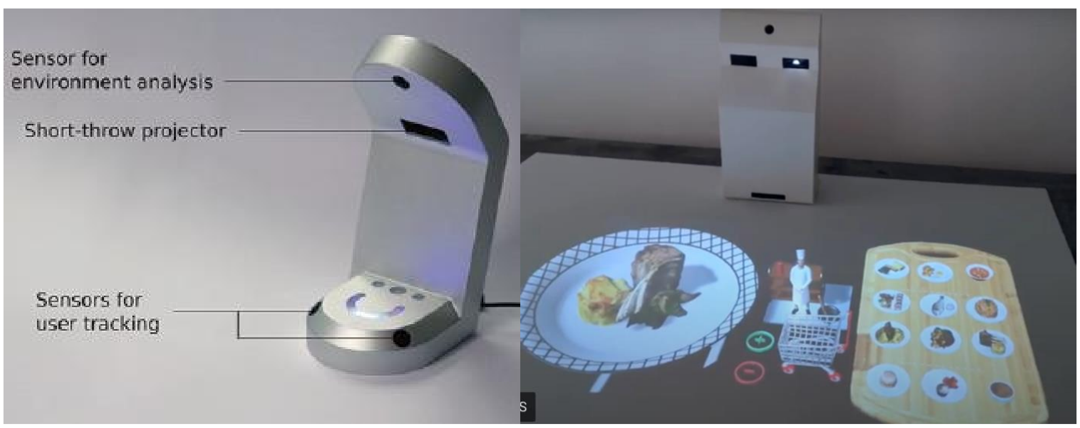


Figure 101: HoloLamp (HoloLamp, 2021)

The Augmented Reality Sandtable (ARES), Figure 102, uses COTS products and U.S. Army-developed software to highlight terrain, objects, or other environmental objects (Spain et al., 2019). The Sandtable Software was developed as open-source, and can be modified for different use cases. The software allows for varying inputs, hardware, sensors, gestures recognized, and display outputs. For example, a Microsoft Kinect camera can be programmed to measure depth (sand height) in conjunction with a projector to map out topography, features, and individuals. When networked, mobile users can contribute to the information presented.

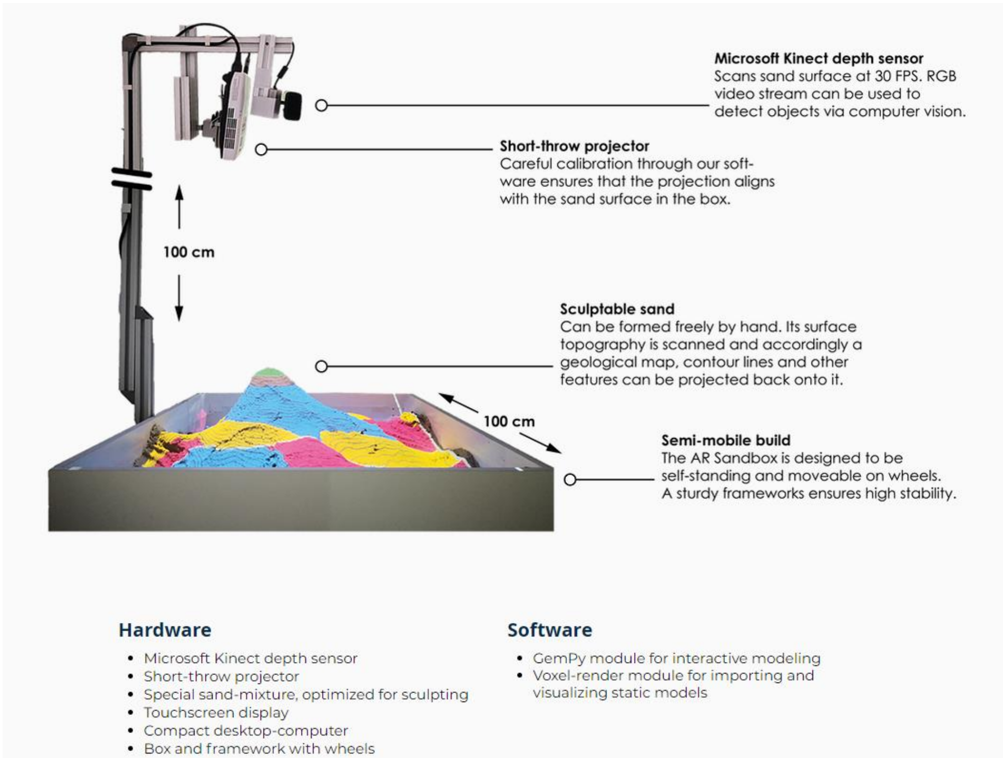


Figure 102: AR Sandbox(GemPy, 2020)

3.9.4 Head-Mounted Displays (HMD)

HMDs can be classified by display into Fully Immersive, Video See-Through, and Optical See-Through (Figure 103):

- Fully Immersive is essentially a Virtual Reality Device
- Video See-Through is becoming less common as
- Optical See-Through has the largest number of devices and potential in the world of AR.

Optical See-Through is further sub-divided into their ocularity (number of eyes required to see something (Figure 104). Vendor-supplied information on features and specifications for HMD devices are discussed in this section.

In the AR Reality realm, the primary devices are Monocular and Binocular.

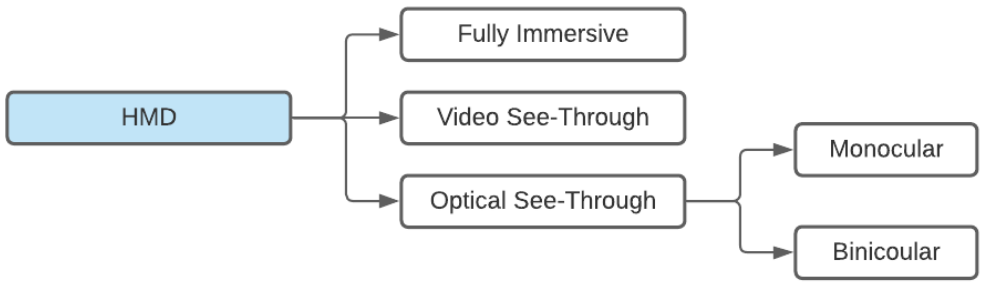


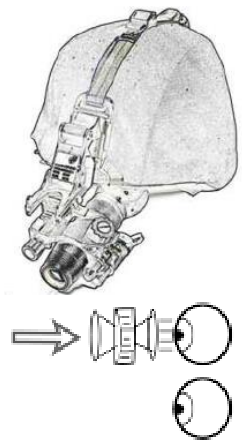
Figure 103: Classification of HMDs

3.9.4.1 HMD – Fully Immersive

Fully immersive devices are essentially VR in that they do not utilize cameras to view the external world. Examples of these include the Oculus Rift and Varjo VR3.

3.9.4.2 HMD – Video See Through

Video see-through devices on HMDs are rare; most devices involve either optical see-through or fully immersive VR only. Most video-see through devices are non-HMD variants such as tablet/smartphone devices. This report identified one leading company in the VR to AR space – Varjo XR-3.



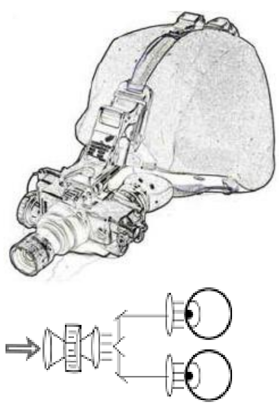
Monocular uses a single view channel to a one-eye while allowing the other eye to view the unaltered real-world environment.

Advantages:

- Low weight
- Small form factor
- Easiest integration and alignment (clip-on)

Disadvantages:

- Binocular Rivalry
- Small FOV
- No "immersion"



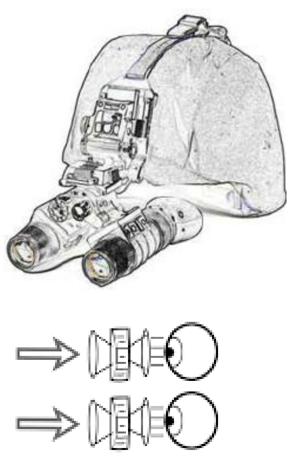
Biocular provides the same single channel to both eyes. Useful for close tasks or when stereopsis is not required.

Advantages:

- No visual Rivalry
- Less weight than binocular

Disadvantages:

- Increased weight
- Limited FOV and peripheral
- No depth cues



Binocular provides two distinct channels for each eye in an attempt to create a stereoscopic view.

Advantages:

- Stereo images
- Larger FOV and depth capabilities
- Highest sense of "immersion" by the user

Disadvantages:

- Heaviest and most complex/expensive
- Alignment sensitivities
- Processing Intensive especially as sensors # increases

Figure 104: HMDs categorized by ocularity.

Adapted from Goodwin (2021); Parush et al. (2011)

3.9.4.2.1 Varjo XR3

The Varjo XR-3, Figure 105, is the extended/augmented reality version of the VR-3 with the inclusion of LiDAR and RGB Fusion with pass-through cameras. It can present a stereo image within a range of 0.4 to 5.0 m. The video pass through is viewed at 90 Hz although latency numbers are not provided. The device costs $8,315 CAD, and uses eye tracking at 200 Hz to produce foveated rendering of the video see-through content.

Figure 105: Varjo XR-3 (Varjo, 2021)

3.9.4.3 HMD – Optical See Through

This is the most common AR display technology for both COTS and MOTS devices. A detailed overview of Optical See-Through is provided in Section 3.6.2.3. AR Optical See-Through devices can be either monocular or binocular as shown in the Figure 106.

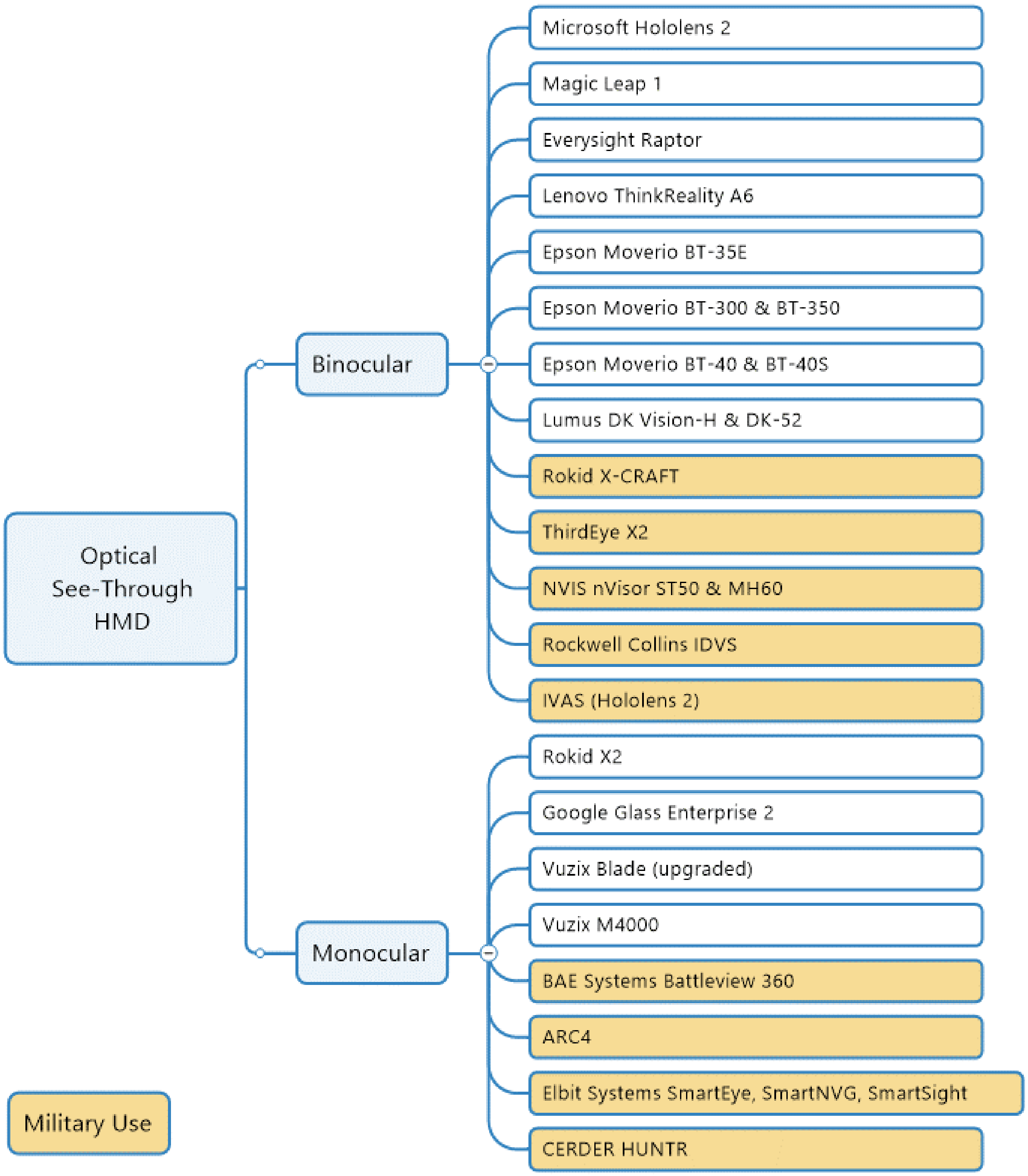


Figure 106: Optical See-Through HMD hardware

3.9.4.3.1 Binocular Optical See-Through Displays

3.9.4.3.1.1 Microsoft Hololens, Hololens 2

The Hololens 2 (2019+), Figure 107, is probably the most well-known of the Optical See-Through Binocular devices as its commercial popularity has drastically increased since the original Hololens 1 launched in 2016. Additionally, Microsoft was awarded a contract with the U.S. Army to develop and adapt the Hololens for IVAS – Integrated Visual Augmentation System and to deliver approximately 40,000 devices for 2021. The Hololens 2 houses one 2K display per eye at 120 Hz with a 47 pixels per degree resolution close to that of the ~60 ppd within the foveal region of the eye. The FOV is 43 degrees horizontal and 29 degrees vertical. Hololens 2 provides both eye and hand tracking and is a standalone unit with all processing occurring on the device. Unfortunately, battery life is only 2-3 hours on full use. The Hololens 2 as of this report has a MSRP of $6,799.

Figure 107: Microsoft Hololens (top) and Hololens 2 (bottom) (Microsoft Hololens, 2021)

3.9.4.3.1.2 Magic Leap 1

Magic Leap 1, Figure 108, has a 50-degree field of view (greater than that of Hololens 1 and 2 from Microsoft) with a 4:3 aspect ratio 1280 x 960 RGB display pixels per eye and 120 Hz refresh rate. The device weighs 316 g and the battery life is about 3.5 hours of continuous use (similar to the Hololens). Magic Leap uses eye tracking and voice commands and can work with users using prescription eyewear through the addition of prescription inserts. Significant recent deals have been struck between Magic Leap and telecom companies and app makers (AT&T, Lucasfilm, Wayfair, Spotify, and Wacom). The Developer Suite of Magic Leap 1 as of this report is $3150 CAD.

Figure 108: Magic Leap 1(Magic Leap, 2021)

3.9.4.3.1.3 Everysight Raptor

The Everysight Raptor, Figure 109, is extremely lightweight with up to 8 hours of continuous battery usage however it is limited in terms of sensors compared to other HMDs. It is mostly a HUD – HMD to project information for cyclists (speed, Heart Rate, Cadence, etc.) and there is no object recognition, AR tracking, etc., only a display. The MSRP is $854 CAD as of this report.

Figure 109: Everysight Raptor (Everysight, 2021)

3.9.4.3.1.4 Lenovo ThinkReality A6 (mid 2021)

Lenovo has developed two VR specific devices (Mirage Solo and Explorer) and at CES 2021 announced they will be launching their first AR HMD. The ThinkReality A6 (Figure 110) has a 1080p per eye, 40-degree diagonal FOV display and uses an Android OS. It offers approximately 4 hours of battery life (6800 mAh) and weight 360 g. As an enterprise solution, it allows developers to create specific AR platforms using SDKs with on-board SLAM recognition. Pricing details are still to be released as of this report.

Figure 110: ThinkReality A6(Lenovo, 2019)

3.9.4.3.1.5 Epson Moverio BT-35E

The Epson Moverio BT-35E (Figure 111) is an interfaced unit, which means that it connects to a variety of output devices via HDMI or USB-C ports. It draws power from the device it is connected to and therefore battery life is not a listed spec. The display is a 1280 x 720 SI-OLED (30 Hz) variant with a diagonal FOV of 23 degrees. The entire headset weights about 119 g with a 45 g interface hub. As of this report, the approximate price of this HMD is $1,119 CAD.

Figure 111: Epson Moverio BT-35E (Epson BT-35 E, 2021)

3.9.4.3.1.6 Epson Moverio BT-300 & BT-350

The Epson Moverio BT-300, Figure 112, and BT-350, Figure 113, use a 1280 x 720 SI-OLED (30 Hz) with a diagonal FOV of 23 degrees. Both variants of the device have a 2950 mAh Li-Polymer battery providing about 6 hours of run time and run their proprietary Moverio OS System with a specific Moverio SDK. The BT-350 is the ruggedized version of the BT-300 as it is IPX-2 Waterproof (against light rain). This ruggedization comes with increased weight (129 grams) compared to the BT-300 (69 grams). As of this report, the BT-300 is $899 CAD and the BT-350 is $1,599.

Figure 112: Epson Moverio BT-300 (Epson BT-300, 2021)

Figure 113: Epson Moverio BT-350 (Epson BT-350, 2021)

3.9.4.3.1.7 Epson Moverio BT-40 and BT-40S

The Epson Moverio BT-40 and BT-40S, are Epson's newest line of AR devices (launch Q2 2021) with a much greater FOV compared to their other models. The BT-40 variants have a diagonal FOV of approximately 34 degrees with dual SI-OLED display at 1920 x 1080 pixels (1080p HD resolution) per eye. The BT-40 is an interface model with a USB-C connection to tablets and PCs for both power and processing. The BT-40S is the standalone Developer Version with a control running Android 9.0 that allows for custom software integration. The contrast of these two devices are also significantly improved at almost 500,000:1. The display technologies for this device are Silicon-OLED 1080p. The BT-40 will be priced at approximately $730 CAD and the BT-40S for $1260 CAD.

Figure 114: Epson Moverio BT-40(S) (Dignan, 2021)

3.9.4.3.1.8 Lumus DK Vision-H & DK-52

Lumus creates multiple transparent displays for a variety of optical see-through HMD manufacturers. They also have created four developer kits to serve as references for OEMs as they develop products. The DK Vision-H has a full on-board processing system (Qualcomm) with two 4MP cameras and tracking sensors built on the Android 6.0.1 platform with an upgrade available to Android 7. It utilizes a waveguide and a 1080p display at 60 FPS with a 40-degree diagonal full overlap FOV. The DK-52 has the same 40-degree FOV with a 720p resolution per eye. Both devices are customizable with optional sensors as they are developer kits.

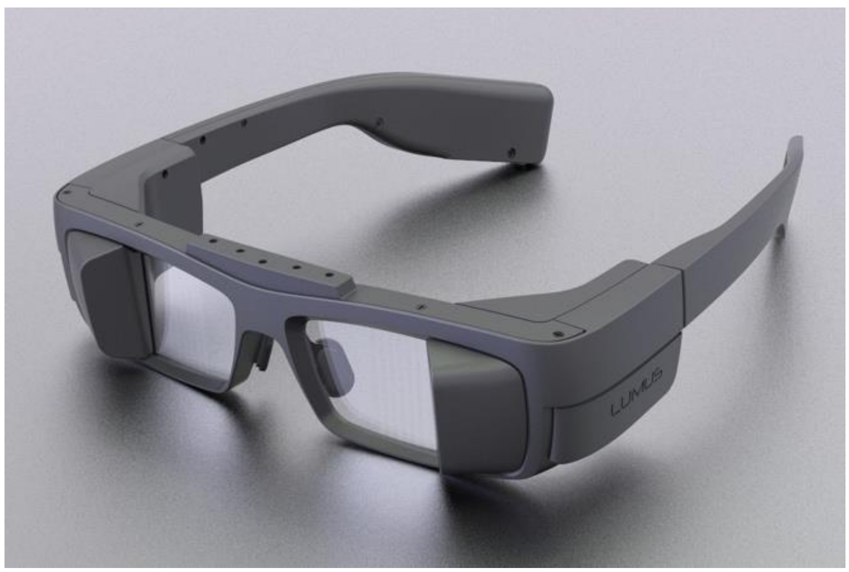


Figure 115: Lumus DK-52 (Lumus DK-52, 2021)

Figure 116: Lumus DK Vision-H (Lumus DK-Vision-H, 2021)

3.9.4.3.1.9 Rokid X-CRAFT

Rokid is a start-up company from China that developed two versatile AR devices, the X2 (monocular) and ruggedized X-CRAFT (binocular). These devices utilize Android as an OS with a 1280 x 960-pixel display using a waveguide with a 60 FPS refresh rate and 40-degree diagonal FOV. The Rokid X-Craft, Figure 117, is a ruggedized binocular display utilizing a waveguide with 40-degree field of view (IP66 dustproof, waterproof, safety zone 1 and zone 2 explosion-proof). The addition of a 5G wireless module increases its capabilities for potential off-board processing.

Figure 117: Rokid X-Craft AR Headband (Rokid X-Craft, 2021)

3.9.4.3.1.10 Third Eye X2

ThirdEye is a US company that has 20 years of augmented and mixed reality development experience for the U.S. Department of Defense (ThirdEye, 2021). They have developed technology including laser rangefinders for pre-shot threat detection, Augmented Reality Scopes' electro-optics design and AR HMDs for the military. Early February 2021 Third Eye announced their HMDs will be utilized by the United States Army Pacific (USARPAC) to support Theater Army mission command functions (Intrado GlobalNewswire, 2021). Their X2 HMD has a 42-degree diagonal FOV using a 1280 x 720 pixel display and a 1900 mAh single rechargeable battery. The device is AR-capable using VisionEye SLAM SDK integration with Android 8.1. Sensors include thermal, flashlight, RGB 13-megapixel camera, ambient light sensor, and depth sensors. The X2 is PPE compatible, ANSI/ISEA Z87.1 (Class E, Type 1), CSA Z94.3 (Class E, Type 1), EN 166, IPO40, and UL 62368-1 certified.

The user interface takes advantage of gaze, voice activation, a wireless controller, and gestures and is useable in a wide range of conditions (indoor, outdoor, artificial light, etc.). The device weighs approximately 170 grams. The ThirdEye X2 Developer Kit comes with a pair of glasses, the VisionEye SLAM Module for $3640 CAD for one unit to $31,366 for 10 units.

Figure 118: ThirdEye X2 (ThirdEye Gen, 2020; ThirdEye X2, 2021)

3.9.4.3.1.11 NVIS - nVisor ST50 & nVisor MH60

NVIS manufactures near-eye display products including head-mounted displays, virtual binoculars, and embedded displays into vehicle and weapons simulators. The nVisor ST50 is a HMD with 1280x1024 OLED display and a 50 degree diagonal FOV. A removable cover allows developers to create VR content if required. No motion-tracking sensors are included but it is compatible with standards from InterSense, Ascension, Polhemus and other motion tracking devices. The ST50 also requires off-board processing in contrast to other HMDs listed here with built in processors. It weighs 1050 g and costs $19,700 USD.

Figure 119: nVisor ST50 showing optical see-through condition (left) and VR condition (right) (NVIS, 2020)

The nVisor MH60 is a helmet-compatible display (compatible with Gentex HGU-84 & HGU-56). The MH60 uses an older technology (LCOS reflective) compared to the waveguide methods for other HMDs (as described above). It utilizes a SXGA 1280 x 1024 display with a 60Hz refresh rate and a 34.4 degree vertical and 43.6-degree horizontal FOV. The MH60 weighs just under 1 kg and does not have cameras or the ability to track its location, although it is compatible with many industry-standard motion trackers as aftermarket options. The MH60 is $23,900 USD. Off board-processing is required via connection to a computer.

Figure 120: nVisor MH60 helmet variant (NVIS, 2020)

3.9.4.3.1.12 Rockwell Collins – IDVS

IDVS by Rockwell Collins allows for both day and night hands-free situational awareness data presentation using low-light image processing to see through fog, smoke, dust storms, etc. It utilizes a 40-degree horizontal FOV WUXGA resolution display along with a custom battery pack with four 18650 batteries (6 hours runtime) or eight CR123 batteries. This device is highly customizable regarding sensors or external power options and can mount to a standard night vision shroud.

Figure 121: IDVS from Rockwell Collins (Rockwell Collins, 2021)

3.9.4.3.1.13 IVAS

The IVAS program and feature sets were described in Section 3.4.5.

The IVAS System is a highly modified MOTS version of Microsoft's Hololens 2 (Figure 122). The IVAS development program organized their builds into four set of capabilities. The goals for Capability Set 4 were to have an integrated AR, low-light/IR fused system, with tactile/voice/gestural control, integrated with the Nett Warrior data for situational awareness, navigational cuing, and rapid target acquisition. The IVAS system also provides the capability for collaborative navigation and mission planning, 3D navigation with user-designated routes, soldier position tracking in GPS-denied areas, auto-target detection with aided detection and classification of targets (man/vehicle/other) and recognition (enemy/friendly/vehicle type), and post-mission after-action review capabilities.

Figure 122: IVAS prototype during training exercise in Fort Pickett, VA (Siter, 2020)

The IVAS Capability Set 4 incorporates the latest HUD 3.0 system with waveguide optics and the latest U.S. government-furnished thermal and low-light sensors to achieve image fusion, in addition to the existing environmental and RGB camera systems on the IVAS headset, as discussed in Sections 3.6.8.1 and 3.9.4.3.1.1 (Figure 123). The sensor goals of the IVAS program were for the low light cameras to enable, as a minimum, detection (80% probability) of a man-sized object at 150 m with 25% illumination (1/4 moon) and ideally up to 90% detection at 150 m with only 5% illumination (starlight). The thermal camera must allow, as a minimum, an 80% probability of recognition of personnel up to 300 m at all light levels, and ideally out to 500 m.

Figure 123: IVAS Cameras and Sensors (PEO Soldier, 2020)

3.9.4.3.2 Monocular Optical See-Through HMDs

3.9.4.3.2.1 Rokid X2

Rokid is a startup company from China that has developed two versatile AR devices, the X2 (monocular) and ruggedized X-CRAFT (binocular). These devices have an Android OS with a 1280 x 960-pixel display that uses a waveguide, with a 60 FPS refresh rate and 40-degree diagonal FOV. The key application of the monocular device is an additional infrared sensor clip-on device with 384 x 288 resolution at 25 Hz frame rate. The device can be used as a non-contact method for measuring body temperature (driven by the COVID-19 crisis). The Rokid is tethered to a battery to reduce the weight on the user’s head (96 g HMD weight). The battery provides 8 hours of usage.

Figure 124: Rokid X2 (Rokid, 2021)

3.9.4.3.2.2 Google Glass – Enterprise 2

Google initially announced that it would stop producing the Google Glass in 2015. However, in 2019 they launched the Google Glass Enterprise Edition 2 (adopted by DHL, GE, & other large manufacturers). It uses the Android 8.1 OS Open-Source platform. It is IP53 (resistant to water spray and limited dust ingression). The display FOV was not published but it includes a pixel count of 640 x 360 pixels. The intention of Google Glass's design is to display content outside the main foveal region into the periphery for users to refer to as needed. This stands in contrast to other HMDs that aim to augment larger FOVs within the main foveal region of the eye.

Figure 125: Google Glass Enterprise 2 Edition (Google, 2021)

3.9.4.3.2.3 Vuzix - Blade Upgraded

Vuzix supplies multiple AR technologies to defence, security, and enterprise customers. The Blade Upgraded (Figure 126), is the oldest of the Vuzix models and is based on Android 5.1.1 (vs. Android 9.0 on the M4000). Its display is a 1:1 aspect ratio (480 x 480 waveguide) with 19 degrees FOV adjustable within a 24-degree FOV window (right eye only). The camera is just 720p (compared to the other models which offer 4K, see below). The inputs from the user are solely touch pads or voice control (no gestures). As of this report the MSRP is $1000 CAD.

Figure 126: Vuzix Blade Upgraded (Vuzix, 2021)

3.9.4.3.2.4 Vuzix - M4000

The Vuzix M4000, Figure 127, is the most recent Vuzix HMD which utilizes a see-through waveguide DLP projector (854 x 480) with 28-degree FOV. It is based off the Android 9.0 OS and is IP67 certified with a number of mounting options (hard hat, headset, safety glasses) and an external battery tether (2-12 hours – hot swappable). The MSRP for the Vuzix M4000 is $3,330 CAD.

Figure 127: Vuzix M4000 (Vuzix, 2021)

3.9.4.3.2.5 BAE Systems - Battleview 360

The Battleview system, (BAE Systems, Figure 128), enables soldiers in combat vehicles to see the real-time view of the world external to the armor of their vehicles by using an optical see-through HMD (monocular) or a video-see through display.

Figure 128: BAE Battleview Systems 360 (BAE Systems, 2021a, 2021b)

3.9.4.3.2.6 ARC4

The ARC4 (Figure 129), is an optical see-through monocular HMD that displays situational awareness information including points of interest, teams, marker designations, or other geo-tagged and registered symbols. It can mount on a helmet rail and is compatible with night vision goggles as well as the ATAK platform previously discussed. The display is an SVGA @ 60 Hz (800 x 600 pixels).

Figure 129: ARC4 (ARA, 2021)

3.9.4.3.2.7 Elbit Systems -SmartEye, SmartNVG, SmartSight

Elbit is an international electronics company that manufactures numerous systems for the defense industry. Their Smart suite includes a Smart Eye, Smart NVG, and Smart Sight.

The SmartEye (Figure 130), is a monocular optical see-through HMD with a 32-degree FOV. It utilizes the Elbit Systems Dominator identification and registration of 3D images to a known data base. It includes tactile controls and inertial/position sensors to locate both the individual user and as well as others. These glasses can interface with other elements of the Smart system – for example, a helmet-mounted night vision sensor.

Figure 130: Elbit Systems SmartEye (ElbitSystems, 2021)

The SmartNVG integrates with worn night vision devices and provides AR capabilities to soldiers as part of the entire Elbit suite. There are two display modules (night display module – NDM, and colour night display module – CNDM). They are both Android OS based and helmet mountable utilizing an OLED display source. The Night Display Module is 852 x 600 and produces monochrome green, the colour version uses an 860 x 600 OLED with a full colour NVG mode.

Figure 131: Elbit Systems SmartNVG (ElbitSystems, 2021)

Lastly, SmartSight, is an add-on unit to both day and night weapons sights to provide situational awareness augmented reality information to soldiers. It displays compass and range data directly on the sight. Blue force and enemy tracking are linked to the other Elbit BMS systems.

Figure 132: Elbit Systems SmartSight (ElbitSystems, 2021)

*3.9.4.3.2.8 CERDEC – HUNTR**

HUNTR (Heads-Up Navigation, Tracking & Reporting System) was developed by Night Vision and Electronic Sensors Directorate for the US Army in order to improve situational awareness (Soldier Systems Daily, 2017).

Figure 133: HUNTR (Soldier Systems Daily, 2017)

4. Fused Night Vision

The term Night Vision Goggle (NVG) is traditionally associated with image intensified-based electro-optical devices that enhance the soldier's perceptual abilities in low light conditions. The term Night Vision System (NVS) will be used to describe imaging sensor-based electro-optical devices that enhance the soldier's perceptual abilities in low light conditions. For the purposes of this section NVG and NVS are defined as systems worn by the user and are differentiated from weapon-mounted or hand-held systems. The terms NVS and NVG will be used equally in this section. NVSs typically include five major sub-assemblies:

- optics and scanner,
- detector and detector electronics,
- digitization,
- image processing, and
- image reconstruction and output.

Not all systems include all these components. NVGs rely on I^2 tube technologies, whereas thermal systems use a scanner (typically a Focal Plane Array or FPA). A variety of terms have been used to describe these technologies and the differentiation between system generations is somewhat confusing. This section introduces the physics behind the different NVG and NVS technologies and provides a short history of major developments.

Core to the NVS electro-optical device is the detector. Detectors are typically designed to operate in one or two spectral regions (see Figure 134). The ultra-violet (UV) region spans .2 to .4 µm wavelengths. The visible spectrum ranges in wavelength from .4 to .7 µm. NVG based on image intensified technologies and Low Light Level sensors (LLL sensors) operate in the Near Infrared (NIR) spectrum (.7 to 1.1 µm). Some NVS systems are based on detectors operating in the Short Wave Infrared (SWIR) spectrum which covers the 1.1 to 2.5 µm band. The Medium Wave Infrared (MWIR) spectrum spans the 2.5 to 7 µm band and while large crew-served and vehicle-based sighting systems operate in this spectrum they are also used in dismounted operations. Other NVS systems operate in the Long Wave Infrared (LWIR) spectrum which covers the 7 to 15 µm band.

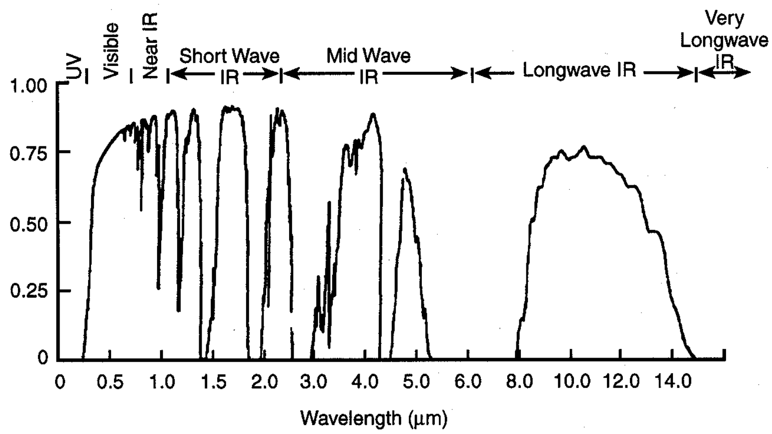


Figure 1-2. Representative atmospheric transmittance over a 1-km path length. The transmittance varies with temperature, relative humidity, and airborne particulates.

Figure 134: Electro-optical Bands

(from Holst, 2000, p. 3)

It should be noted that elements in the atmosphere attenuate the transmission of energies in certain wavelengths (e.g., carbon dioxide molecules attenuate wavelengths at 4.2 μm). Therefore, the relative performance of different types of detectors can be influenced by the test environment.

NVS technologies typically use the NIR, SWIR, and LWIR spectral bands. Image Intensification sensors and NVGs operate in the NIR region while infrared (IR) sensors operated in the SWIR and LWIR wavelengths. The term IR has been commonly used to identify systems which rely on thermal radiant signatures to identify targets as opposed to those which rely on reflected light. Most laymen associate IR images with the scene of a “hot” object on a cooler background – see Figure 135. SWIR system images (see Figure 136) more closely resemble those of an NVG (see Figure 137) and thus do not have the appearance of a typical IR image.

Figure 135: LWIR Image

Figure 136: SWIR Image

Figure 137: Traditional NVG Image

IR technology traditionally has been used to detect and classify objects, while I^2 technology has been used to recognize and identify targets. It is possible to detect an object with much lower resolution than that required for recognition or identification. "The diffraction limited resolution of a perfect optical system is defined by the diameter of the optics and the wavelength of interest. For small objects the resolvable power is described by the following equation (Rayleigh Criterion):

$$\theta \min = \frac{1.22\lambda}{D} Radians$$

Where Θ is the smallest angle resolvable between point sources; D= aperture diameter; and λ is the wavelength of light.

While image intensifiers may have inherently more power to resolve smaller objects than LWIR imagers (.7 to 1.1 µm versus 7 to 15 µm), the image intensifier tubes are inherently noisy and thus do not achieve the potential advantage in resolution. NVS sensor advances have not reached the level of resolving performance of I^2 technology.

NVGs can also be categorized according to the image presented to the eye, and can be described as monocular, biocular, or binocular. Within the past five years systems have been developed that allow the user to switch between monocular and binocular vision.

- The monocular system has an objective lens assembly, a single image intensifier tube, and a housing assembly. The intensified image is presented to one eyepiece and other eye is unaided – see Figure 138.

Figure 138: Monocular AN/PVS-14

* The biocular system has an objective lens assembly, an image intensifier tube, a housing assembly, and two eyepieces. The same intensified image is presented to both eyepieces – see Figure 139.

Figure 139: Biocular AN/PVS-504

* The binocular system uses two objective lens assemblies, two image intensifier tubes, and two eyepieces. Unique intensified images are presented to each eye – see Figure 140.

Figure 140: Binocular AN/PVS-15

* Newer systems allow the user to select either monocular or binocular vision. The adaptive system uses two objective lens assemblies, two image intensifier tubes, and two eyepieces. The design allows users to rotate eyepiece assemblies independently – see Figure 141.

Figure 141: Binocular AN/PVS 31A NVG (Image copyright L3 Harris)

4.1 In-Service Canadian Forces NVGs

At present the CAF regular and reserve forces utilize two different NVG systems the monocular AN/PVS-14 (MNVG) and the bi-ocular AN/PVS-504A goggle. The CAF does not possess AR capabilities in the regular army. The NVGs used by the Canadian Special Operations Forces Command (CANSOFCOM) are not included in this review.

4.1.1 AN/PVS-14 Monocular Night Vision Goggle (MNVG)

The monocular AN/PVS-14 (MNVG) is a lightweight, high performance, passive, third generation I^2 NVG system (Gen III Omnibus 4) - see Figure below. The AN/PVS-14 is either worn on the head as a goggle system or attached to the soldier's helmet. The goggle assembly is a head-mounted self-contained night vision system, which contains one monocular unit consisting of an objective lens assembly, an image intensifier tube, a housing assembly, and a monocular eyepiece assembly. The housing is mounted to a face mask assembly which is held by head straps to the user's head. The assembly incorporates an infrared (IR) light source that provides illumination to permit close in viewing through the goggles. Other features include automatic brightness control, bright source protection, low battery indicator, and a high-resolution unity F1.2 lens.

Figure 142: Monocular AN/PVS-14 goggle. (Image copyright HSI®)

Figure 143: Monocular AN/PVS-14 goggle (in raised position) mounted on a CG 634 Helmet. (Image copyright HSI®)

Introduced in 2003, the MNVG is designed to provide the user with personal night vision capabilities such as but not limited to:

- Close combat related situational awareness;
- General-purpose personal night observation;
- Assistance with tactical movement and obstacle traverse;
- Assistance with close-in task performance;
- Target acquisition; and
- Assisted target engagement (in association with a Laser Aiming Device (LAD)).

An effective NVG allows soldiers to attack an enemy before the enemy can find and attack them. An effective NVG will enable troops to manoeuvre and use their personal weapons at night with close to the same effectiveness that they would have during daylight.

4.1.1.1 Observed AN/PVS-14 Deficiencies

A recent knowledge elicitation exercise on night vision equipment was conducted by Angel and Ste-Croix (2018), and some of the key results of this exercise are summarized here.

The current performance of many of the MNVGs held in units is deficient. The in-service MNVG was acquired in 2003 to meet urgent operational needs and the image intensification tubes have a finite life span. The MNVG has been used regularly over the past 15 years such that they no longer perform as well as new. An image intensification tube manufacturer (Harris) notes that after 2500 hrs of use a Generation 3 tube as found in the AN/PVS-14 will not perform effectively in dark (starlight) situations. During the recent Future Small Arms Requirements (FSAR) field study of the 20 systems examined at Oscar Company, 3 RCR, only four systems would have passed minimal acceptance standards used by the U.S. Army (as tested with the TS-4348/UV). This snapshot suggests that the current fleet of MNVGs held by the CAF needs replacement. The current tube performance of the majority of the MNVG fleet is comparable to older Generation 2 NVGs freely available on the open world market and in many cases less capable than systems available to potential adversaries.

The performance of the MNVG is deficient. Even when new, the AN/PVS-14 Generation 3, Omni IV systems had limited capabilities in reduced illumination conditions. Soldiers complain that they cannot detect targets under forest canopies or at the operational distances required. The in-service systems do not function effectively under poor light conditions. Soldiers are forced to utilize the IR lights on their MNVG and auxiliary IR flashlights on their rifle to help illuminate the scene. Systems with enhanced fused capabilities are available that may reduce the need for the use of auxiliary illumination.

The MNVG does not support the performance of role-specific, close-in tasks at night. In order to read paper maps, handheld GPS systems, and compasses at night, etcetera, soldiers must use visible light, To avoid giving away their position, soldiers are forced to hide beneath blankets (shrouds). The requirement to use light shrouds increases the vulnerability of the patrol.

The MNVG does not give soldiers adequate depth perception in complex terrain. Injuries have been reported when soldiers fall as they could not perceive that the shadow on the ground was actually a hole. Crew commanders report that they cannot assist drivers in negotiating obstacles because of a lack of depth perception. Soldiers reported that they suffer multiple collisions, trips, etc. when using the MNVG. Systems that provide better depth perception cues are available.

The narrow FOV (40°) of the MNVG is felt to be deficient by some experts. Some experts believe that reconnaissance patrol members, airborne pathfinders, and vehicle crew commanders require a wider FOV for better situational awareness, more so than the average soldier at night.

The use of the MNVG over one eye creates safety issues when conducting live fire and movement. In order to ensure safety, soldiers must verify the locations of other soldiers and the limitation of a 40° field of view (FOV) NVG mean they must frequently turn their neck to conduct proper shoulder checks using the non-occluded eye. Systems are available that reduce this hazard.

Soldier performance using MNVGs in the presence of light sources is deficient. The presence of light sources at night results in bright halos around the source that veil the area near the point source. The veiling halo glare is problematic when operating in an urban area, enemy targets can be effectively hidden near light point sources from friendly soldiers wearing the MNVG. Technology is now available that reduces the light-source halos.

The helmet-mounting system of the MNVG is deficient. The Canadian Army did not field its CG634 helmet with pre-drilled NVG mounting plate holes (there are delamination risks if individuals decide to drill holes for themselves). In order to mount the MNVG to the helmet a mounting and adjustment bracket and a system for attaching a mounting plate to the helmet is required. The current system is unstable, the weight and center of gravity of the NVG causes the NVG to shift while performing combat manoeuvres. Soldiers complain that the helmet mount straps loosen and do not remain secure. Soldiers are personally purchasing after-market ratchet tensioning and shroud systems (flexible eyecup that stops light emissions so as not to indicate position) that are more secure and stable. Newer mount systems can reduce the wobble present when the MNVG bayonet-style mount is inserted into the socket of the adjustment and mounting bracket.

The weight and balance of the MNVG is deficient. The design of the MNVG causes soldiers to tighten their helmet chin and nape straps excessively to keep the NVG positioned properly. This imbalance results in neck pain, noticeable discomfort and neck fatigue. Technology and techniques are available that reduce the discomfort associated with the forward turning moment.

The position adjustability of the MNVG system is deficient. The current helmet mount and adjustment system does not allow the soldier to adjust the position of the MNVG as desired. The current system only allows the user to adjust the fore/aft position of the NVG and the tilt angle of the NVG. Newer systems allow the user to adjust fore/aft, vertical, and tilt position to ensure their goggle is correctly placed.

The flipped-up position of the MNVG is deficient. There are numerous occasions when soldiers do not need to use their NVG. The current MNVG can be rotated up and away from the face using its adjustment bracket system. The system flips the NVG so that it is over the user's helmet, which means that the NVG is often struck in certain operational situations, such as on vehicle interiors or when moving under windows or doorways. The current system greatly increases the profile of the soldier. There are alternate systems that reduce the profile of the NVG when not being used.

The reliability of the auto-shut off system is deficient. The MNVG can un-expectedly turn off when not being used (e.g., during shooting), forcing the soldiers to manually turn the system off and on again to get it to work. The MNVG is designed to turn off when flipped out of the way.

Unfortunately, the shock of weapon firing can cause a magnet in the mount to accidentally activate the shut-off contacts of the MNVG. The effect of shooting on MNVG shut-off is not tested during electro-optic inspection. Having MNVGs shut off during combat is extremely problematic, suggesting that the current fleet of MNVGs needs replacement or extensive refurbishment.

The reliability of the MNVG attachment and mounting systems are deficient. The MNVG attachment and mounting systems are worn and subject to accidental release. Although the MNVG was fielded with removable demist shields to reduce fogging, many of these removable shields have been lost. Soldiers remove scratched and damaged shields as they reduce visibility at night.

The design of the MNVG does not support maintainability. Simple issues such as a missing battery cap retention wire or the replacement of the IR illuminator lens require the return of the MNVG to the manufacturer for repair resulting significant loss in MNVG availability. The diopter adjustment ring frequently gets broken requiring return to second line maintenance organizations. The performance of the current replacement image intensification tubes is less than that of the original tubes.

The MNVG is not compatible with winter or summer off-road mobility systems which require different impact-style helmet systems (off-road and ski-doo crash helmets).

The MNVG is not waterproof.

The MNVG is obsolescent in a number of armies. Coalition allies are investing in new capabilities especially in the area of AR and fusion.

In summary the deficiencies with the in-service MNVG are as follows:

- The Canadian Army does not hold enough systems for operations, training, and force generation purposes
- The MNVG does not have the capabilities required to overmatch near-peer and potential adversary threats
- The MNVG does not support the performance of role-specific tasks (e.g., Pathfinder, Leader)
- The design of the MNVG and mount is deficient
- The reliability and availability of the MNVG is deficient

4.1.2 AN/PVS-504A Biocular Night Vision Goggle (NVG)

The biocular AN/PVS-504A goggle is a lightweight, early third-generation image intensifier system – see below. The biocular AN/PVS-504A (Figure 144) is either worn on the head as a goggle system or attached to the soldier’s helmet using a special adapter mount. The goggle assembly is a head-mounted self-contained night vision system containing one biocular unit, which consists of an objective lens assembly, an image intensifier tube, a housing assembly, and a binocular eyepiece assembly. The housing is mounted to a facemask assembly, which is held by head straps to the user's head (Figure 145).

Figure 144:Biocular AN/PVS-504 goggle (Image copyright HSI®)

Figure 145: Biocular AN/PVS-504 goggle head harness system (Image copyright HSI®)

This older biocular NVG was retrofitted with new Generation III NVG tubes in 2003. The biocular NVG is issued to select units such as Armoured, Engineer, Service Battalion, and Artillery Regiments. The biocular NVG has relatively the same capabilities as the AN/PVS-14 but in a heavier form factor. The AN/PVS-504A goggle utilizes a different head harness system and a different helmet bracket assembly than the MNVGs.

4.1.2.1 Observed AN/PVS-504A Deficiencies

The AN/PVS-504 has the same if not greater deficiencies as the AN/PVS-14. The AN/PVS-504A helmet attachment system is unique to Canada and thus access to parts in operations is problematic. The weight of the biocular AN/PVS-504A is unacceptable, the AN/PVS-504A NVG is very heavy.

The deficiencies of the AN/PVs-504 are similar to the AN/PVS-14.

4.2 Fusion Systems and Technologies

The aim of this section is to summarize the current state-of-the-art fused NVG and NVS technologies and future trends in NVG fusion technology for use by DRDC Toronto to support their upcoming research efforts. The section will review the function and performance of different types of fused NVG and NVS devices and include descriptions of the technology maturity, strengths, and limitations.

4.2.1 Assumptions

This review addresses the need for man-portable fused NVG and NVS with a particular emphasis on systems at the dismounted infantry level. The fused NVG and NVS technologies that primarily support vehicle, airborne, or fixed installations have not been included.

It is assumed that the Canadian infantryman in 2025 will perform essentially the same missions and tasks as they do today. Although their needs for NFE in 2025 may differ from their needs today, they will still require head-mounted sensors, weapons-mounted sensors, hand-held sensors, etc.

Any deficiencies noted with the current fleet of CAF NVGs will serve as a starting point for the future needs analysis.

Although limited information is available, emerging technologies will be examined where possible using the 2025 production horizon. For this horizon, it is assumed that potential fused NVG and NVS technologies were in their initial system design and development phases in 2019. This allows a five-year window for system design and development, and a one-year window for initial low-rate production.

The performance of NVGs and NVSs is affected by multiple factors, such as scene content, observer experience, atmospheric transmittance, ambient illumination, system performance, and so on. Where possible (given the sensitivity of the information), empirical data with references to the experimental conditions will be presented to indicate fused NVG performance. It should be noted that NVG performance as stated by manufacturers may be achievable only under optimal conditions. For example, typical manufacturer detection range conditions are determined for a still human target on green grass or person moving out in conditions which provide 5 km visibility along an unobstructed line of sight.

4.3 Technology Classification

Following the search, all NVG technologies identified were classified according to the following scheme of fused NVG and NVS sensing approaches and technologies:

- Optically fused NVGs based on I^2 low-light technology and uncooled Long Wave Infrared (LWIR) sensors. The optically fused NVGs are older generation systems and were based on I^2 and LWIR technologies or I^2 and HUD information.
- Digitally fused NVSs are based on day sensors, low light sensors, LWIR, and Shortwave Infrared (SWIR) technologies.

4.4 Results of the Literature Review

This literature focussed on advances in the past 10 years. A number of different technologies are used in fused NVGs and NVSs. The focus of recent research has been on the development of low light sensors, SWIR and LWIR technology. These systems were classified according to the scheme identified in section 4.3. The generic description of the technology, maturity, limitations, and strength of the technologies are given first. Specific examples of the technology are then presented. When available, detailed specifications and performance values are also provided.

4.4.1 Low Light Sensor Technology

Initial fused NVG goggles used an optical fusion approach. Images captured using an I^2 tube were combined with images captured using LWIR sensors using an optical combiner. ITT and Insight were the first companies to produce effective optically fused Enhanced Night Vision Goggles (ENVGs). At the same time Litton Electro-Optical Systems (LEOS) developed a digitally fused NVG that relied on different technologies. Advances in low-light imaging technology will be presented below.

4.4.1.1 Image Intensification Technology

NVGs have been fielded for over 50 years and generally use I^2 technology. The term generation is used to describe significant improvements in performance. The use of generations is sometimes confusing because the Night Vision and Electronics Sensors Directorate (NVESD) of the US Army's Communications-Electronics Command (CECOM), as the sponsor of many of the improvements in NFE technology, has differentiated image intensification systems according to how systems were made. Generation 1 systems use different technologies than Generation 1 or 3. Even within a Generation there can be differences in performance. The US through its omnibus purchases identified desired improvements in performance. thus Generation 3, Omnibus 7 NVGs out-perform earlier Generation 3 Omnibus 4 NVGs. The use of Generations and Omnibus terms are confusing. Manufacturers would like to differentiate NVGs by performance leading to considerable confusion in the NVD world.

Traditional NVGs rely on a special tube, called an image-intensifier tube (I^2), to collect and amplify infrared and visible light – see Figure 146.

Figure 146: MX-11769 Image Intensifier Tube (Image copyright Will's Optics, 2021)

Light can be direct, such as moonlight or starlight, or reflected. An objective lens collects the available light and channels the energy towards a photocathode. The photocathode converts the light energy (photons) into electrical energy (electrons) by the photoelectric effect. The number of electrons transmitted by the photocathode is multiplied by thousands by the use of a glass microchannel plate (MCP). An MCP is a thin glass disk containing more than 10 million channels. The individual channels are used to maintain the alignment of the resultant electrons with the original photons – see Figure 147.

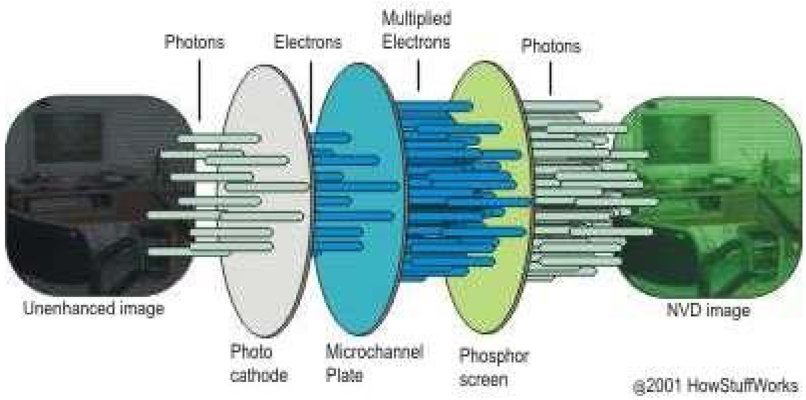


Figure 147: Image Intensifier Tube (Image copyright How Stuff works, 2001)

(from How StuffWorks (n.d.). Retrieved Jan 1, 2006, from http://science.howstuffworks.com/nightvision5.htm)

The sides of the MCP are energized with high voltage electricity (5000V). Pulses of voltage accelerate electrons down offset channels so that when they bombard the side walls, other electrons are released (electrons are multiplied from 50,000 to 100,000 times). These electrons are then accelerated and cause further electron releases. The electrons are accelerated out of the MCP and hit a screen coated with phosphors. The energy of the electrons hitting the screen causes the phosphors to reach an excited state and release photons. These phosphors create the typical green image on the screen that has come to characterize night vision. The photons released are typically focussed and magnified using an ocular lens. The images can also be captured using CCD cameras or more sophisticated CMOS devices.

The performance of humans with NVGs depend on a large number of factors (amount of ambient light, contrast of the target against its background, target size, movement, observer contrast sensitivity and visual acuity, etc.) Suffice to say that the lower the ambient light conditions and the smaller the target the more challenging it will be to detect, recognize and identify the object. Alpha Photonics (2020) provides some performance results for different technologies- see Figure 148. The reader will note the significant improvement in detection performance of later generations in very low light levels. The detection distance reported also requires caution in interpretation as the authors have witnessed significantly lower results in human detection, recognition and identification field tests.

	Full moon 0,1 Lux	½ of the moon 0,05 Lux	¼ of the moon 0,01 Lux	Starry night sky 0,001 Lux	Cloudy night sky 0,0001 Lux
Without a night vision device	230m	130m	45m	—	—
Gen. I	300m	200m	150m	100m	50m
Gen. II / ***Gen. II+***	630m	630m	590m	390m	145m
Gen. III / ***ECHO, SuperGen®, XD-4™, XR5™, Intense 4G***	>810m	>810m	>770m	>530m	>200m

Figure 148: Performance of NVG technology versus ambient light levels (from www.alpha-photonics.com, 2020)

4.4.1.1.1 Generation 2+ Image Intensification

Early Generation 2 Two (Gen 2) I^2 technology was based on an image-intensifier tube, which is used to collect and amplify infrared and visible light. Light can be direct, such as moonlight or starlight, or reflected. An objective lens collects the available light and channels the energy towards a photocathode. The photocathode converts the light energy (photons) into electrical energy (electrons) by the photoelectric effect. The number of electrons transmitted by the photocathode is multiplied by thousands by the use of a glass microchannel plate (MCP). An MCP is a thin glass disk containing more than 10 million channels. The individual channels are used to maintain the alignment of the resultant electrons with the original photon that used a microchannel plate to amplify electrons emitted from a photocathode. Generation 2 systems differ in design from Generation 2+ systems.

Gen 2+ NVG image-intensifier tubes utilize advances in MCP manufacture and photocathodes. The new S-25 photocathode has increased spectral sensitivity. Gen 2+ systems rely on proximity-focused tubes that allow the design of smaller systems. Finally, Gen 2+ systems possess advanced electronic modules that support automatic gain control and bright spot protection. Gen2+ systems more closely resemble Gen 3 systems than the old Gen 2 systems.

Restriction of Gen 3 technology export had forced European researchers and manufacturers to lead the way in advancing Gen2 + I^2 technology. Gen 2+ technology was first developed by Photonis in 1989 and has been advanced by non-US manufacturers. Gen 2 + systems go by the names of Gen II Plus, SuperGen, HyperGen, XD4, XR5 and Onyx. The figure of merit (FOM) of the latest Gen 2 + tubes resemble those of Generation 3 Omnibus 7 technology.

Table 3: Image Intensification Tube Developments[1]

Generation	Resolution lp/mm	Signal to Noise ratio (SNR)	Figure of Merit (FOM)	Halo (mm diameter)
Gen II Plus® (circa 1962)	36	13	468	
SuperGen® (circa 1990)	51	21	~1536	

Generation	Resolution lp/mm	Signal to Noise ratio (SNR)	Figure of Merit (FOM)	Halo (mm diameter)
XD4® (circa 1999)	64	~21	~1400	
4G Echo (white phosphor- circa 2018)	74	~23	1600-1800	.7-1.0
XR5 (circa 2001)	64	~24	~1600	
4G Echo + (white phosphor- circa 2018)	80	25	Min 2000	.95
XD5® (circa 2009)	72	28	2016	.6-.8
Intense 4G	76	30	~2300	
Gen III Omni 1 (circa 1982)	~36	~16.2	~583	1.47
Gen III Omni 4 (circa 1996)* (CAF in-service MNVG)	~64	~21	~1344	1.25
Gen III Omni 6 (circa 2002)	~64	~25	~1600	.90
Gen III Omni 7 (circa 2006)	~64	~28	~2300	.70
Gen III Omni 8 (circa 2019)	~72	~33	2300-2400	.65

[1]Notes: Caution is advised when comparing performance of image intensification tubes as tubes can have a spectrum of performance. Handpicked tubes have fewer manufacturing blemishes and thus perform better than average tubes.

4.4.1.1.2 Generation 3 Image Intensification Technology

Generation 3 devices refer to image intensification tubes developed in the U.S. This generation introduced gallium arsenide (GaAs) as the photocathode material. Generation 3 devices offer twice the resolution as early Generation 2 devices and are cheaper to manufacture. Tube diameter was reduced from 25 mm for Generation 2 to 18 mm or 16 mm. Considerable consolidation in the tube manufacturing world occurred during the initial production of Generation 3 devices. As the US equipped its forces with NVGs they increased the required performance with each omnibus procurement contract. U.S. NVGs are characterized by Generation and Omnibus (Omni) technology requirement. Over the course of 20 years (1982-2006) considerable advances were made with I^2 technology in the U.S.

Advances in I^2 technology stalled in the U.S. since the fielding of Generation 3 Omnibus 7 systems. The interest in fused NVG systems in the U.S. has seen funding directed towards non-I^2 based technology. The authors have seen reference to Omnibus Generation 8 when P45 white phosphor screens are utilized.

ITT introduced a gated power supply which helped reduce blooming in high light level environments bright with point light sources. Streetlights, runway markers, beacons, etc. caused haloing problems which limited NVD performance in light polluted urban environments. Northrop Grumman (NG) discovered that they could reduce haloing effects by reducing the distance between the MCP and the photocathode – see Figure 149 and Figure 150. Haloing is caused by electron scattering within the MCP-photocathode gap. NVESD required all Generation 3 omnibus VI proposals to include anti-haloing technology or processes.

Figure 149: Bloomed Image Caused by Headlights

Figure 150: Effects of Anti-blooming Technology

For the purposes of this report, we will classify those I^2 systems described as thin-filmed, filmless, gated thin-filmed, etc. as Generation 3 Omnibus 7.

The term Figure of Merit (FOM) is used to describe the performance of an I^2-based NVG. FOM uses NVG resolution and the NVG's signal to noise ratio. Resolution utilizes line pairs per mm (lp/mm) and latest generation systems have resolving power greater than 70 lp/mm. The signal to noise ratio (SNR) is a dimensionless value that determines I^2 tube's performance in low-light conditions. SNR is determined by dividing the light signal that reaches operator's eye by the perceived noise. Good performing I^2 tubes have values of SNR starting at 20 and above. This means that signal received by the user is 20 times higher than the background noise.

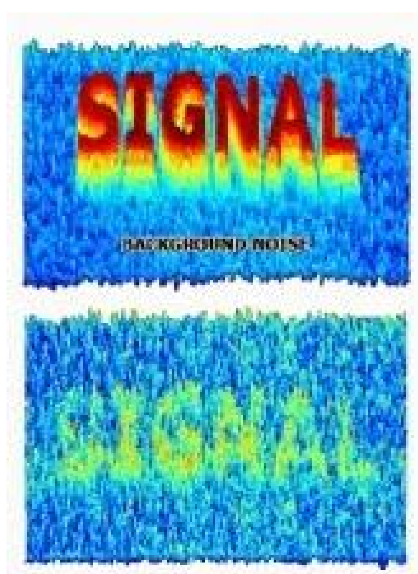


Figure 151: Signal to noise ratio visualization

FOM is defined as resolution (in lp/mm) x SNR. FOM is used as parameter by the US which determines the "exportability" of the NV System. The standard I^2 US export release parameters for general end users are non-auto-gated NVGs with a FOM not to exceed 1400 for ground and 1600 for aviation end-use. The halo for these NVGs will be no smaller than 0.85 mm. The FOM of Gen III Omnibus V NVGS are as follows:

- Gen III Omni V- FOM 1400 (64 lp/mm & SNR 23)
- Gen III Omni VI, VII –FOM 1800 (72 lp/mm & SNR 25)
- Gen III Omni VII,VIII- FOM 2100 (70 lp/mm & SNR 30)
- Harder (HD) Gen3 – FOM 1800-2400 (air use) (no written specs - $50,000 ANVIS goggles)

While FOM is used in the US, firms in Europe have marketed the term "4G". The 4G standard describes a set of capabilities that deliver high performance in all field conditions.

- An extended bandwidth of photon collection designed to deliver consistent image quality across environments (from below 400 nm to above 1000 nm)
- A FOM greater than 1800
- A resolution greater than 57 lp/mm even in polluted light environments (e.g., urban areas, entering a building where the light is suddenly switched on)
- A halo size not larger than 0.7 mm around the brightest objects seen in the image to provide detail around light sources.

There are many variables affecting the detection range performance for image intensification systems. The major variables affecting detection performance of image intensification technology are the following:

- The generation (I vs. II vs. III) of the image intensification tube.
- The environmental lighting conditions affect the ambient light present that the image intensification tubes multiply; increases in ambient light conditions lead to a corresponding improvement of detection range.
- The target size (the larger the target, the further it can be detected by an image intensification system, as shown in Table 4.

Table 4: Detection Ranges for Image Intensification Tube Generations for Different Environmental Lighting Conditions and Target Sizes.

1st Gen.	Full Moon	Partial Moon	Star Light	Overcast
	250m	200m	150m	100m
	750m	500m	300m	150m
2nd Gen.	Full Moon	Partial Moon	Star Light	Overcast
	500m	450m	300m	150m
	1000m	800m	550m	300m
3rd Gen.	Full Moon	Partial Moon	Star Light	Overcast
	650m	500m	375m	200m
	1250m	1000m	800m	550m
Filmless, Thin-filmed, "4th Gen."	Full Moon	Partial Moon	Star Light	Overcast
	750m	600m	400m	250m
	1400m	1150m	950m	650m

(Adapted from: How night vision works. (n.d.). Retrieved Jan 1, 2006, from http://www.atncorp.com/HowNightVisionWorks).

Research is also ongoing by the US to extend the photocathode wavelength response. This will provide imaging of extended wavelength pointers, up to 1 µm or slightly longer.

4.4.1.1.3 White versus Green Phosphor Evaluations

While early NVG generations used P20, P22 (green), and P43 (yellow-green) phosphor, P45 (white) phosphor dominates today. P45 spectral emission matches the peak wavelength sensitivity of the eye (545 nm) and is reported to feel more natural in low light causing less eye fatigue.

Scientific studies comparing human performance with P43 and P45 are limited. In 1996, Rabin and McLean examined the performance of human observers with NVGs that used either P22 or P43 phosphor. The results indicated that there was no difference in visual acuity but subjects using P43 had better contrast sensitivity. According to U.S. Army Flightfax (2020):

> *Several organizations have conducted evaluations of the Generation 8 (High FOM IIT), including the Army and Air Force Research Labs, the US Army Aeromedical Research Lab (USAARL), and the 160th Special Operations Aviation Regiment (SOAR). These have included*

bench tests and user-flight evaluations. While the bench tests did show a marked improvement of the HFOM Type 8 IIT over the legacy Type 6 and 7 IIT when compared, there was a nominal difference between the P45 white and P43 green phosphor tubes. Surprisingly, there was an overwhelming user preference for the P45 white tubes.

According to the USAARL study, "although the laboratory measurements did not find any significant differences between the two matching white and green phosphor ANVIS for resolutions, gain, halo sizes, automatic brightness control (ABC) responses, smear, etc., the flight assessments showed almost a unanimous preference for the white phosphor ANVIS. This suggests there are other factors considered by the flight evaluators that are not measurable or evaluated in the laboratory." (USAARL Technical Memorandum (TM) 2017-12).

In 2011 a study was undertaken by Homeland Security- Science and Technology Division comparing PVS-14D monocular BVGs with a Photonis XR5™ Onyx white phosphorous intensifier tube (64 lp/mm and an SNR of 23) or an ITT Night Vision & Imaging Pinnacle® Series 9815G green intensified tube (64lp/mm and an SNR of 25) (Homeland Security, 2011). The Photonis XR5 Onyx based NVG was rated higher by users over the Pinnacle series NVG for image clarity, eye fatigue and perception. The use of a white phosphor display may have improved the performance of the XR5 Onyx based NVG even though the luminance gain of the Pinnacle series was higher (better performance in extreme darkness).

4.4.1.1.4 Factors Affecting NVG Performance

NVG performance is affected by factors beyond the design of the I^2 tube. The larger the I^2 tube the better its performance. Early NVG tubes were based on 25 mm diameter tubes. The tubes have steadily reduced in size to 18 and now 16 mm. The impact of moving to smaller 16 mm tunes may not be significant for wide field of view goggles utilizing four tubes but may be a factor when only one (monocular) or two tubes (binocular) are used. Smaller 16mm tubes are lighter than comparable 18mm tubes.

The field of view of most US NVGs is 40°. Larger FOV are available. Some systems use special lenses to increase FOV. Thales systems have a 51° FOV and thus are wider than conventional US NVGs. NVG performance is also affected by the quality of the optics used in the system. High resolution optics can increase total NVG resolution by more than 10%. NVGs are available today that offer high performance I^2 tubes but low-grade optics.

NVGs may include optical filters to make them less sensitive to laser threats and to enhance performance by aviators (compatible with cockpit displays).

4.4.1.2 Night Vision Systems based on Image Intensified Close Coupled Devices (ICCD)

Intensified Close Coupled Devices (ICCD) are based on a system that couples image intensified tubes with CCD sensors using a fibre optic cable. ICCD cameras are used in ultra-high speed imaging applications. The development of low light applications for cell phones has meant that ICCD systems have been replaced in many applications with complementary metal–oxide–semiconductor (CMOS)-based systems.

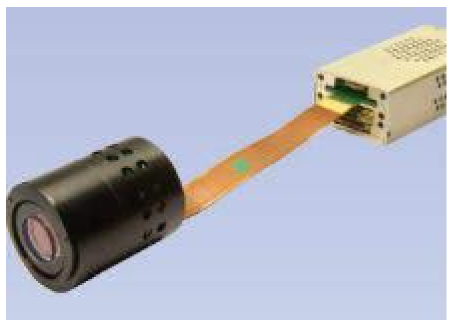


Figure 152: High resolution Image Intensified CCD Camera System (Image copyright Defence Vision Systems, 2013)

4.4.1.3 Night Vision Systems based on Intensified Complementary metal–oxide–semiconductor CMOS Devices (ICMOS) sensors

Intensified CMOS Devices (ICMOS are based on a system that couples image-intensified tubes with a CMOS sensor. ICMOS cameras are used for ultrahigh speed imaging applications. The rise in cell phone low light applications has meant that ICCD systems have been replaced in many applications with complementary metal–oxide–semiconductor (CMOS)-based systems. The ICMOS module from Photonis has a 1280 x 1024 sensor with 10.6 µm pitch.

Figure 153: Photonis ICMOS Analog. The system is a low light intensified camera module (Image copyright Photonis Inc, 2021B)

4.4.1.4 Day Light – Low Light CMOS Cell Phone Camera Sensors

Day light CMOS sensors are ubiquitous in cell phones and offer resolutions up to 100 megapixels in 2021. The Samsung ISOCELL GN2 image sensor utilizes 1.4 µm pitch pixel technology and has 12.5 megapixel video resolution at 480 fps.

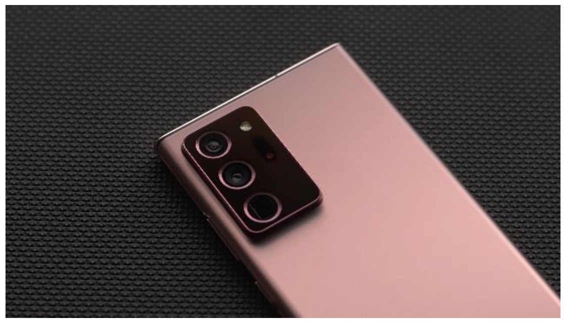


Figure 154: Cell phone camera using the Samsung ISOCELL GN2 system. (Image copyright Jhaveri, 2021)

The Samsung ISOCELL GN2 image senor can simulate larger 2.84 µm pitch pixel based on 4 in 1 pixel binning technology, making it more effective for low light applications. Daylight CMOS sensors are suitable for fusion applications during the day.

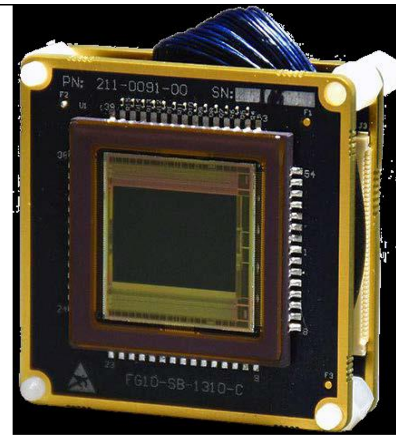
4.4.1.4.1 Night Vision Systems based on Dedicated Low Light CMOS Cell Phone Camera Sensors

Low light CMOS sensors have been available for a number of years. Advances in the design of CMOS architecture has led to improvements in NIR imaging. Nyxcel® reports a 25% increase in imaging sensitivity at 940 nm with advances in silicon pixel thickness. Other advances in "deep trench isolation" also improve Nyxel's quantum efficiency. The 0S05A20 is 5 MP Nyxel CMOS sensor.

Researchers at W&WSens Devices have found that incorporating holes in pixels can improve image sensor performance in the NIR “"*Silicon photodiode-based CMOS sensors with backside-illumination for 300 to 1000 nm wavelength range were studied. We showed that a single hole in the photodiode increases the optical efficiency of the pixel. In near-infrared wavelengths, the enhancement allows 70% absorption in a 3 microns thick Si. It is 4x better than for the flat pixel. We compared different shapes and sizes of single holes and hole arrays. We have shown that a certain size and shape in single holes pronounce better optical efficiency enhancement. The crosstalk was successfully reduced with trenches between pixels. We optimized the trenches to achieve minimal pixel separation for 1.12 microns pixel.*" Image Sensors World (Wednesday, November 25, 2020).

Advances in low light CMOS sensors will provide limited support at night. Due to the small pixel pitch sizes only incremental improvements in low light performance have been observed.

SiOnyx is supporting the IVAS (Integrated Visual Augmentation System) program with digital night vision camera based on 1.3MP CMOS technology. The SIONYX Aurora (Standard) is a colour digital night vision camera. The patented ultra-low light sensor technology empowers the viewer to see in full colour down to 1 milli-lux or near moonless starlight conditions. The Aurora (Standard) camera comes with an integrated compass, GPS, accelerometer and is augmented reality (AR) capable. The Aurora cameras utilize the XMB-1310 Camera Core.

	
Figure 155: U.S. Army IVAS System	**Figure 156: SiOnyx XMB-1310 Camera Core. Powering the low light capability of IVAS (Image copyright SiOnyx, 2019)**

4.4.1.5 Night Vision Systems based on sCMOS Technology

The literature identifies differences between standard CMOS quality and high scientific grade CMOS quality. Scientific grade (sCMOS) sensors have fewer defects and blemishes than typical CMOS sensors. sCMOS sensors provide full colour night vision. sCMOS sensors have been used in scientific research areas such astronomy but are finding more applications in fused NVG systems.

The circa 2012, Photonis Lynx sCMOS sensor is a monochromatic 1.3MP sensor with 9.7 µm pitch pixels. The system provides imaging performance in the day and at night (3/4 moon).

Figure 157: Lynx CMOS Monochromatic Sensor (Image copyright Photonis Inc (2021C)

The Lynx sensor's resolution is equivalent to 51lp/mm with a SNR of 42. The sensor reportedly can detect objects down to 1 milli-lux. The resolving power of the senor can be increased by reducing shutter speed. The Photonis colour Kameleon 1.3MP sensor sCMOS sensor operates down to 4 milli-lux in full frame rates.

Third Generation sCMOS systems are capable of imaging down to .7 milli-lux. The Fairchild Imaging system HWK 4123 is capable of imaging down to 1 milli-lux at a 9MP format.

In summary, sCMOS systems have better low light performance capabilities than conventional CMOS systems but at a significant cost. Colour night vision sensors are available. The HFiS X26 Medium Format CMOS Night Vision camera utilizes an sCMOS sensor with 10-megapixel sensor with 19 µm pixels. SPI Infrared utilizes the Broad-Spectrum Thin Film Array (BsTFA) CMOS technology. The sensor itself produces 4K High Definition (HD) colour imagery down to light levels as low as 1 millilux, achieving video frame rates of 60 Hertz and signal-to-noise ratios that meet or exceed those of the latest image intensifiers. Video footage on the company's website shows impressive full-colour imagery taken under overcast starlight conditions.

4.4.1.6 Night Vision Systems based on Electron Multiplying CCD (EMCCD) Sensor Technology

Introduced in 2001, EMCCD cameras are capable of detecting single photon events and are thus very sensitive and are used in the scientific community. The design of the sensor amplifies the number of electrons released by each photon. The Hawk 252 is capable of operating down to 50µ lux i.e., better than I^2 Generation 3 performance. The 1280x1024 8 µm pitch technology is used in surveillance applications.

Figure 158: Hawk high resolution EMCCD Camera (Image copyright Photonics Online, 2021)

There are a few drawbacks of EMCCD technology. The amplification mechanism has a diminished signal-to-noise ratio. It is possible to achieve respectably high dynamic range with larger pixels but only at slow readout speeds or frame rates. Presently, the largest commercially available EMCCD sensor is a back-illuminated 1024 x 1024-pixel device at a significant cost premium.

EMCCD sensors are being replaced by EBCMOS systems in dismounted operations.

4.4.1.7 Night Vision Systems based on Electron Bombarded CMOS (EBCMOS) Sensor Technology

Intevac has patented the bounding of a highly sensitive imaging sensor with a high resolution, CMOS chip (EBAPS). The electrons emitted by a Generation III image intensifier photocathode are injected directly onto the CMOS. The EBCMOS gain process is inherently low noise with an excess noise factor that is substantially less than a microchannel plate-based Generation-III image intensifier or the avalanche gain process in an Electron Multiplying CCD (EMCCD, Kf of 1.4). The low noise EBCMOS gain process eliminates the need for an MCP and enables higher SNR at the lowest light levels. This offers the possibility of higher performance for an EBAPS based camera relative to a standard I^2 camera based on Gen-III tube technology using an MCP for gain or EMCCD based cameras. The EBAPS sensors are state of the art systems. Until recently EBAPS sensors were used in aerospace application but recently (2020) Intevac was awarded a contract to develop EBAPS- based NVS' for the Special Operations communities.

Figure 159:Intevac EBAPS- based NVG (Image copyright Optics.org, 2020)

Intevac is developing its next generation EBAPS camera based on the ISIE6 (Intevac Silicon Imaging Engine), SXGA (1280 x 1024 array, 6.7 µm pixel), EBAPS sensor with a 2/3-inch optical format. Currently Intevac commercially offers the EBAPS- based NightVista M611-05 low light camera with a 1600x1200 pixel FPA based on 10.8 µm pitch pixels.

EBAPS- based night vision will be prohibitively expensive for general infantry use in the foreseeable future. Photonis in Europe has developed its own EBCMOS capability and supplies its DigitOwl -EB7 handheld night viewer with an EBCMOS FPA. Photonis produces 2, 4 and 7MP EBCMOS sensors. The system is available in 7MP and 4MP resolutions and is capable of operating down to 10µm Lux. Photonis offers a 1.3MP Lynx 1280x1024 EBCMOS sensor. The Photonis EBCMOS sensors are being used in UAVs today. Nexvision is developing a night vision system for special forces and will utilize an EBCMOS night vision sensor.

The cost on an EBAPS based NVG is not available in the open literature.

EBCMOS sensors may be available in the future from non-US sources.

4.4.1.8 Night Vision Systems based on SWIR Sensor Technology

InGaAs-based SWIR imagers have been available for approximately 10 years. Sensors Unlimited in the US was one of the first companies to develop SWIR based systems for dismounted infantry operations. Early SWIR sensors were limited to sub 1MP video resolution (320 x 256 and 640 x 512 using 12.5 µm pitch pixels. Today 1.3MP (1280x1024) 12.5 µm pitch pixels sensors are available. ITAR free systems are now available from Sensors Unlimited. The 1280JSX SWIR Digital video camera from Sensors Unlimited reports partial moon to daytime imaging capabilities.

Figure 160: Sensors Unlimited Mini-SWIR 1280JSX High Definition Camera (Image copyright Sensors Unlimited, 2021)

SWIR image sensors have been produced by bonding a photodetector (usually InGaAs-based) to a silicon readout circuit. These sensors can be made extremely sensitive, but the technology is quite expensive for mass manufacturing and limited in size of pixel and number of pixels (Image Sensors World, Dec 2020).

While the US had the initial lead in SWIR technology, the gap has closed. Imec (Belgium) in 2020 unveiled a prototype high-resolution SWIR image sensor with record small pixel pitch of 1.82 µm. It is based on a thin-film photodetector that is monolithically integrated on a custom Si-CMOS readout circuit. A fabrication-compatible process flow paves the way to high-throughput, wafer-level manufacturing. The Imec technology largely exceeds the capabilities of today's InGaAs-based SWIR imagers in terms of pixel pitch and resolution, with disruptive cost and form factor potential. New applications are enabled even in cost-sensitive domains, such as in industrial machine vision, smart agriculture, automotive, surveillance, life sciences, and consumer electronics.

Advances in SWIR technology may reduce the cost and improve the resolution and availability of SWIR sensors. The SWIR advances presented by Imec may lead to significant changes in fusion approaches, high resolution SWIR sensors may be made cheaply and could replace low light CMOS sensors altogether.

4.4.1.9 LWIR Microbolometer Technology

Uncooled Vanadium oxide microbolometers have been the technological basis of LWIR sensors in the past 20 years. Early sensors were based on 50µm pitch pixels with 160x120 and 320x240 sensor arrays. Pixel pitch sizes have steadily reduced to 25, 17, 12 and now 10 µm. Sony Sensor resolutions have improved to 1280x1024 FPAs. Leonard DRS currently offers 640 x512 array FPAs using 10 µm pitch sensors as part of its product lines. The 10 and 12 µm pitch microbolometers are the leading edge of LWIR design. Sierra Olympic has developed a full HD 1920v1200 12 µm pitch microbolometer targeted towards UAV applications.

	
Figure 161:Tenµm™ 640 camera from Leonard DRS (Image copyright Leonardo DRS, 2018)	**Figure 162: Sierra-Olympic VAYU HD 1920x120 Camera (Image copyright Sierra-Olympic Technologies Inc., 2021)**

FLIR utilizes 12 µm pitch FPA cores in its Lepton® micro thermal imager. The camera can be found on miniature UAVs, cell phones, vehicles, augmented reality, wearable technology, etc.

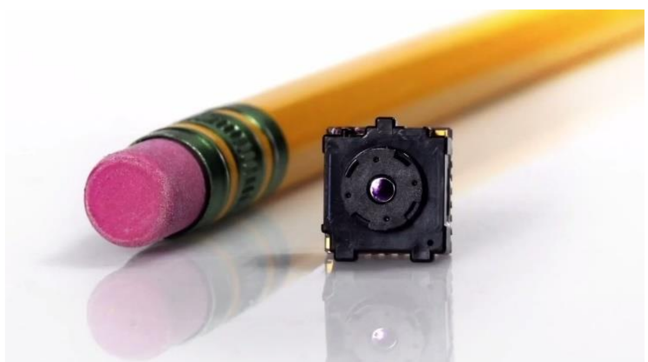


Figure 163:FLIR Lepton 3.5 160x120 resolution thermal imaging camera (Image copyright FLIR, 2020A)

Pixel pitches of 8 µm are currently at the R&D stage (in 2015 Selex ES launched SuperHawk, an MWIR detector which offers a 1280 x 1024 resolution <u>cooled</u> FPA on a pixel-pitch of just 8 µm). The SuperHawk NVG is aimed at aerospace applications. The drive to smaller pitch sizes for dismounted operations may have to wait until technical issues surrounding manufacture and pixel sensitivity are resolved. Very small pixel sizes can lead to signal leakage known as crosstalk which can result in increased signal noise; manufacturers must develop techniques that isolate pixels from each other.

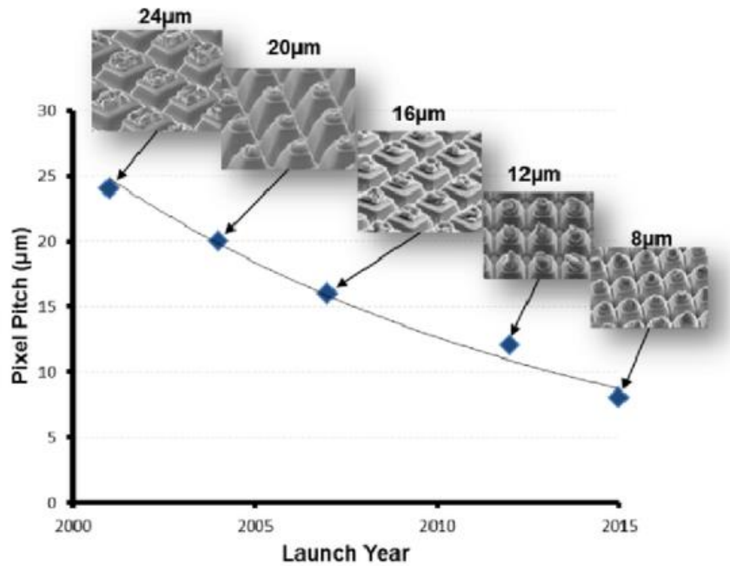


Figure 164: Trends in pixel pitch size reduction. (Image copyright McEwen, Jeckells, Bains & Weller (2015))

As illustrated in Figure 164, just as 17 µm pixel pitch designs are common today, 12 µm pixel pitch designs may be commonplace for the next 20 years. Systems today have over 30 times the resolution of systems first evaluated less than 20 years ago. In general, smaller pixels increase scene resolution.

Larger FPAs on their own do not necessarily improve object detection as the detected object size remains constant. For equal pixel pitch density FPAs, larger sized FPAs increase the size of the scene observable.

4.4.1.9.1 Dedicated LWIR-Based Night Vision Systems

NVS based on just LWIR sensors are available in monocular and biocular formats. While these systems have limited resolution, they do have good target detection capabilities. Dedicated LWIR systems are marketed to law enforcement and the fire fighter communities. The FLIR Breach PTQ136 is a compact monocular NVS. The PTQ136 system uses a 320x256 VOx 12 µm pixel pitch microbolometer.

Figure 165: FLIR Breach PTQ136 Thermal Imaging Monocular (Image copyright FLIR, 2020B)

Hand-held thermal cameras are used in temperature screening applications and in firefighting operations. There is a risk to using dedicated LWIR thermal goggles in combat at lower resolution goggles cannot differentiate friend from foe at a distance.

4.4.2 ENVG Fusion Systems

ITT and Insight were some of the first companies to produced fused NVGs. Images captured using an Image Intensification (I^2) tube were combined with images captured using LWIR sensors using an optical combiner. ITT (see Figure 166) and Insight were the first companies to produce effective optically fused Enhanced Night Vision Goggles (ENVGs). At the same time Litton Electro-Optical Systems (LEOS) developed a digitally-fused NVG that relied on different technologies.

4.4.2.1 ENVG Monocular Fused NVG Series

The AN/PSQ-20 Enhanced Night Vision goggles (ENVGs) were based on combining the image from a 16mm I2 tube and a 320 x 240 resolution microbolometer. The ENVG (I) only entered service in limited numbers. The system was heavier than the MNVG and the batteries required premium lithium batteries to operate. The four batteries did not last long and the ENVG thermal system failed more quickly than reported in advertised literature. The system weighed approximately 910 grams and was heavier than the MNVG.

Figure 166:AN/PSQ-20 ENVG (I) (U.S. Army Photo, 2008)

The AN/PSQ-20 formed the bases of the AN/PSQ-20A Spiral enhanced Night Vision Goggle (SENVG) had a battery pack with 3 batteries for longer operating times and the battery pack attached to the back of the helped balance the weight on the soldier's helmet.

Figure 167: AN/PSQ-20B SENVG (Image copyright Night vision Home, 2021)

In 2010 Northrop Grumman EOS (now L3 Warrior Systems) began developing the ENVG III programme covered an alternative design designated AN/PSQ-20B. The systems use a Generation III Pinnacle tube and a thermal sensor. Earlier iterations of the ENVG had two modes – fused vision, or I2 only. The ENVG III added more modes to the thermal imager to enhance target detection capabilities. It can show either the I2 or thermal imagery, or be used in one of three fusion modes:

- overlay (which showed the hotter parts of the thermal image),
- outline (with thermal imagery given a bright white outline that targets or objects easier to see, and
- full fusion (which combines the full output of the I2 and thermal channels).

Figure 168: ENVG III (Image copyright World Defence News, 2017)

The latest version of the ENVG III utilizes 12µm pitch pixel sensors and a higher resolution than ENVG I.

The initial cost for the ENVG I was approximately $14,500SD. The cost for the ENVG III/FWS-I is now approximately $70,000USD.

The ENVG-III is a candidate for evaluating augmented reality in an NVG for the CAF.

4.4.2.2 ENVG-B Binocular Fused NVG

The ENVG-B is a binocular version of the ENVG series. The system includes a binocular NVG utilizing a white phosphorous display. A thermal sensor is attached to the right I2 tube so it will be positioned centrally when in use. Like the AN/PVS-31 A, the ENVG B allows the operator to rotate the I2 tubes independently out of the line of sight (Figure 169). The EVG-B utilizes 12 µm pitch pixels. As a binocular system, the ENVG-B is relatively heavy at over 700 g.

Figure 169: ENVG-B Fused system (U.S. Army Photo, 2021)

The goal for the ENVG-B system was to have a 50% probability of man-sized target detection at 300 m (threshold) and 550 m (objective). The ENVG-B thermal channel can display the weapon reticle from the Family of Weapon Sights (FWS-I) in its picture in picture capability. Digital information can be displayed vice a thermal weapon sight reticle - see Figure 170.

Figure 170: ENVG-B displaying command and control information along with a sight reticle in picture in a picture mode (U.S. Army Photo, 2021)

The ENVG-B can use the US "One Terrain Database", a comprehensive 3D map of the world. The size of the files may mean pre-loading map files prior to mission rehearsal and execution. The ENVG-B can connect wirelessly to other devices. The U.S. Army will be purchasing over 100,000 ENVG-Bs and thus it will be a standard fusion system for years. The cost for the ENVG B is approximately $60, 000USD.

The ENVG-B is a candidate for evaluating augmented reality in an NVG for the CAF.

4.4.3 Thales Fusion Systems

The European company Thales has developed fusion systems for the French FELIN and the German GLADIUS soldier system programs. Thales has developed a number of fused systems:

- Minie-D (fused I^2 and command and control imagery)
- Minie-DIR (fused I2 and IR images plus connectivity to command-and-control systems)

4.4.3.1 Minie-D Fused Information System

The Minie-D is an ultra-compact NVG allowing remote aiming, optical data display fusion – see Figure 171. The Minie-D is not equipped with a thermal sensor but can present reticle or map information into the NVG, as shown in Figure 172 and Figure 173. The Minie NVG systems use European Gen2+ or Generation III I^2 tubes.

Figure 171:Minie-D fused NVG (Image copyright Thales, 2013)

The system has a larger I^2 Field of View (FOV) than contemporary U.S systems (51 versus 40°). At less than 370g the system is very light. Thales reports that the Minie-D is compatible with a variety of video standards (CCIR, RS170, VGA, SVGA). Costs for the Minie-D system are not available in the open literature.

The Minie-D is a candidate for evaluating augmented reality in an NVG for the CAF.

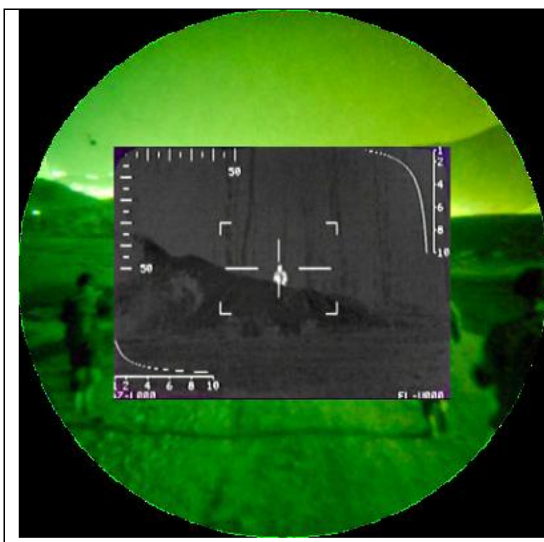


Figure 172: Minie-D showing weapon sight feed (Image copyright Thales, 2013)

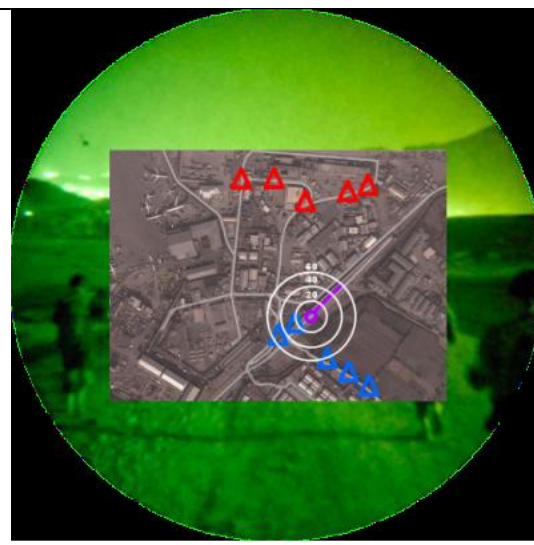


Figure 173: Minie- D showing command and control information (Image copyright Thales, 2013)

4.4.3.2 Minie-D/IR Fused System

The Minie-D/IR is a fused I^2 and IR NVG. An IR sensor module is attached to a modified Minie-D NVG- see Figure 174. Like the Minie-D, the Minie-D/IR can also display command and control information. The IR systems can display images in full, contour or threshold mode – see Figure 175. The IR system utilizes a 336x256 pixel microbolometer which uses a 800x600 colour display.

Figure 174: Minie-D/IR (Image copyright Thales, 2016)

At 490 grams the Mine D/IR is significantly lighter than comparable ENVG monocular and binocular systems.

Figure 175: Minie-D/IR image display modes (Image copyright Thales, 2016)

Given the success of the ENVG-B it could be assumed that Thales will develop a binocular version of its Minie-DIR system and may soon add a thermal imager clip on system.

Costs for the Minie-D/IR system are not available in the open literature.

The Minie-D/IR is a candidate for evaluating augmented reality in an NVG for the CAF.

4.4.3.3 Thermoteknix Fuser IR NVG

In addition to the very large NVG manufacturers there are smaller companies producing fused NVGs. The Thermoteknix FuseIR is a light weight monocular fused NVG. The FuseIR is not for sale or use in the US suggesting proprietary United Kingdom technology.

Figure 176: Thermoteknix FuseIR NVG (Image copyright Thermoteknix, 2021)

The FuseIR utilizes a 384 x 288 17µm pitch FPA with a 31° FOV microbolometer sensor. The I^2 subsystem is reportedly based on a high performance I^2 tube. The system performance is reportedly capable of detecting man-sized targets at 468 m and identification at 58 m. The system operates in three modes, I^2 only, thermal only and fused.

Thermoteknix also offers a clip-on uncooled thermal imager for use with existing I^2 based NVGs. Clip-on systems are discussed in the next section.

4.4.4 Clip-On Thermal Imaging Modules

A number of companies have developed clip-on modules which augment I^2 systems with a thermal overlay. One of the first systems fielded is the COTI™ (clip-on thermal imager) system. The initial COTI™ system has been refined and now is the basis of other systems such as the ECOSI (Enhanced Clip-On SWIR Imager). Other companies also produce clip-on modules.

4.4.4.1 COTI™ Clip on Thermal Imager

The COTI™ is a miniature thermal sensor that projects information into an I^2 tube. The COTI™ is supplied with clamps allowing the user to connect to a variety of monocular and binocular NVGs. The COTI™ is based on a 320x 240 microbolometer with a 20° FOV. The COTI weights 150 g (including battery). According to Costa-Defense (2021) there are three display modes:

- Full: thermal. Shows heat-producing subjects using a full thermal glow, which potentially adds display clutter. Recommended to be used when stationary.
- Patrol. Causes high-contrast thermal to glow but leaves the image mostly uncluttered. Recommended to be used while moving.

- Outline. Outlines heat-producing subjects and allows the operator to use the NVD for identification as well as targeting with IR Lasers.

Figure 177: COTI™ Clip-On Thermal Imager (Image copyright NVD, 2021A)

Figure 178: COTI™ Clip-On Thermal Imager attached to an AN/PVS-7 NVG (Image copyright the Firearms Blog, 2019)

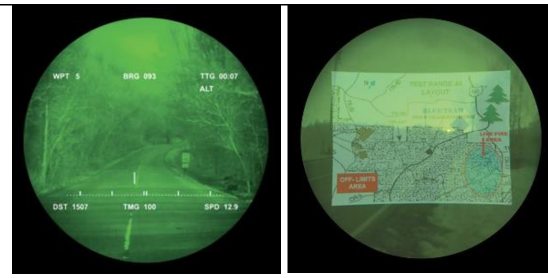
The COTI™ was introduced over 10 years ago and has been updated using new microbolometer technology. The cost for the COTI™ is approximately $4000 USD.

4.4.4.2 Low Profile NVG Clip on Thermal Module (COTM)

Steiner Optics designed the AN/PVS 21 low-profile binocular NVG for special operations and its low profile makes it compatible with parachute operations. The system uses see-through optics and a port where HUD information can be projected into the night vision image. While the original HUD allowed basic information (direction, altitude) to be displayed, a new CEHUD (Conformal Enhanced Head-Up Display) allows video information to be displayed. The CEHUD accepts analogue NTSC/PAL format color video signals or NTSC/PAL black & white video signals. While the website reports digital video feeds can be overlaid directly onto the operational view via an SVGA OLED, communications with Steiner Optics suggests this has not been pursued. While the AN/PVS-21 has inherent fusion capabilities, it is also possible to attach a clip-on thermal imager- the Steiner Clip-On Thermal Module (COTM).

The cost for an AN/PVS-21 NVG clip on module is approximately $14,500 USD. The cost for the AN/PVS-21 NVG itself is approximately $16,000 USD.

The AN/PVS-21 with COTM is a is a candidate for evaluating fusion in an NVG for the CAF. The analogue CEHUD system is not easily compatible with digital AR applications.

	
Figure 179: AN/PVS-21 Low Profile NVG with clip on thermal module (COTM) (Images copyright Steiner Optics Inc., 2021A)	**Figure 180: Sample AN/PVS-21 Conformal Enhanced Heads-Up Display (CEHUD) overlays (Images copyright Steiner Optics Inc., 2021B)**

4.4.4.3 E-COTI™ Enhanced Clip-On Thermal Imager

The E-COTI™ is an updated COTI™ with a 640 x 480 17 µm pixel pitch thermal sensor. The manufacturer suggests that users will be able to detect man-sized targets out to 450 m. The E-COTI™ has an augmented reality capability that provides navigation, route following, and geo-referenced information. If used with an Android device the system can be used for identifying other personnel, waypoints, etc. The AR system uses KML and GPX data formats for route planning. The system can also store images, navigation tracks, etc. The system is also compatible for parachute landing navigation (glide paths and landing point information). The E-COTI™ comes with an internal or external battery pack. The E-COTI™ with internal battery weighs 125 g.

Figure 181: E-COTI™ Enhanced Clip-On Thermal Imager (Image copyright NVD, 2021B)

The cost for the E-COTI is approximately $16,000 USD.

The E-COTI is a candidate for evaluating augmented reality in an NVG for the CAF.

The E-COTI has been reversed engineered in China and they have produced their own 640 x 512 12 µm pitch version- Infray Jerry-C clip on device. The cost for the Infray Jerry CE5 Clip-On Thermal imager is approximately $4700 CAD.

Figure 182: Infray Jerry CE5 Clip-On Thermal imager attached to a binocular NVG. (Image copyright Falconclaw, 2021)

4.4.4.4 ClipIR and ClipIR XD Clip on Thermal Imager

The ClipIR is a clip-on thermal imager similar to the E-COTI. The ClipIR utilizes a 384x288 25µm pitch FPA. The ClipIR XD system is under development (as of 2019) and possesses a 640 x 480 17 µm pitch FPA.

Figure 183: ClipIR XD clip on thermal imager (Image copyright Thermoteknix, 2021)

The ClipIR XD is equipped with a digital magnetic compass as well as an external video interface that allows the injection of AR information into the system (ATAK).

If Thermoteknix has completed the development of the ClipIR-XD it may be a candidate for evaluating augmented reality in an NVG for the CAF.

The cost for the ClipIR XD is not available in the open literature.

4.4.4.5 ECOSI Clip-On SWIR Thermal Imager

The ECOSI is a clip-on SWIR imager. The system is used to allow users to identify SWIR aiming lasers, pointers, beacons, strobes, etc. The E-COSI can also act as HUD for augmented reality and situational awareness system. The specifications for the E-COSI are not open to the public.

Figure 184:ECOSI Clip On SWIR Thermal Imager (Image copyright Optics 1, 2021)

The E-COSI uses a 7-PIN connector and can import, display, and export RS-170 Video. It can connect to external accessories: GPS, Smart Power Pack, etc. as well as PC/Android for picture download and Nav File upload. It also connects to situational awareness applications like ATAK.

The cost for the E-COSI Clip On SWIR module is not available in the open literature.

The E-COSI is a candidate for evaluating augmented reality in an NVG for the CAF.

4.4.5 Clip on AR Modules

Several clip-on AR HUD system is available for use with NVGs.

4.4.5.1 CoVis Covert Video Head-Up Display (HUD)

The Thermoteknix CoVis Covert Video Head-Up Display (HUD) can inject tactical data into an NVG. Similar in operation to the COTI systems, live or pre-programmed mission data can be presented from AR or ATAK systems. The system is compatible with Arc4. The system is small and light.

Figure 185: CoVis Covert Video Head-Up Display (HUD) (Image copyright Thermoteknix, 2021C)

Figure 186: CoVis Overlay (Image copyright Thermoteknix, 2021C)

The cost for the CoVis module is not available in the open literature.

The CoVis is a candidate for evaluating augmented reality in an NVG for the CAF.

4.4.5.2 SmartNVG

The SmartNVG from Elbit Systems is a clip-on system that allows the presentation of AR and command and control information into an NVG. The SmartNVG has two displays, a night display module and a color night display module. The SmartNVG will reportedly work with an Android device (ATAK). The night display utilizes an 852 x 500 monochrome pixel display while the color night display utilizes an 800 x 600 full color display.

Figure 187: Color night display module (Image copyright Elbit Systems, 2017B)

Figure 188: Night display module (Image copyright Elbit Systems, 2017B)

The cost for the SmartNVG module is not available in the open literature.

The SmartNVG display modules are candidates for evaluating augmented reality in an NVG for the CAF.

4.4.6 Fused Ground Panoramic Night Vision Goggle- AN/PSQ 36

In 2019, L3 Technologies introduced a fused variant of its Ground Panoramic Night Vision Goggle (GPNVG). The F-Pano is a GPNVG that has been modified to include a an LWIR sensor mounted centrally on the goggle. The GPNVG is a capable but expensive system.

Figure 189: Fused Ground Panoramic Night Vision Goggle (GPNVG), F-Pano version. (Image copyright Janes, 2019)

The GPNVG is a wide field of view (97°) NVG based on four Generation III 16mm I^2 tubes. The FOM for the GPNVG is approximately 1800. The latest GPNVG systems use white phosphorus displays. The GPNVG (F-Pano) reportedly weighs 800 grams.

The GPNVG (F-Pano) can be networked with command-and-control systems including the Android Tactical assault Kit (ATAK) as well as to AR software.

The cost for GPNVG alone is approximately $42,000 USD. The cost for the F-Pano version is not available in the open literature.

The GPNVG (F Pano) may be too expensive a system for evaluating augmented reality in an NVG for the CAF.

4.4.7 High Resolution Wide Field of View Digital Night Vision System

In 2017 L3 Photonis developed a wide field of view digital NVS for the US The Digital NVS replaces the 16 mm I2 tubes with high resolution (1600 x 1200) low light sensors. The Digital NVS is currently limited by display technology. According to US patent US9,618,746 B2 (2017) micro displays suitable for use in the Digital NVS were limited to 1280 x 1024 pixels. Currently, 2072 x 2072 displays are available.

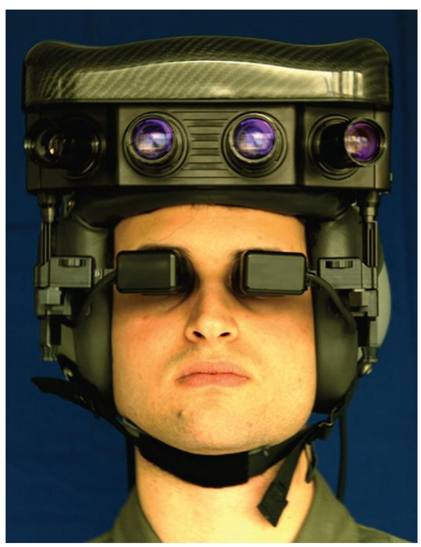


Figure 190: High Resolution Wide Field of View Digital Night Vision System (Image copyright Browne, 2016)

4.4.8 Fused SWIR & LWIR

A fused LWIR and SWIR sensor system has been developed by Sensors Unlimited. The LWIR system is used to detect objects of interest and the SWIR system is used for detailed examination. The scientific community has evaluated fusion approaches but no MOTS or COTS fused SWIR and LWIR NVG was considered (refs).

4.4.9 Research Trends

The literature review identified two additional research thrusts which may have bearing on the fielding of future fusion systems: the emerging technology of Smart Contact Lenses and engineered materials (ENMATS). A focus of past research was the development of wide field of view NVGs but with higher resolution in the center. While wide field of view NVGs are not in production, a patent on such a system is presented as a third development thrust.

4.4.9.1 Smart Contact Lenses

Mojo Vision is developing an AR smart contact lens which will allow the overlay of symbols and text on the user' natural vision. The system utilizes nanoLEDs (1.8 µm pixel size) and can project 256 x 256 information direct into the retina. Mojo Vision is researching adding edge detection enhancements for the visual impaired. Using a small low light image processor, the system is reportedly able to enhance contrast, zoom, and or enhance edge detection. Note: Edge detection capabilities are a feature of most fused systems today.

Figure 191: Artist's display rendition of Mojo Vision's smart contact lenses (Image copyright Cardinal, 2020)

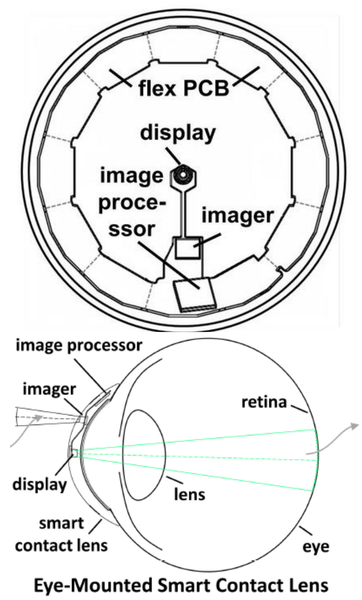


Figure 192: Mojo Vision smart contact lens design. (Image copyright Mojo Vision, 2021)

The system is still in development and Mojo Vision needs to ensure that the lenses are safe to use. Mojo Vision will receive development support from NASA (NASA iTech 2020 Cycle I challenge). An effective contact lens display will make the development of future space helmets simpler.

4.4.9.2 Engineered Materials

The US Defence Advanced Research Projects Agency's Extreme programme has sponsored the academic and industry communities to exploit the phenomenon known as second harmonic generation to convert IR wavelengths to visible ones. By using tiny 'nano-antennae' in the form of discs of dielectric aluminium gallium arsenide crystals embedded in optically transparent material, incident IR light is mixed with a strong laser ‘pump’ beam to generate a new visible image. The conversion happens directly without an intermediate electronic stage but does require batteries. By embedding and powering nano crystals in a thin film, the system might be able to convert invisible, infrared light to the visible spectrum. If realized, every soldier could be wearing an advanced set of ballistic eyewear that displays thermal signals, (i.e. the system will converts photons from infrared to visible light directly). Research is underway to scale-up the size of the nano crystal films to cover the area of a spectacle lens. Professor Dragomir Neshev at the Australian National University believes that a practical application is possible soon (Phys Org, 2016).

4.4.9.3 Wide Field of View Foveal Night Vision Systems

Li, Yu, Guo, Tang, Wang, and Cole (2016) submitted a patent for a Wide Field of View (FOV) Foveal Night Vision System. Through the use of optics and 40° FOV system is extended to an 80° FOV. Optically increasing the FOV without compensation reduces the resolution of the system. Li et al. utilized wave front coding to increase the foveal resolution of the system. Li et al. developed a system where resolution is highest in the center and decreases at the periphery. Higher FOV improves off-axis threat detection (i.e., flash detection). Lower resolution peripheral displays can alert the user to movement and thereby improve situation awareness. The Li et al. system has a wide FOV with minimal weight penalty(it is lighter than the Panoramic or Wide Field of View NVG with four tubes). Kent Optronics markets a Wide FOV Foveal NVG.

Figure 193: Retrofit WFOV AN/PVS-15 binocular NVG (image copyright Kent Optronics, 2014)

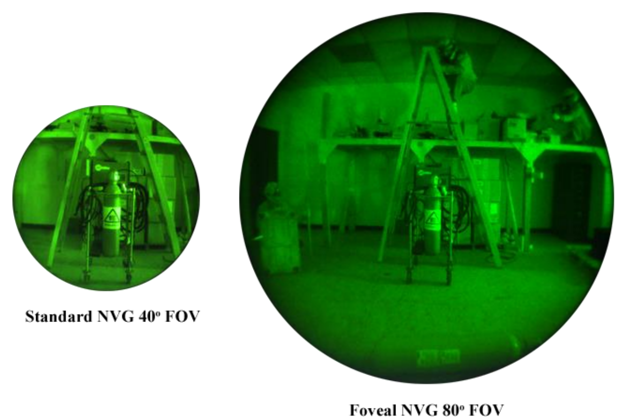


Figure 194: Comparison of 40° to 80° FOV (image copyright Kent Optronics, 2014)

The cost for the WFOV AN/PVS-15 NVG is not available in the open literature.

In principle, wave front coding technology could be used to develop wide FOV digital NVGs.

4.5 Discussion

A number of potential fused NVSs are available for evaluating their efficacy in operational scenarios. The commercial cost of the systems varies. The most expensive include the ENVG III /FES-I Night Vision and Targeting Systems ($64,995 USD) and the ENVG B AN/PSQ-36 ($57,950 USD)for. At the opposite end of the spectrum is the E-COTI clip-on thermal imager (approx. $8,400 USD). Older ENVG I (AN/PSQ-20A) cost approximately $14,500USD each (commercial price) but do not support any AR augmentation. When compared to a new AN/PVS-14 with Pinnacle tubes and a green phosphor screen at an approximate cost of $3600 USD, all fusion systems are significantly more expensive. The AN/PVS-14 with a white phosphor screen can also sell for up to $4,600 USD for commercial systems.

Utilization of E-COTI or ClipIR-XD thermal clip-on systems with state of the art AN/PVS-14 with white phosphor screens appear to be suitable compromise for evaluating thermal and AR fusion in an NVG.

The efficacy of adding just AR information into an existing AN/PVS-14 MNVG could be realized by using the CoVid system from Thermoteknix or the SmartNVG system from Elbit. The CoVid, ClipIR-XD and SmartNVG systems also have the advantage that they are non-ITARS controlled.

If the ATAK software is utilized in AR research, then interfaces developed for day use could be ported over for operations at night with the E-COTI, CoVid, ClipIR-XD and SmartNVG systems.

Fused NVGs capable of displaying command and control information are available today. The systems could support the evaluation of AR at night. The fused NVG systems have better night performance than the IVAS.

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The goals of this project were to assess the state of the art in augmented reality and fusion systems for use by soldiers, to research available commercial-of-the-shelf (COTS) and military-off-the-shelf (MOTS) systems, and to evaluate system capabilities and features against possible Canadian Army uses. Following a review of the state and goals of the Canadian Army's night vision program, the report then considers two seemingly separate and distinct areas—augmented reality (AR) and night vision fusion—that are merging and combining capabilities due to advancements in hardware and software technologies.

This report is organized into separate sections for AR and night vision fusion to keep common technologies and developments together. The AR section provides a definition and then expands on the continuum of extended reality. AR capabilities and functionality are described with examples from civilian applications, and enabling technologies are also discussed. These AR capabilities are then reviewed and discussed in the context of common soldiering tasks and activities. Infantry examples of AR use are provided, as well as examples of past and present Army AR programs. Finally, the hardware, displays, and software technologies within the worlds of mixed reality are described in more detail using developmental, Commercial-Off-The-Shelf (COTS) and Military-Off-The-Shelf (MOTS) systems.

The section on night vision fusion begins with an introduction to low-light sensor technology as well as image intensification systems. An introduction to thermal systems and long-wave infrared (LWIR) technology is provided. Major fusion programs and product lines are reviewed and discussed. Finally, novel research efforts are presented that have implications for future AR and sensor fusion systems.

Les objectifs de ce projet étaient d'évaluer l'état de l'art en matière de réalité augmentée et de systèmes de fusion à l'usage des soldats, de rechercher des systèmes commerciaux disponibles sur étagère (COTS) et militaires sur étagère (MOTS), et pour évaluer les capacités et les caractéristiques du système par rapport aux utilisations possibles de l'Armée canadienne. À la suite d'un examen de l'état et des objectifs du programme de vision nocturne de l'Armée canadienne, le rapport examine ensuite deux domaines apparemment séparés et distincts - la réalité augmentée (RA) et la fusion de la vision nocturne - qui fusionnent et combinent des capacités en raison des progrès du matériel. et technologies logicielles.

Ce rapport est organisé en sections distinctes pour la fusion de la réalité augmentée et de la vision nocturne afin de maintenir ensemble les technologies et les développements communs. La section AR fournit une définition, puis développe le continuum de la réalité étendue. Les capacités et fonctionnalités de la RA sont décrites avec des exemples d'applications civiles, et les technologies habilitantes sont également abordées. Ces capacités de RA sont ensuite examinées et discutées dans le contexte des tâches et activités militaires courantes. Des exemples d'utilisation de la RA par l'infanterie sont fournis, ainsi que des exemples de programmes de RA passés et présents de l'armée. Enfin, les technologies matérielles, d'affichage et logicielles dans les mondes de la réalité mixte sont décrites plus en détail à l'aide de systèmes de développement, Commercial-Off-The-Shelf (COTS) et Military-Off-The-Shelf (MOTS).

La section sur la fusion de la vision nocturne commence par une introduction à la technologie des capteurs à faible luminosité ainsi qu'aux systèmes d'intensification d'image. Une introduction aux systèmes thermiques et à la technologie infrarouge à ondes longues (LWIR) est fournie. Les principaux programmes de fusion et gammes de produits sont passés en revue et discutés. Enfin, de nouveaux efforts de recherche sont présentés qui ont des implications pour les futurs systèmes AR et de fusion de capteurs.