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InfraRed (IR) and Fused Sensors for the Soldier

A. Wayne Antesberger
U.S. Army Research Development and Engineering Command (RDECOM)
Communications and Electronics Research, Development, and Engineering Center (CERDEC)
Night Vision and Electronic Sensors Directorate
10221 Burbeck Rd
Ft. Belvoir, VA 22060

Abstract

This paper will present performance and soldier advantages of the new generation of uncooled InfraRed (IR) sensors, the fusion of these sensors with other technologies, and system design considerations while placing emphasis on helmet mounted IR sensors. The goal is to develop sensors for our Dismounted Warrior that provide a decisive overmatch capability with the lowest power, lightest weight, and lowest cost to improve their lethality, mobility, survivability, and sustainability. The new generation of medium performance IR sensors is being integrated in multiple systems approaches for a variety of applications to include helmet mounted or headborne systems. The advantages of IR sensors include high target contrast, obscurant penetration, and the ability to passively perform in total darkness. The challenges to helmet mounted IR systems are Field of View (FOV) and resolution, weight/Center of Gravity (CG), power consumption, latency, and frame rate. The developments occurring as a result of efforts at the U.S. Army RDECOM CERDEC Night Vision and Electronic Sensors Directorate are intended to provide soldiers with a versatile imaging capability including IR sensors, Image Intensified (I^2) sensors, or a fusion of technologies. Applications of these sensors include weapon mounted sensors for targeting, helmet mounted sensors for mobility, and handheld sensors for situational awareness. There is growth potential for these technologies and system approaches for interfacing with other U.S. Army programs where existing displays and sensors can be used as a baseline.

Introduction

Today's soldiers face a variety of terrain, environments, and situations in the course of performing their mission. It is our goal to provide them with the best possible technologies and associated capabilities to assist in the accomplishment of their various tasks and overall mission. Soldier tasks are diverse and include personal sustainment, communication, mobility, surveillance, situational awareness, navigation, target acquisition, and target engagement. There is a large cadre of equipment to address each of these soldier tasks and there is an accepted and approved Basis Of Issue Plan (BOIP) for what equipment is required for each assigned soldier role. Ultimately, the soldier will decide which equipment is appropriate for any given mission based upon weight, power, reliability, and the capability provided.

Combination or fusion of various technologies and capabilities has the potential to dramatically improve soldier ability. Fusion can consist of situational awareness information from above echelons, non imaging sensor information from a Local Area Network, information from other non imaging or disposable unmanned sensors, or laser detectors to indicate relevant activity otherwise not immediately obvious.

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High on the list of desirable soldier equipment capabilities are those sensors and systems that enable or enhance his ability to see. The soldier environment dictates the ability to see in many diverse and unfamiliar conditions. The soldier may need to observe various ranges in varying ambient lighting conditions. Being able to observe covertly has the potential to improve survivability. There are several technologies available to the modern soldier that have proven beneficial and are part of the standard Basis Of Issue Plan (BOIP), such as Image Intensifiers (I^2) and Thermal Weapon Sights (TWS). Soldiers recognize the capabilities of these technologies as beneficial to their mission and will carry them without question. However, no single system or technology will be the optimum solution to all soldier visibility or informational needs.

Thermal imaging systems allow the soldier to see in a variety of adverse conditions to include obscurants and the complete absence of light. Thermal imaging systems have proliferated through the military in the last two decades and are becoming more and more prevalent with commercial applications also becoming commonplace. Thermal imagers traditionally operate in the MidWave InfraRed (MWIR, 3 – 5 microns) or LongWave InfraRed (LWIR, 8 – 12 microns) bands and collect radiated energy well beyond the visible spectrum. The soldier capability and survivability improvements provided by thermal imaging are significant. Warm areas of potential soldier interest are prominently displayed with improved contrast and are generally difficult to effectively camouflage. Initially fielded and most current thermal systems employ exotic semiconductor materials, a means of cooling (cryogenic or other), mechanical scanning, and significant weight with excessive power consumption when compared to the dismounted soldier's resources. Some previous and currently fielded systems include scanned Mercury Cadmium Telluride (HgCdTe) Detector Arrays with mechanical cryogenic coolers, Joule Thompson coolers or Thermo Electric Coolers (TEC). Other systems incorporated chopped Thick Film FerroElectric Focal Plane Arrays of Barium Strontium Titanate (BST) and still others used staring Platinum Silicide (PtSi) or Indium Antimonide (InSb) Focal Plane Arrays (FPA) with mechanical cryogenic coolers. The early thermal imaging systems were generally tripod or vehicle mounted and had a burdensome logistics trail. Subsequent developments and technical advances allowed thermal imagers to become dismounted soldier weapon sights for target acquisition and engagement on crew served and eventually individual weapons through the 1990s.

Due to their size, weight, and power consumption, the currently fielded thermal imaging systems are not the optimal dismounted soldier solution on an individual weapon; however, they provide enough of an operational advantage that they are universally desired by soldiers familiar with their capability.

Today's Developments

Recent breakthroughs have provided thermal imaging technologies with significant improvements to the standard soldier equipment and capabilities. Uncooled thermal imaging technology is poised to revolutionize the dismounted soldier's ability to perform missions. Current uncooled thermal imaging is based on microbolometer FPAs manufactured using advances in the Micro ElectroMechanical Systems (MEMS) technology arena. FPA picture elements (pixels) are comprised of microbridge structures deposited on an appropriate Read Out Integrated Circuit (ROIC) usually of Silicon. Any material with a high Thermal Coefficient of Resistance (TCR) is applicable, with the most common materials of choice being Vanadium Oxide (VOx) or Amorphous Silicon (α-Si). Two dimensional staring FPAs are configured from different sized and structured pixels, and with different pixel counts, to optimize system performance to requirements or application. The arrangements and shapes of pixels are usually two dimensional rows and columns, with planar absorbing surfaces supported by thermally and electrically conducting 'legs' for thermal isolation. Pixel 'pitch' is the measurement between pixels from any reference point on one pixel to a spatially identical reference on an adjacent neighbor; some standard pixel pitches are 50, 38, and 25 microns and are usually the same vertically and horizontally. The shape and structure of the pixel is configured to maximize absorption area (fill factor) for a given FPA pitch. The different pixel structures that have been demonstrated involve single or multiple layers with multiple layers having an advantage in fill factor, as the isolation supporting legs are underneath the absorbing area. To further maximize efficiency the pixel creates a resonant cavity between the absorbing surface of the pixel and the ROIC. Scene energy can be absorbed on the underside of the pixel surface after reflection from the ROIC. The general goal is to maximize absorption and thermal isolation of the pixel from the ROIC to achieve desired sensitivity and provide a thermal time constant capable of supporting intended system video frame rates. These two characteristic performance parameters are usually in direct conflict with each other (inversely proportional). However, normalized sensitivities have been demonstrated at less than 50 mK with a 15 mS thermal time constant; normalized in this case is a measurement convention of f/1 optics at a 30 Hz frame rate. Such performance is suitable for relatively small system optics and standard video rates. Future developments could include ROIC with pixel sites arranged in staggered rows and columns, or pixels with alternative outlines and surface shapes to further improve fill factor and/or emphasize different performance parameters. For example, a curved pixel could better absorb energy from extreme angles of incidence and better accommodate system applications requiring ultra wide Field of View. FPA resistance to shock and vibration has not been a problem to date; however, with the advent of new FPA approaches it should remain in the forefront of considerations for military applications.

To simplify uncooled microbolometer operation, the pixel resistance is inversely proportional to the impingent scene energy and is assigned a gray scale value for display. The pixels are addressed, read, and processed sequentially by row. The generic approach to determine pixel resistance is to apply an electrical bias pulse through a voltage divider consisting of the pixel resistance and a ROIC resident reference resistor. The resultant current is changed to a voltage with a ROIC trans-impedance amplifier. The analog voltage is converted to digital data for ease of manipulation with Digital Signal Processor (DSP) or Field Programmable Gate Arrays (FPGA) based processing. Essential baseline processing consists of Non Uniformity Correction (NUC) which normalizes the pixel response across the FPA and temperature range using previously stored calibration, or correction, data tables. Ancillary components for uncooled thermal imager systems can be single stage TEC for FPA temperature stabilization, or a shutter to block scene energy and provide a uniform background, which aids in the NUC process. Some manufacturers use both a TEC and a shutter, while others use either or neither. In all cases, attempts are made to produce a system with isothermal imaging components because temperature change of the pixel as a result of scene energy is quite small and fluctuations can impede signal or NUC.

The performance of uncooled thermal imagers has progressed to the point of enabling systems applications previously reserved for only their cooled counterparts, without the need to power or accommodate coolers, scanners, or choppers. Consequently, the size, weight, volume, complexity, and power consumption is drastically reduced. In all approaches to the uncooled NUC process, timelines from ‘power on’ to useable if not specification compliant imagery are greatly reduced when compared to cooled systems. Images are available in seconds rather than minutes spent waiting for the FPA to cool down to operating temperature. Reduced timelines are manifested as power savings with the ability to leave the sensor ‘off’ until needed and the ability to implement ‘standby’ modes. Advantages in acquisition cost, life cycle cost, and system reliability will also be realized.

Applications (uncooled thermal)

The most obvious and immediate soldier application for uncooled thermal imagers is in the weapon sight arena. The improvement of all characteristic performance parameter areas of soldier concern, while maintaining range performance, make uncooled highly attractive. Reductions in power consumption of 70%, and weight of 30%, have been realized over currently fielded equipment with increased Field of View and equivalent range performance. The IR capability has traditionally benefited the soldier by providing for quick target detection via increased contrast. Drastic weight reduction of the IR weapon sight further reduces time from detection to engagement.

Range performance is traded with FPA sensitivity and optics (Field of View, f/#, and magnification) and is usually a compromise between capability requirements and soldier acceptability. Considering weapon sight systems based on uncooled 640 X 480 FPAs with 25 micron pixels, range of personnel detection for small arms or crew served weapon sights can be 2 km, with a 6 degree Field of View. The same weapon sight provides an acceptable system size, with weight under 1.8 kg (4 lbs), while consuming 3 Watts of power. The currently fielded Thermal Weapon Sight for comparison weighs 2.5 kg (5.5 lbs) and consumes 8-10 Watts depending upon ambient conditions. The implications to soldier load, logistics, and life cycle cost with application of uncooled thermal imagers are staggering while still providing the necessary soldier capability.

The next step beyond weapon sights for soldier application of uncooled thermal imagers is enabled by their continuing miniaturization and performance improvements. For the first time, dismounted soldiers will have access to helmet or head mounted thermal imagers. The capability advantage for target detection in defilade and ‘no light’ conditions is significant when compared to currently fielded equipment. Considerations for headborne thermal imagers are standard in terms of weight and CG. The total headborne weight should be limited to 2.5 kg (5.5 lbs) to reduce the potential for serious neck injury and the system CG should be as close to the head CG as possible. Determining requirements for FOV, resolution, and range performance is not easily accomplished, but initial prototypes are close to currently fielded systems in those characteristics and are generally being accepted.

Current uncooled thermal imagers which are applicable to headborne systems will likely be based on the 320 X 240 pixel count FPA with 25 micron pixels due to size, weight, and power considerations. Such a system would have a sensor housing no more than a 16.5 cc (1 in^3) with optics, weigh 114 g (0.25 lbs), and consume approximately 2.5 Watts with the addition of a display. A 320 X 240 based system with a forty (40) degree Field of View objective lens and unity magnification will provide for personnel detection of approximately 290 meters depending upon clutter and atmosphere. In contrast, a 640 X 480 uncooled thermal sensor with a forty (40) degree Field of View would provide personnel detection in excess of 500 meters, but at an expense of 100 cc (6 in^3), weigh over 225 g (0.5 lb), and consume upwards of 3 Watts with a display.

Utility of a thermal system as the sole soldier mobility sensor is somewhat in question due to effective resolution and thermal contrast limitations in some conditions, such as thermal equilibrium caused by precipitation.

Applications (fused IR and I^2 Sensors)

I^2 systems perform very well in terms of enabling the soldier to see in limited ambient light conditions and they continue to improve. I^2 systems collect reflected ambient light, predominantly in the visible spectrum, and amplify it thousands of times to present a useable image to the soldier. Whether configured as a head mounted mobility sensor or weapon targeting sensor, the resolution, Field of View, weight, and power consumption of I^2 systems make the technology a probable mainstay on the battlefield for years to come. Personnel detection for the typical I^2 headborne system, with nominal forty (40) degree Field of View and unity magnification, is 150 to 300 meters depending upon ambient light and background clutter levels. The headborne weight of a PVS-7 biocular I^2 system is 0.8 kg (1.75 lb) with helmet mount with PVS-14 monocular systems being even lighter. The longevity of I^2 systems is further supported by their compatibility with Near InfraRed (NIR) aiming lights and illuminators to aid in target engagement at a system power consumption of about 150 milliWatts.

InfraRed on the Head is a revolutionary capability concept, but is it enough? The improved ability to detect potential targets of interest, or increased situational awareness with IR imagery is reasonably well documented, but is the increased contrast based on thermal signature enough to displace the I^2 technology? Improved Range performance and target detection is obviously a significant capability, and the speed of target detection as a result of increased contrast is a significant soldier advantage. However, there are other soldier tasks and capabilities to which IR imagery cannot contribute adequately, such as not penetrating glass, or close tasks demanding high resolution such as equipment maintenance. It currently seems unlikely that I^2 will be displaced because of its superior performance in most battlefield conditions. When FOV and resolution are considered in the modeling process, personnel detection range performance is comparable between the two technologies, but only in low clutter conditions without obscurants and at least some ambient lighting. If the conditions deteriorate, and they will, then IR imagery begins to have an advantage over I^2 in terms of range performance.

Clearly, if the soldier can combine the advantages of multiple technologies his capability to perform the multitudes of tasks will improve. The resolution, aiming light compatibility, and the ability to see through glass of I^2 systems, combined with the rapid target detection and obscurant penetration of thermal imagers, will provide the future dismounted soldier a significant operational advantage over adversaries with standard equipment capabilities, all else being equal. The design concerns then become performance capability of combined sensor technologies and soldier burden in terms of weight, power, volume, complexity, and cognizance. Soldier attention cannot be dominated by the employment or operation of his equipment; it must be immediately easy to use and not a perceived burden.

There are multiple engineering solutions available for combining the two imaging technologies of most interest, and most have already been evaluated in lab and field experiments. The simplest conceptual approach for fusing IR and I^2 would be to present each technology to one soldier eye and let his brain fuse the images. For convention, it will be referred to as Level 0 fusion. Limited investigations have been performed on this technique, but one can easily imagine the image discrepancies to cause disorientation, or at least discomfort, if not total soldier unacceptance. Misalignment and image disparity of the separate sensors can be assumed with the associated eye fatigue or nausea; conclusions can be drawn to avoid this approach without the consideration of ‘image rivalry’ due to brightness or which is the ‘dominant eye’. Additionally, it has been shown in Human Factors testing that an ‘unaided eye’ can be beneficial, even in extremely low light conditions [1].

The first reasonable step for combining IR and I^2 sensors is an optical ‘overlay’, with some form of optical combination in the eyepiece area of a direct view I^2 sensor to inject the display image from the IR sensor output. For convention, it will be referred to as Level 1 fusion and is generally accomplished by a beam splitter or combiner. Processing overhead for this type combination is minimal and consists of NUC for the uncooled IR sensor. Other considerations include image registration as a result of different sensor apertures and differences in image latency which can degrade performance and soldier acceptability. There is parallax for the different sensor images, and there is latency between the instant direct view I^2 sensor and the electronically coupled IR sensor, even if the IR sensor is only 1 video frame behind. There are temporal artifacts and image discrepancies created by the IR latency and they become more evident to the soldier with more dynamic scene content and system motion. The soldier will benefit by directly observing the I^2 sensor because there is no image displacement to confuse very close range tasks.

The next step in technical sophistication would be to merge sensor electrical output signals for presentation on a headborne or helmet mounted display. This approach allows for more freedom in system configuration, as the I^2 system no longer *must* be direct view and aligned with the soldier’s natural line of sight. An electronically coupled I^2 imager is needed to replace the direct view I^2 sensor component, as most I^2 systems are based on the direct view of the tube phosphor screen. Therefore, the I^2 sensor must be optically coupled to a Complimentary Metal Oxide Semiconductor (CMOS) or Charge Coupled Device (CCD) to generate appropriate electrical signals for combination and manipulation. Considerations for coupling an I^2 sensor to a visible staring array sensor are dominated by the unavoidable resolution degradation and the need to preserve Field of View. There are emerging visible Near InfraRed (VisNIR) Low Light Level cameras which may have applicability here as a replacement for an I^2 sensor coupled to a visible imaging array; they include Commercial Off The Shelf (COTS) silicon, Electron Bombarded Active Pixel Sensors (EBAPS), or Indium Gallium Arsenide (InGaAs) sensors. However, the performance benchmarks of Resolution vs. Light Level with all of these alternatives will be a compromise, if not significant degradation, when compared to direct view I^2 for the immediate future. The possibility of active illumination is generally not a desirable soldier option. In addition, the cost of some alternatives is not attractive if large numbers of systems for fielding is considered without the benefit of commercial quantities. The IR sensor is inherently adaptable to this approach due to its ever present video signal output.

When provisions are made for the different sensors (I^2 /VisNIR and IR) to have electrical signals (analog or digital video), then a determination can be made for the method of combination. Options for combining video signals include mixing or fading of two analog video signals, and will be referred to as Level 2 fusion, or digital processing and manipulation of two digital video signals pixel by pixel, which is considered Level 3 fusion. In either case, special attention must be paid to ensure spatial and temporal synchronization of the two signals. Analog mixing requires less complicated architecture and electronics hardware and ultimately should consume less power. Digital manipulation requires a more complicated processing architecture and could introduce unwanted latency, but would allow for more image processing options and features. Some image processing options for digitally fused imagery include temporal or spatial filtering, interpolation, moving target indication, or emphasis on certain 'key indicators' or 'traits' thereby reducing the cognitive load on the soldier. In addition, the electronically coupled sensor's output is generally available as digital data prior to a change to analog signal and the fused system could avoid some power consumption for the digital to analog conversion process.

All of the combining techniques require some control input to find the correct ratio of sensor signals and optimize performance for the situation, task, and lighting conditions. The system controls must always be simple to allow quick adjustment with one hand (or less?). System defaults for adjustment settings would allow the soldier to concentrate on other tasks while achieving improved performance over baseline fielded systems.

The configuration of a fused sensor is critical to soldier utility and acceptability. Whether configured for a weapon or head mounted system application, the IR and I^2 sensors optical axis should be mounted as closely as possible to each other to minimize optical alignment difficulty. The previous discussion of parallax and image displacement suggests both sensors should remain as close as possible to the soldier's natural line of sight. The system design constraints to minimize image parallax and image displacement are significant; however, electronic manipulation of the signals could mitigate these concerns and minimize their effect on the soldier. Alignment of the two sensors must be addressed by either mechanical or electrical means. Mechanical alignment can be performed at initial system integration, but should have a means to adjust during the system life cycle in case of optical misalignment due to shock or other causes. Optical overlay systems allow mechanical alignment adjustment and would allow some electrical alignment by moving the IR image in the display. Small amounts of electrical alignment can be accomplished by shifting the images with respect to one another with timing. Alignment of sensor axes and display, and the minimization of displacement, is also critical despite the soldier task at hand. Misalignment of sensors and display can cause serious operational difficulties as a result of unknowingly looking in an unintended direction. To complicate matters, the increased Field of View required of headborne sensors used to provide mobility generally do not lend themselves to a coaxial lens solution for IR and I^2 sensors, and the lens system would be rather long and create CG and Individual Movement Technique (IMT) difficulties. Headborne systems will likely have separate apertures and neither will necessarily align with the soldier's natural line of sight. Alignment will be adjusted by the soldier and will probably be aligned at extended ranges to ease discrepancy. The IR imager information may not improve close soldier task accomplishment; therefore given the choice, the VisNIR sensor should be mounted more closely to natural line of sight than the IR sensor. To further complicate the design, the system needs to accommodate different soldiers and additional soldier equipment (for example: corrective glasses, goggles, or chemical mask).

Boresighting of a weapon sight to a small arms weapon, such as the M4, is usually done at 25 meters which is also accurate at 300 meters due to bullet trajectory. If the sensor optical axes are different, then one sensor must be used as reference and include the aiming reticle, because any attempt at alignment with both sensors would be range dependant. The other sensor would then only provide additional situational awareness information rather than aid in target engagement.

To minimize weapon boresighting issues for fused systems, it has proven to be advantageous to pursue weapon sights with coaxial optical systems for the different sensors. One approach is a combination of reflective optics for the I^2 sensor around the refractive optics for the centrally located IR sensor. This optical approach is generally possible due to reduced Field of View requirements, and tolerance to a longer overall system configuration for a weapon sight as opposed to a headborne sensor system. The Fused Multispectral Weapon Sight (FMWS) prototypes provide coarse mechanical optical alignment which is supplemented with electrical alignment. The electrical alignment can be accomplished in the field by the soldier and is range independent because of the coaxial optical system.

The prototype Universal Soldier Sensor (USS) illustrates some of the optical alignment and image displacement concerns during recent user evaluations. The USS is a soldier ensemble with a COTS Silicon VisNIR CCD imager for high light conditions and aiming light compatibility with an analog mixed uncooled IR sensor on the head (two apertures), a uncooled thermal weapon sight capability, and a handheld uncooled thermal probe all capable of being displayed on a Helmet Mounted Display (HMD). Special attention is paid in equipment training and by the user in operation to ensure the display is aligned with the sensors because the current design allows complete, independent movement of the HMD with respect to the sensors causing disorientation if not aligned.

Optical vs. Electrical and Analog vs. Digital

Optical overlay of image sensors (Level 1) is the most direct approach and consumes the least amount of power when compared to other techniques, but configuration options are limited. Image displacement issues are minimized because of the direct view of the high resolution I^2 system, but discrepancies of image latency are evident. Power consumed would include the I^2 system at 150 mW, the uncooled IR sensor at 1.25 Watts for a 320 X 240 pixel count FPA, and a display for the IR sensor at about 1 Watt, which totals almost 2.5 Watts. Commercial batteries, such as eight (8) CR 123 Lithium, would operate such a system for approximately 6.5 hours before replacement.

The most rudimentary of electrical video signal combination would require the addition of a visible imager for the I^2 sensor and a mixing or fading circuit to combine the sensor videos in the analog domain (Level 2). The CMOS or CCD visible imager coupled to the I^2 sensor would consume 0.3 Watt for VGA resolution; any higher resolution would be lost in the analog composite video signal format limitations (NTSC/PAL). The mixing circuit consumes about 2 Watts in prototype form, but could be further optimized or Application Specific Integrated Circuits (ASIC) could be produced (time and money). The addition of over 2 Watts power consumption for the VisNIR sensor and the mixing circuit would reduce the operational life of the same eight (8) CR 123 batteries to approximately 4.5 hours if the IR and display components remain unchanged. Video latency would exist, but would not be as apparent to the soldier because there would be no discrepancy between the different image signals; both would be delayed equally. Soldiers can generally tolerate latencies less than 100 mS, but acceptability is reduced for any delay exceeding 60 to 70 mS.

The eventual goal of IR and VisNIR sensor combination is in the truly digital domain (Level 3) to provide increased resolution over standard analog video, provide the ability to perform additional image processing, eliminate unnecessary conversions to/from analog video signals, and accommodate input format for most applicable display technologies especially at the increased pixel count formats. Uncooled IR sensors have inherent digital video data as a result of the Non Uniformity Correction (NUC) process. VisNIR sensors could easily provide for QVGA (1280 X 960) resolution, and displays are available with QVGA or similar formats; each component would consume approximately 1 Watt. DSP or FPGA based combination of the digital video from the sensors would consume approximately another 2 Watts for a total system power consumption of over 5 Watts. The operational life of the same eight (8) Commercial Off The Shelf (COTS) batteries would be reduced to 3 hours. QVGA pixel count formats with a forty (40) degree Field of View will provide a Snellen acuity of 20/60, or 0.55 cycles per milliradian in low contrast and light conditions. Most legislative districts require better vision to operate a motor vehicle. Some performance gains will be noticed by increasing the brightness of the display to compensate for eye response in very low light conditions, but it is hard to argue QVGA performance will provide the soldier adequate resolution in all conditions without extensive system characterization and human factors testing.

It's difficult to convince the soldier that a reduced visual acuity performance, for drastically increased power consumption, is an advantage over what he is currently issued. Power, size, and weight are constantly an issue for soldier acceptability and arrive at the forefront when resolutions and/or Field of View are increased. QXGA (2048 X 1536) formats could provide for Snellen acuity of 20/30, or 1.1 cycles per milliradian, and would be commensurate with previously fielded I^2 systems. There is an extreme penalty in power consumption when compared to the direct view I^2 system using currently available components with this approach. Unfortunately, there is no readily available miniature flat panel display to accommodate a QXGA format, especially considering the military environment.

Power and battery life comparisons for the different system approach and component resolutions are reasonably estimated from prototypes and projections and are contained in Table 1. It becomes fairly obvious that the life cycle cost for some of the higher resolution designs is prohibitive for fielding unless some of the components can be 'powered down' or placed in 'standby' when not needed. An additional concern is thermal signature for the soldier when dissipating significant amounts of power.

Table 1

System Approach and Power Consumption	Image Intensifier/VisNIR	IR sensor	Mixing Electronics	Display	Total (Watts)/ Battery Life (hrs) 8 - CR123
Optical Overlay	0.150 W (direct view I^2)	1.25 W	N/A	1.00 W	2.4 W / 6.5 hrs
Analog Mixing	0.300 W	1.25 W	2.00 W (prototype)	1.00 W	4.55 W / 4.5 hrs
Digital Mixing (QVGA)	1.00 W	1.25 W	1.75 W	1.25 W	5.25 W / 3 hrs
Digital Mixing (QXGA)	2.00 W	1.25 W	3.00 W	1.50 W	7.75 W / 2 hrs

Operational Considerations (Range Performance)

Range performance of IR and I^2 imagers can be modeled and have been tested in a variety of configurations and Fields of View for different soldier applications. Weapon Sights are generally required to have significant standoff ranges with associated magnification and narrow Field of View, while head mounted sensors are unity magnification with as much Field of View possible for the best user acceptance.

Predicted range performance in various conditions will give indications of what to expect from the different sensors and how they would complement each other to improve soldier situational awareness and completion of long range tasks. Snellen acuity will help predict the ability to perform short range tasks. The weapon sight performance modeling is contained in Table 2 and the headborne sensor performance modeling is contained in Table 3. All assumptions for modeling include realistic system tradeoffs for objective optics size and f/#, and other basic conservative inputs which have been correlated to field testing.

Table 2. – Weapon Range Performance Modeling [2, 3]

System Configuration	Resolution (cycles per milliradian)	Range Performance (low clutter)	Range Performance (high clutter)	Range Performance (obscurants, low clutter)
320 X 240 LWIR w/6 degree Field of View	1.5 cyc/mr	1050 meters	400 meters	675 meters
640 X 480 LWIR w/18 degree Field of View	1.0 cyc/mr	850 meters	325 meters	500 meters
640 X 480 LWIR w/6 degree Field of View	3.1 cyc/mr	2200 meters	900 meters	1200 meters
18mm I^2 (direct) w/18 degree Field of View high light high contrast	0.61 cyc/mr	760 meters	300 meters	195 meters

Table 3 – Headborne Mobility Sensor Performance Modeling [2, 3]

System Configuration 40 degree Field of View	Resolution (Snellen Acuity)	Resolution (cycles per milliradian)	Range Performance (low clutter)	Range Performance (high clutter)	Range Performance (obscurants, low clutter)
320 X 240 Uncooled IR	20/150	0.23 cyc/mr	290 meters	110 meters	150 meters
18mm I^2 (direct view) high light/contrast	20/23	1.5 cyc/mr	300 meters	110 meters	50 meters
18mm I^2 (direct view) low light/contrast	20/135	0.250 cyc/mr	50 meters	20 meters	0 meters
18mm I^2 coupled to 640 X 480 CCD high light/contrast	20/75	0.46 cyc/mr	75 meters	20 meters	0 meters

Interface for import/export of other information/imagery

There is a potential to include an external interface for fused imaging sensors, and the potential is increased with a digital or microprocessor based system, especially if the soldier is equipped with a computer architecture communicating on a battlefield network. The fusion of external information will give the soldier improved situational awareness, whether the external information is location of ally or threat, the presence of local area agents, or a single snapshot image of what's around the next corner or over the next hill. An interface from a weapon sight to a headborne display adds the ability to conduct reconnaissance and surveillance from cover, if not engage targets. The most immediate and simple interface would probably be the import of analog video from a weapon sight; and could easily be injected into the display signal path of any IR or IR/I^2 headborne sensor. This approach will be valid for the immediate future or until pixel counts and resolution exceed the capabilities of current analog video standards (NTSC or PAL). Some other 'standard' must be sought to accommodate the subsequent higher resolution hardware when analog capabilities are exceeded. Commensurate with the higher pixel count is probably a digital interface, with a potentially higher conductor or signal path count, which will increase from the two conductors required for basic analog video. Whether the conduit is wire, fiber, or eventually RF, available options include IEEE-1394, USB 2.0, or other emerging digital video industry formats. Using commercial interfaces and formats would keep costs lower and allow for more options and upgrades as products become available. The interfaces would remain electrically compatible as commercial, but the connectors and cables (if needed) would require environmental hardening.

Conclusions

Recent breakthroughs in uncooled thermal imaging technology have enabled dramatic improvements to soldier capabilities including weapon sights and the potential for headborne thermal imaging while reducing his burden. However, the variety of soldier tasks and environments cannot currently be satisfied with only thermal imaging. To fully take advantage of currently available technologies, the soldier will rely on the combination of more than one technology and its specific attribute. Fusion of sensor technologies is only now being considered and will likely take many forms for many applications and advantages over the next decade. The most immediate system capability goal for headborne or weapon mounted applications is the combination of IR and I^2 technologies.

The available resolution limitations and dramatically increased power consumptions of digitally fused IR and I^2/VisNIR sensors will most likely preclude soldier acceptance and fielding for the immediate future. Soldier advantages over currently fielded equipment will be provided by optically fused solutions for the next several years. Also, the interim solution of the Level 1 optically fused system would have the advantage of increased reliability due to the avoidance of 'single point failure' should either channel suffer malfunction.

It is difficult to convince a soldier that less resolution would improve his performance in the case of a Level 3 fusion system. However, with the addition of IR sensors, and the detection/speed of detection capability they provide, the total system performance of a digitally fused sensor system may be better than a currently fielded, solely I^2 device over all of the various battlefield conditions.

References

[1] "Human Off-Road Mobility, Preference, and Target detection Performance with Monocular, Biocular, and Binocular Night Vision Goggles" – U.S. Army Research Laboratory, V. Grayson CuQlock-Knopp, Dawn E. Sipes, Edward Bender, John O. Merritt, AUG 1996.

[2] IR model is NVTHERM, with following assumptions:

40 mK Normalized Noise Equivalent Difference of Temperature (NNEDT, 30Hz @ f/1)
100 mK Three Dimensional Noise (σ_{tvh})
80% optics transmission
70% probability of detection
N_{50} = 0.75 cycles for man detection (low clutter)
N_{50} = 2.0 cycles for man detection (high clutter, with signal to clutter ratio < 1) [3]
Target Area = 0.75 meters
Target Temperature Difference = 1.25 degrees
80% atmosphere (for a clear day)
Concentration Length = 2 (for obscurants)
Mass Extinction = 1 (for obscurants)

Visible Models are Minimum Resolvable Contrast (MRC) II and Image Intensified CCD with the following additional assumptions:

I^2 system with Gen III tube
Gain = 30,000 (footcandles in / footlamberts out)
Sky to Ground Ratio = 2
f/1.2 @ 95% transmission
Man in fatigues/Dirt road background/Clear starlight illumination (high light/contrast)
Man in fatigues/mixed soil background/Overcast starlight illumination (low light/contrast)
Fiber optic coupling for I^2 CCD (5 micron)

[3] "Introduction to InfraRed and Electro Optical Systems" – Ronald G. Driggers, Paul Cox, and Timothy Edwards, copyright 1999.