Invited Paper

Overview of benefits, challenges, and requirements of wheeled-vehicle mounted infrared sensors

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Abstract:

Requirements for vehicle mounted infrared sensors, especially as imagers evolve to high definition (HD) format will be detailed and analyzed. Lessons learned from integrations of infrared sensors on armored vehicles, unarmored military vehicles and commercial automobiles will be discussed. Comparisons between sensors for driving and those for situation awareness, targeting and other functions will be presented. Conclusions will be drawn regarding future applications and installations. New business requirements for more advanced digital image processing algorithms in the sensor system will be discussed. Examples of these are smarter contrast/brightness adjustments algorithms, detail enhancement, intelligent blending (IR-Vis) modes, and augmented reality.

1.0 Introduction

As the cost of infrared (IR) imagers decreases, their application increases. Vehicle sensors are an increasing market for commercial and military manned and unmanned ground vehicles due to the benefits provided, as listed in Table 1. These benefits are realized whether the driver is in the vehicle or remotely located, or driven by a computer in an autonomous vehicle.

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Table 1: Benefits of Infrared driver Viewing enhancement with Infrared Imagery:

- Improved Situational Awareness at Night
- Increased detection range of animals on road or side of road (day or Night).
- Increased detection range of pedestrians
- Better vision through Dust and Fog (especially in convoys on dirt roads.
- Recognizing traffic signs by their shape at ranges beyond headlights at night.
- Covert approaches for Law enforcement and military

Infrared imaging can provide a driver with superb situational awareness at night at ranges beyond headlights. The driver can see the mountains ahead, the curve of the road and structures on the side of the road, all used during daytime driving to judge speed and timing of turning. Because a passive infrared imager detects the self-emission of objects, there are no abrupt range limitations that headlights and active laser imagery suffers from. IR imagery also provides the driver with easy detection at night of pedestrians and animals (especially in bushes on the side of the road). A deer can easily be seen and recognized, even partially obscured by bushes, at ranges far greater than headlights can illuminate, or that one can see during the day.

Due to its ability to penetrate fog and dust, infrared imagery provides the driver (human or computer), with improved vision in dusty, smoky and foggy conditions.

Law enforcement and military vehicles have additional benefits for vehicle mounted infrared sensors. The increased situational awareness is a heightened requirement. With infrared imaging, people and crowds can be ascertained and the threat level judged. Another attribute of infrared imaging on vehicles is the ability for a covert approach at night for law enforcement or military operations; police forces can approach a site with no head lights on, at night.

Gimbaled, stabilized sensors on vehicles (as shown in figure 5 and 6) dramatically improve all of the benefits, since they can be steered to an area of interest, typically have multiple fields of view and can be equipped with sensors in outer bandpasses, laser rangefinders, designators and LIDAR imagers. However, these systems weigh and cost more than a simple fixed field-of-view “strap-down” camera.

A future development that FLIR Systems is working on is three dimensional infrared imaging. This provides the optimal imagery for operating a vehicle, especially a remotely operated vehicle or a two wheeled vehicle such as a motorcycle or bicycle. Infrared sensors such as the Quark camera core (figure 7) are small and low cost enough to provide true binocular imagery; however, the display is still a challenge.

Currently, three dimensional displays lack the durability for wide spread vehicle applications, especially military vehicles. Additionally they have drawbacks such as viewer fatigue, small cone angle for viewing, high cost, and size limitations. Also, some require drivers to wear glasses or goggles, which is a limitation. Nevertheless, 3D infrared is easy to drive off of and feels natural quickly.

Accident rates are lower for both commercial and military vehicles equipped with visible cameras. They are even lower for those equipped with infrared cameras due to the benefits listed above. There are 1.1 million deer-vehicle accidents each year, costing 3.5 billion in property damage.

2.0 Requirements:

The requirements for vehicle sensors depend on the application. Typical applications are driving aids such as the militarized sensor of figure 1 or the commercial version of figure 2, wide area situation awareness sensors (figures 3 and 4), Intelligence, Surveillance and Reconnaissance ISR (figures 5 and 6) and targeting. Table 2 details some typical requirements for vehicle mounted sensors by application.

Figure 1: A militarized DVE (Drivers Vision Enhancement) system installed on a Humvee, providing unprecedented night vision driving with awareness far beyond what headlights can provide.

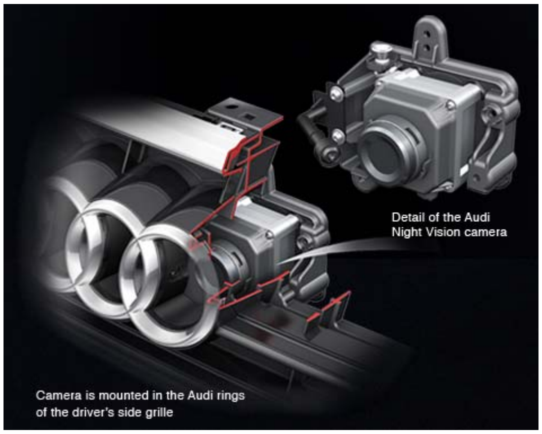

Figure 2: A mounting for a commercial automotive infrared camera

Figure 3: FLIR's Wide Eye sensor provides 180 Degree field of view for situation awareness and force protection.

Figure 5: A gimbaled ISR sensor installed on an Unmanned Ground Vehicle, providing the remote human controller or computer driver with excellent intelligence, surveillance and reconnaissance ability.

Figure 4: 180 degree wide stitched image from three infrared sensors mounted on a vehicle.

Figure 6: A gimbaled ISR sensor installed on a retractable post on a Land Rover.

Figure 7: The Quark LWIR camera is the world's smallest production infrared camera.

Table 2: Typical requirements for wheeled vehicle infrared sensors

Requirement	Human Drivers Aid	Autonomous Vehicle	Situational Awareness	ISR	Targeting
FOV	40 to 60 degrees, fixed.	40 to 60 degrees fixed, zoom optional	180 to 360 degrees fixed	2 degrees to 30, Zoom	1 to 30 degrees in multiple steps
Bandpass	LWIR	Visible and LWIR	Visible and LWIR	Visible, SWIR and MWIR	Visible and MWIR min, with optional SWIR and LWIR.
NEDT	<70 mK	<40 mK	<60 mK	<30 Mk	<25 mK
Laser Rangefinder	No	Yes	No	Yes	Yes
MTBF	>15,000 hours	>10,000 hours	>5000 Hours	>1500 hours	>1000 hours
Cost Sensitivity	High	Moderate now, high in the future	Moderate	Moderate to Low	Low
Weight	<2 Kg	<5Kg	<5Kg	Typically less than 30Kg	Typically less than 50Kg
# of dimensions to the imagery	Two, but three preferred	Two, but three preferred	Two , but three preferred	One	One

The vibration and shock profiles can be quite large, so shock mounting the sensors is often essential for DVE applications, but not for military targeting applications as those systems are designed from the beginning to survive and operate through extreme conditions.

If mounted near the engine or radiator (as is the case on many commercial applications) the thermal environment can be difficult. Even on commercial vehicles the temperature range can exceed that of Mil-Std-810.

3.0 Commercial Automobile Sensors

For commercial sales into the Drivers Viewing Enhancement market segment, FLIR first entered into discussions with BMW through the Swedish automobile safety designer/manufacturer Autoliv in 2002. The first product introduced into this market was called Night Vision (NV1) which was introduced on the 2006 7-Series BMW and was later offered on the 5 and 6-series vehicles. This was an imaging only product and consisted of a 38um pixel pitch 320x240 VOx bolometer in a sealed IP-67 ruggedized housing with a built in automatic window heater for icy conditions. The camera had a horizontal FOV of 36 degrees utilizing an f/1.4 lens. It operated on a 12V DC supply and provided 30 Hz analog video outputs.

A derivative aftermarket model called PathfindIR was also offered by FLIR in 30Hz for domestic sales and reduced 9Hz frame rate versions for export compliance. For the OEM version to meet export compliance for tamper protection, care had to be taken to ensure a coded handshake between the camera and serialized electronics preventing camera operation when disconnected from the vehicle. This handshaking has remained a key attribute along the full evolution of family of night vision products. The follow on Night Vision 2 came to market in 2009 and is currently offered on BMW and Audi vehicles. The NV2 also utilized a 320x240 VOx bolometer but the pixel pitch shrank to 25um. The horizontal FOV was reduced to 24 degrees and used an f/1.1 lens. The enclosure features a replaceable window in case of rock damage or excessive abrasion. The 30Hz video interface between the camera and ECU migrated from analog to digital to improve signal to noise ratio (SNR). The big differentiator for the NV2 product was the Pedestrian Detection and Warning (PDW) capability with a 300m range that operated by combining the camera information with the vector motion information obtained from the vehicle's CAN (Control Area Network) bus.

The Night Vision 3 product is to be shipped on Daimler vehicles in 2013 and consists of a 320x240, 17um pixel pitch Wafer Level Packaged (WLP) VOx bolometer. This state-of-the-art WLP packaging technology serves to maintain product performance while facilitating higher volume production processes to support the increased demands as infrared technology adoption expands. Several NV2 attributes remained common, but enhanced, to include; horizontal FOV at 24 degrees while utilizing a f/1.0 lens, the protective window remains replaceable, the digital video interface between camera and ECU remained digital but migrated to an automotive SERDES standard, the internal camera shutter for flat field function was physically relocated to provide greatly enhanced image quality and the ECU development for the NV3 enables both Pedestrian Detection and Animal Detection (PDAD?) for increased safety.

Several of the challenges with night vision automotive sensors are technical in nature, but a large majority of them concern the reliability of the product – especially when it is considered a safety device.

Some of the technical challenges in the commercial automotive Night Vision (NV) product line concerned the packaging of the device itself. Due to the fact that the camera has to be mounted outside the car windscreen (infrared cannot see through glass) in order to operate, the package has to meet the IP-67 standard. In the early NV designs, the mounting of the camera was critical for the Pedestrian Detection algorithm to function accurately. In later designs the algorithms were improved to alleviate this constraint. In order to keep the window clear of debris a washer nozzle sprays in association with the headlight washer system. The package is also well insulated and the thermal mass is mounted in such a way as to ensure rapid temperature swings do not affect the IR camera performance, i.e. when driving from a heated garage into sub-zero conditions. The front window has a tough coating to meet abrasive conditions (i.e. blowing sand) and is able to survive severe rock strikes. In later automotive Night Vision camera versions the window is easily replaceable in the event the window is ever damaged. From an algorithmic standpoint, being able to detect pedestrians and animals in a scene that is, in effect, continuously zooming toward the camera is a challenging environment. Especially when travelling at highway speeds, at least a 320 resolution camera is needed to get enough pixels on target to be able to warn reliably at a 100m range. Finally, the integration into the car via the CANBUS is required in order to not only detect the animal/pedestrian hazard, but to also incorporate the direction and speed of the car to effect not just detection but also a potential strike warning.

As the Night Vision product is designed into OEM vehicles, the inherent need for reliability is required to be in the region of single digit to zero PPM failures. This is accomplished by extremely rigorous methodology for hardware design. Software typically is required to be coded using Automotive SPICE (Software Process Improvement and Capability Determination); a set of technical standards that documents the software development. Product validation is extensive and requires large samples to undergo the full gamut of performance and environmental tests as a stand-alone device as well as logging thousands of miles in OEM test vehicles. Once in the field, the ability of the camera to self-diagnose has to be built in as part of the product and in certain circumstances (i.e. a dead pixel) the field technician can correct the camera while it’s still in the car.

After the product validation process, the OEM automotive supplier has to pass a Production Readiness test to ensure all critical metrics in the build process are monitored and tracked. The main supplier is not only responsible for their own readiness but also that of their sub-suppliers in order to achieve this certification. Finally, there is a manufacturing capacity validation test via a Run at Rate evaluation to make sure there is more than enough capacity, including surge capacity and yield impacts, to meet the OEM multi-year forecast. This whole process typically takes 18 months before the camera is placed into production.

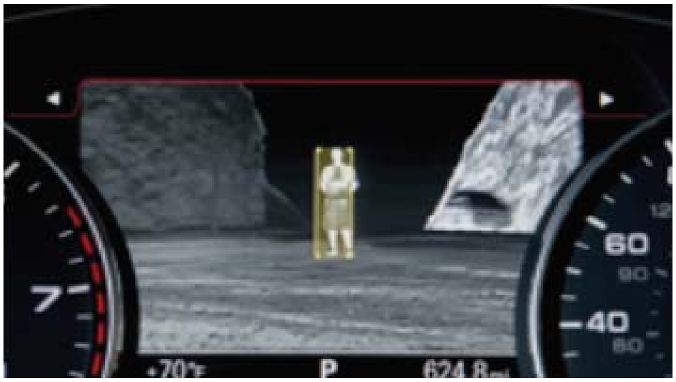

Figure 8: Pedestrian Detection in Audi Cluster Gauge

Figure 9: Pedestrian Detection (Image courtesy BMW)

4.0 Military Vehicle Sensors

Military ground vehicle infrared sensors include installations on manned and unmanned vehicles as depicted in Figures 1, 2 and 5. UN Forces and worldwide military vehicles have a pressing need for enhanced drivers’ vision and nighttime situation awareness, such as the 180 degree FOV vehicle sensor shown in Figure 3 and 4.

There are several reasons for a driver's enhancement including driving at night with lights off so as not to be a target, covert approaches in mission, enhanced and long range situation awareness and simply driving on unimproved roads at night.

However, the military's missions also include ISR, force protection and targeting from vehicles. For these missions, a longer range system with increased multi-spectral and multi-focal length imagery is required as shown in Figures 5 and 6. These systems must be fully militarized, reliable with full support and forward based repair facilities established before they are fielded.

Also, mounting an EO/IR system near a gun on a military vehicle can result in very high shock. The sensor needs to survive multiple shocks so metal fatigue and material selection is critical. Some focal planes (especially any material that exhibits pizeo-electric properties) can have momentary outages or flashes when a gun is firing. Additionally the muzzle flash and hot bullets can cause the AGC to reduce gain to a level such that the background image is lost. For locating near a gun, the focal plane needs high dynamic range and specialized image processing to retain the image when firing.

5.0 Image Processing for Vehicle Sensors:

During the past 10 years the progress in data processing capability in field programmable gate arrays (FPGAs) has seen a huge improvement when it comes to processing power/watt. Also, the processing power in a graphical processing unit (GPU) available today for a normal PC can exceed what a room-sized supercomputer had in the mid 90's. During the last 5 years, substantial efforts have been spent by the mobile industry to develop smart phones with ever increasing functionality. The outcome from this is families of system on chips (SoC) with miniaturized multi-cored processors with unprecedented performance in terms of processing power/watt.

The above mentioned progress has helped to push the business of vehicle mounted IR-cameras to introduce advanced image processing and video analytics capabilities. The processing power can, depending on the application, be differently distributed; close to the sensor for some applications (smart sensor) or many cameras connected to a centralized processing hub (low cost sensor).

5.1 Detail enhancement and dynamic range compression

In terms of luminance levels, IR-video data is typically of high dynamic range, i.e. a much higher dynamic range than what can be displayed for a human. Due to the human limitations there is no point in transferring more than 8-bit grayscale video data other than for post-processing needs, if a display is to be used. Due to the above reasons and, of course, to be able to reduce the data transfer bandwidth, the dynamic range of the raw IR-video (typically 14-bit) has to be compressed. The most important task for the adjustment algorithm is to perform this dynamic range compression and at the same time preserve small details and other video content that can be of importance for the operator. In the case of IR-cameras for driver's vision enhancement, the IR-luminance can vary dramatically during an employment. The temperature difference between hot exhaust pipes and a cold sky is dramatic and, without an intelligent image presentation algorithm, this can totally wash out the image. Advanced non-linear algorithms, such as STACE^{TM} by FLIR Systems, can reduce the risk of this happening (Fig 10 and 11).

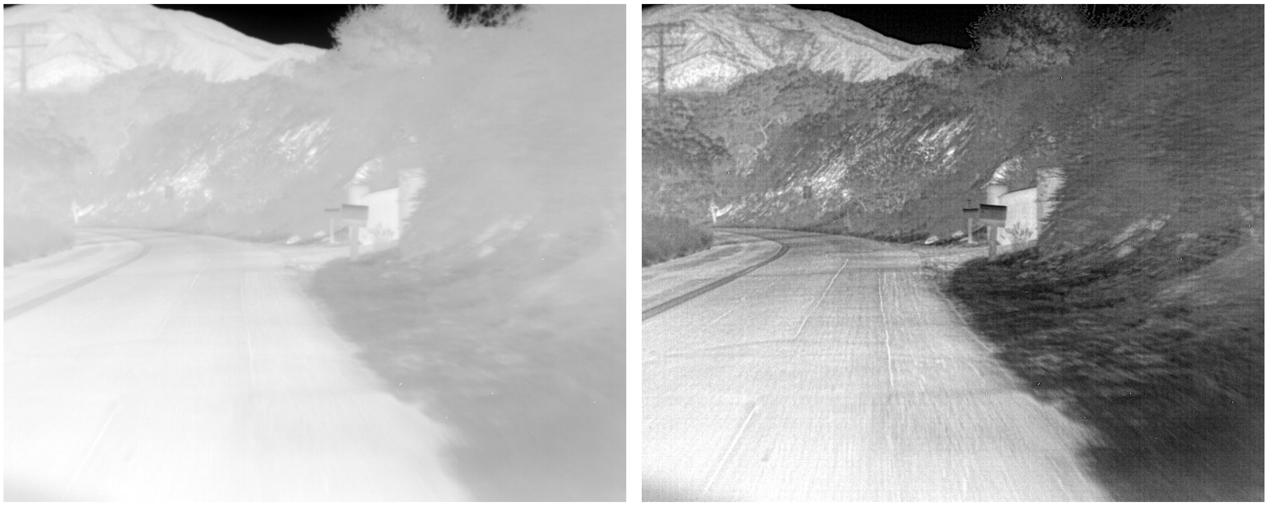

Figure 10: Example of a difficult scene to handle for an IR-sensor. To the left: The cold sky stretches out the dynamic range and makes it difficult to see fine details with a normal image adjustment algorithm. To the right: The same image with STACE algorithm applied.

Figure 11: Example of a difficult scene to handle for an IR-sensor. To the left: The hot exhaust pipe stretch out the dynamic range and make it difficult to see fine details with a normal image adjustment algorithm. To the right: The same image with STACE algorithm applied.

In the future, more advanced methods can be implemented. The main focus will be on local image processing, such as local contrast enhancement and image de-convolution. Another growing field is the use of image databases for finding correct image adjustments for driving.

5.2 Image noise reduction

The progress in de-noising methods, particularly driven by the need to take photographs in low level light, is gradually finding its way to the IR industry. The analogue to low light for IR is the absence of temperature differences in the scene. This particularly happens in rainy, foggy or dusty conditions when the video can appear very noisy. The problem is best tackled in two ways due to the character of the noise. (1) **White noise due to poor photon statistics:** can be reduced using novel methods developed for visual images, such as block-matching, nonlocal means or transform based methods. (2) **Residual fixed pattern noise mainly from readout electronics and stray-light:** is best reduced by calibrating the differences between the sensor elements towards the scene, i.e. scene-based non-uniformity correction. These methods are closely connected to the character of IR-video and are not always applicable to visual video. Combining these new techniques, will have a great impact on the usability of IR-sensors in difficult environments.

5.3 Fusion and multispectral analysis

Increased capability within the vehicle mounted cameras where one can expect to see a rise in demand is multispectral and fused video. Examples of this are the fusing of visual video with video from near-infrared band (NIR), short-wave infrared (SWIR) or long-wave infrared (LWIR). FLIR has recently deployed an algorithm for blending video from its Tau LWIR bolometer with color day-TV for driver's vision cameras. In order to make a nice looking image with good transition between the different channels, much effort has been spent to match the two cameras FOV's, including differences in image distortion. When the channels are spatially aligned the fusion is applied pixel-wise, based on the information content in each wavelength band. By using this kind of smart fusing algorithm the number of cases when the operator has to switch back and forth between the different channels is minimized and the information content in the fused video is maximized for the particular scene. Below are some examples of what the advantages of fusing day-TV with LWIR video can be, as compared to using single channels:

- Daytime: A better handling of high dynamic range scenes with both strong highlights and shadows.
- Daytime: Color information is present without having to switch to visual.
- Nighttime: Color information from traffic lights, car lights, or other signals is overlaid on the IR-video.
- Nighttime: A better handling of scenes that are partially illuminated by streetlights or other lights.
- Nighttime/Daytime: To be able to read texts on signs and cars without switching to visual.

5.4 Combining range capability and situational awareness

One basic challenge when it comes to IR driver vision enhancement cameras is to simultaneously have a good range capability in the direction of the road and a wide field of view (FOV) on each side of the road for situational awareness. New high definitions sensors with small pixel-pitch may partially solve this problem. One cheaper solution to this problem is to stitch together the video from two smaller FOV cameras with standard definition. In order to achieve a seamless feeling between the videos in the latter case, one has to take into account both differences in image distortion and synchronize the settings for the camera's respective adjustment algorithms. The same techniques apply to the case when video from three or more cameras are stitched together to create panoramas.

5.5 Augmented reality, pedestrian detection and 3D imaging

A topic that could see a dramatic increase in demand is augmented reality. It can be simple but useful things, such as using overlay graphics to indicate the width of the vehicle or the road. It can also have more advanced features such as adding information to objects along the road or displaying hidden objects or structures. By combining augmented reality, video analytics, and also with help from 3D image reconstruction one can build a powerful and robust system for classifying and identifying objects, detect pedestrians, read signs etc. The result can then be directly displayed for the operator. Another use of 3D reconstruction is to create virtual views for increased situational awareness.

6.0 Summary:

It is clear that the advent of driverless ground vehicles for commercial, police and military applications indicates a growing market for infrared vehicle sensors for close-in situation awareness, drivers vision enhancement, far range situational awareness as well as ISR and target designation. Each of these applications has different requirements and challenges. The ongoing movement to HD formats and 3D vision provides increased benefit for vehicle sensor but stresses the image processing and display technologies.