**FNIR** **Fusing far and Near InfraRed imaging for pedestrian injury mitigation**

# Final report

## *Publishable part*

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## Revision log

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# 1. Final publishable summary report

## 1.1 Executive summary

Road accidents involving pedestrians are far more frequent at night than during the day. More than 12,000 pedestrians and cyclists are killed and almost 300,000 are seriously injured in the EU every year. The most important factor is the driver's dramatically reduced range of vision in the dark. Fewer pedestrians would be killed or seriously injured if vehicles were equipped with improved Night Vision systems with driver warning strategies and image analysis algorithms capable of detecting pedestrians up to 120 m ahead.

There are two types of Night Vision technologies on the market with complementary strengths: far infrared (FIR) and near infrared (NIR) systems. FIR systems are passive, detecting the thermal radiation at wavelengths in the interval 8-12 µm. NIR systems use a light source with a wavelength of around 0.8 µm to illuminate the object and then detect the reflected light. The main advantages of NIR systems are the high resolution and driver acceptance of the picture. In contrast, FIR systems offer a superior range and pedestrian detection capability. Widespread use of both technologies is currently limited by the system cost.

The objective of the project was to demonstrate the next generation Night Vision system with automatic detection of upcoming hazards at an affordable cost. A combined NIR/FIR system enables substantial system cost reduction and increased performance through sensor signal fusion. The combined system reduces costs by reducing FIR sensor resolution, by reducing computing capacity and by using innovative European technology for moulded FIR optics and FIR sensors designed for mass fabrication.

The project has created European industrial exploitation opportunities. Such opportunities include infrared detector technology, optical components and affordable Pedestrian Collision Avoidance Systems.

*Main objectives in summary*

- Reduce the number of killed and seriously injured pedestrians and cyclists by developing the next generation infrared Night Vision system for automobiles incorporating pedestrian accident avoidance functionality.
- Develop a new and more efficient Night Vision system concept by fusing FIR and NIR sensor technology. Fusion will improve system performance while at the same time allow substantial cost reduction of the combined sensor system by making use of the complementary properties of the FIR and NIR sensors.
- Reduce system cost by developing a low cost FIR sensor system concept.
- Focus on pedestrians leaving subsequent projects to cover cyclists and animal detection.
- Lay the base for a new European industry which can achieve World leadership as Infrared Night Vision system supplier

## 1.2 Summary description of project context and objectives

### 1. 2.1 Introduction

Section 1.2 introduces the issues, goals and organisation of the project. Subsequent sections present project results. Figure 1 shows the focus of each of the sections that discuss the results.

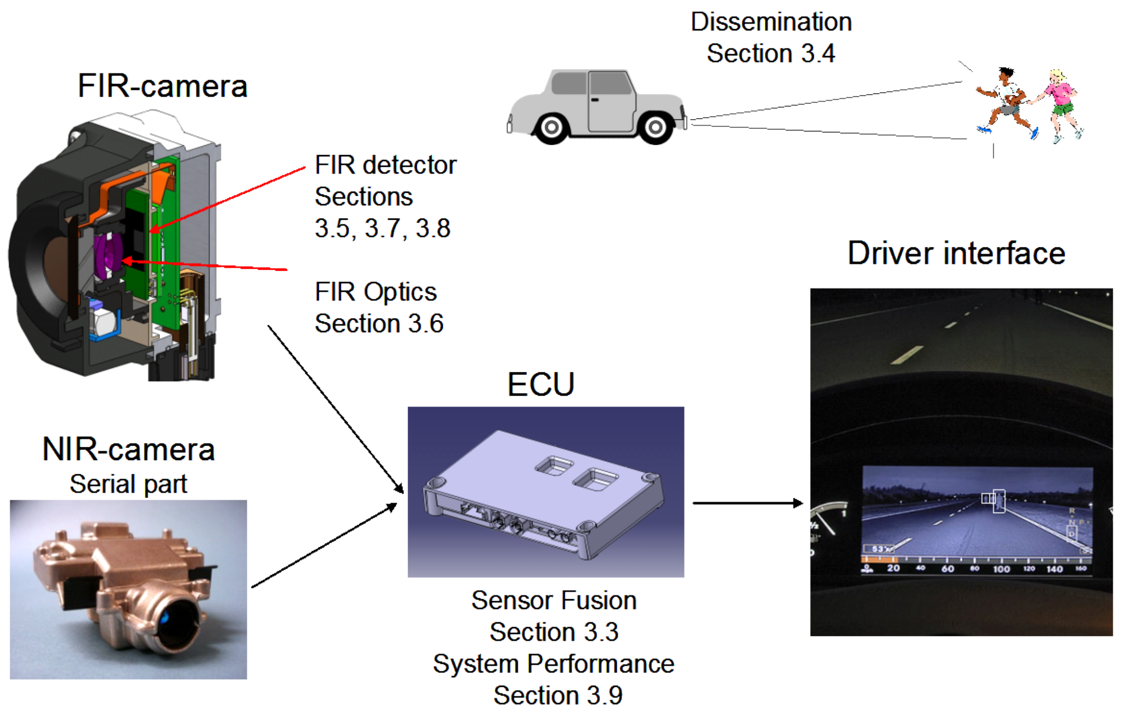


*Figure 1. FNIR Night Vision system based on fusion of FIR and NIR sensors and the major components covered in the project.*

Road accidents involving pedestrians are far more frequent at night than during the day. Night time traffic in densely populated areas like Japan can be as high as 40% of the total traffic volume, while typical numbers for industrialized countries are 20-25% [Rumar 2002]. Analysis of US traffic fatalities by the University of Michigan Transport Research Institute (UMTRI) has shown that the risk of a pedestrian fatality is around four times higher at night than during daylight hours, after all the contributing factors are taken into account [Sullivan 2001]. Although higher alcohol consumption, increased fatigue, and greater exposure to animals on the road are partly to blame, an important factor is the driver’s dramatically reduced range of vision.

Even though there is evidence showing that high beams are under-used [Sullivan 2003], with high beams used less than 10% in most regions [Rumar 2000], the core of the problem is that high-beam headlights can rarely be used owing to the frequent presence of oncoming traffic. The introduction of systems that automatically shift between high and low beam or that adjust the beam pattern depending on the presence of on-coming vehicles will likely improve the situation, but will not eliminate the reduced range of vision in darkness. The experience is especially challenging for older drivers who typically can detect dark vertical objects at distances of only 30 to 50 m when driving with low-beams and facing oncoming vehicles. The corresponding detection distance for young drivers, 40 to 60 m, is not much better [Rumar 2002]. Given typical driving speeds in darkness, pedestrians become visible only 1.5 - 3.0 s before the moment of closest approach. The main safety benefit of Night Vision systems is therefore to mitigate the problem of poor visibility of pedestrians and other vulnerable road users under low beam conditions. A detection range of up to 120 m is desired to allow the driver sufficient advanced notice, considering driver reaction and braking time at common vehicle speeds on country roads.

Night Vision systems use infrared (IR) cameras and are designed to complement the regular headlamps of a vehicle. There are two types of Night Vision technologies on the market; far-infrared (FIR), also referred to a long wave infrared (LWIR), and near-infrared (NIR) systems. A FIR system is passive, detecting the thermal radiation at wavelengths between 8 and 12 µm. Warm objects are highly visible in the FIR image. In contrast, an NIR system actively illuminates the scene using a near-infrared light with a wavelength in the 800 nm range and then detects the light reflected by objects. Both technologies apply proprietary algorithms to detect pedestrians in the image and to highlight their locations to the driver.

Night Vision systems were first introduced in the 2000 Cadillac Deville (FIR) and by Lexus/Toyota in 2002 (NIR). The first generations of Night Vision systems with automatic detection and alerts for pedestrians considered at risk of an accident are currently available in BMW (FIR), Audi (FIR), Honda (FIR), Mercedes (NIR), and Toyota (NIR) vehicles. Market penetration is limited as these systems are currently available only as optional equipment in premium cars. Cost-reduction efforts, rating and regulatory initiatives are expected to encourage a wider take-up in the vehicle market.

Consumers are likely to support the sensing technology that delivers satisfactory performance at the lower cost. Given that the capabilities of NIR and FIR at alerting drivers to pedestrians (and other vulnerable road users) partly complement one another, sensor fusion drawing on both technologies may be required to meet driver expectations at a reasonable cost. This report describes the efforts of a European consortium directed at such an approach.

The objective of the FNIR project was to demonstrate a next generation Night Vision system with automatic detection of upcoming hazards that can be produced at an affordable cost. This project has demonstrated that sensor fusion of NIR and FIR reduces system cost and increases system performance. The two main cost drivers of the FIR sensor are currently the resolution of the camera and its sensitivity. The combined system reduces costs by reducing FIR sensor resolution, by reducing computing capacity, and by using innovative technologies for moulded FIR optics and FIR detectors designed for mass fabrication. An analysis of the relationship between critical performance parameters established the trade-off between cost reduction, FIR sensor resolution, and computational constraints.

### 1.2.2 Objectives

Cost is a major issue that drives any automotive or other high-volume application. However, cost considerations must be kept in mind when fulfilling some other vital requirements such as a minimum acceptable level of performance. A major goal of the FNIR project has therefore been to understand the cost vs. performance trade-off of a fusion system. This knowledge will ensure that design choices will be avoided that either fail to meet the requirements or that over-specify system components and build in unnecessary costs.

The next generation of automotive Night Vision systems should offer automatic pedestrian recognition with a performance beyond current Night Vision systems at a lower cost. This trade-off is illustrated in Figure 2

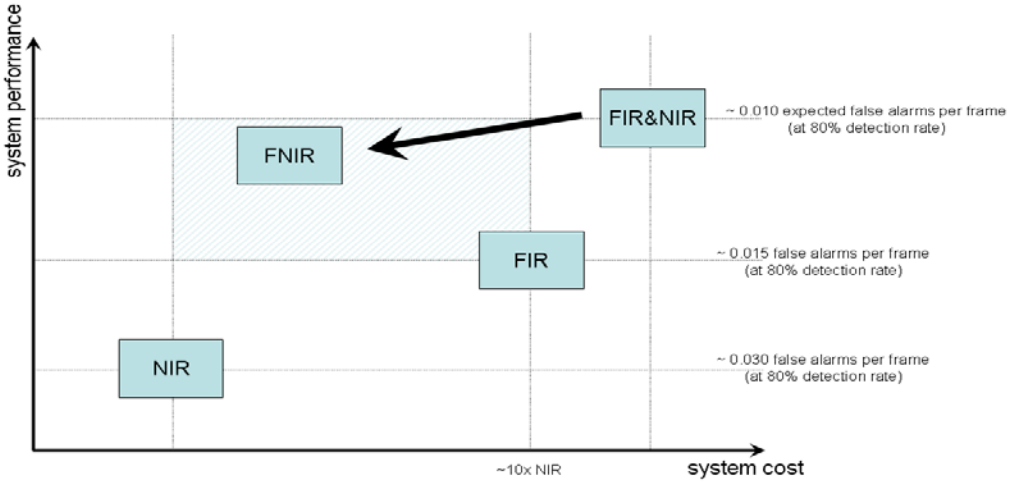


*Figure 2. Cost reduction while retaining high performance by fusing NIR and FIR sensors.*

The consortium pursued a multi-sensor approach that fuses the high resolution and image quality of a NIR sensor and the detection capabilities of an FIR sensor. The consortium has shown that the fusion approach has a high potential to meet ambitious requirements for detection performance. In that context, the main objectives were to support the claim that performance of an infrared based pedestrian detection system at night can be significantly improved by fusing data from both sensor types. This potential can be advantageous in at least three ways. It can:

- Focus on the false alarm rate.
- Focus on the detection rate.
- Focus of system cost, while keeping performance over a certain level.

The third objective is of great importance to low-cost systems, because high-end FIR sensors are the major cost driver. Improving thermal sensitivity and designing new sensor packaging technology were therefore major thrusts within the FNIR consortium. The repackaging and its use of innovative technology for moulding of highly complex optical surfaces for FIR optics makes FIR sensors fit for mass fabrication.

To meet the first two objectives - decreasing the false alarm rate and increasing the detection rate, the consortium investigated and established the recognition performance for a combination of the low resolution FIR sensor and a NIR sensor. By combining two sensor technologies, the project demonstrated that it is possible to reduce the demand for resolution and sensitivity on the FIR sensor and to arrive at a lower total system cost. The consortium therefore set out to investigate different combinations of sensors and to compare the fused system with a state-of-the-art FIR sensor system. The goal was to demonstrate that it is possible to design a low cost dual sensor system that has the same or better performance as the more expensive FIR sensor system. This involved investigating the influence of reduced sensor resolution on recognition performance in a systematic way. These requirements are important input on the hardware system specification.

The required level of performance increase also determines the FIR sensor resolution and computational constraints. Establishing the trade-off between cost reduction and performance requirements requires an analysis of the relationship between critical performance parameters. The goal is to determine the maximal reasonable degradation (cost reduction) of the FIR-sensor, which in combination with a NIR sensor yields a system performance sufficient for a next generation night vision system at minimal system cost. The target area of the system performance is the shaded zone in Figure.2. Sufficient performance will likely vary depending vehicle type. Cars sold in high volumes are more sensitive to component cost, which will influence the exact target location within the shaded area.

The consortium felt that it would not be meaningful to specify a false alarm rate for the system to achieve. Precise figures depend too much on the arbitrary composition of evaluation data (e.g. type of environment, weather conditions, clothing etc.) as well as on the individual design of the driver assistance system itself. Further, the focus within this project was not only to prove the superiority of fusion techniques, but also to explicitly consider the effect of degrading one of the sensors. Understanding the relationships between the detection performance and sensor parameters, like resolution and sensitivity, is essential when aiming for low-cost systems. To our knowledge, the FNIR project was the first to cover those issues in the field of image-based pedestrian recognition. It was important to identify which parameters have a primary influence on the detection results and the relative sensitivity to those parameters. Substantial cost savings can be achieved by avoiding over specification of parts or of the complete system.

# 1. 3 Description of results

## 1.3.1 Results - Sensor Fusion vs. FIR only

While reducing the cost of the FIR sensor, improved performance can be achieved by fusing FIR and NIR sensors. Early investigations revealed that for the purpose of FNIR, fusion on the feature level is preferable. The fusion framework invented here is capable of realizing a pedestrian detection system superior to the single sensor system. It is an extension to the well-known cascade detection first introduced by Viola and Jones [Viola et. al. 2001] for detecting faces in images. Such a cascade is capable of separating regions within images into two classes, namely the pedestrian and background class using a chain of classifier stages (Figure 3). In order to combine the information from FIR- and NIR-images at the same time the individual classifier stages were trained using the AdaBoost algorithm [Freund et. al. 1997] to select the most significant features from both sensors at the same time (MultiSensorBoosting). The selection of features from the different sensors was obtained statistically. The discriminative power of the features from the FIR and NIR sensor then resulted in a very efficient cascade.

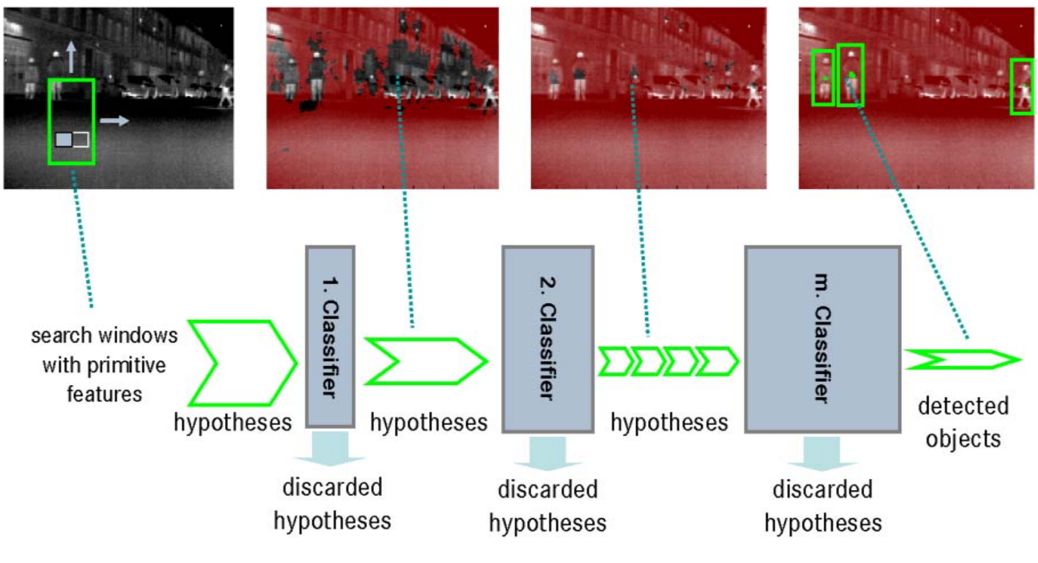


*Figure 3. Principle of cascaded classifier.*

Due to the different location of the two sensors, associated with a disparity and an ambiguous association, feature level fusion can't be realized by an overlay of the two images. This problem is solved by using a hypotheses generator that produces all possible hypotheses pairs. The implication is a huge amount of hypotheses which required an intelligent search strategy, a course-to-fine-search organized as a hypotheses-tree.

The overall sensor fusion architecture is outlined in Figure 4. It consists of three processing layers: In a first step hypotheses are generated within the searching space. Hypotheses originating from the different sensors are then associated based on model information (ego-motion, camera) and on detection results from the previous detections. In the second processing step, the features are calculated and organized in a combined set for both sensors. Then, the classification is carried out using the cascaded classifiers.

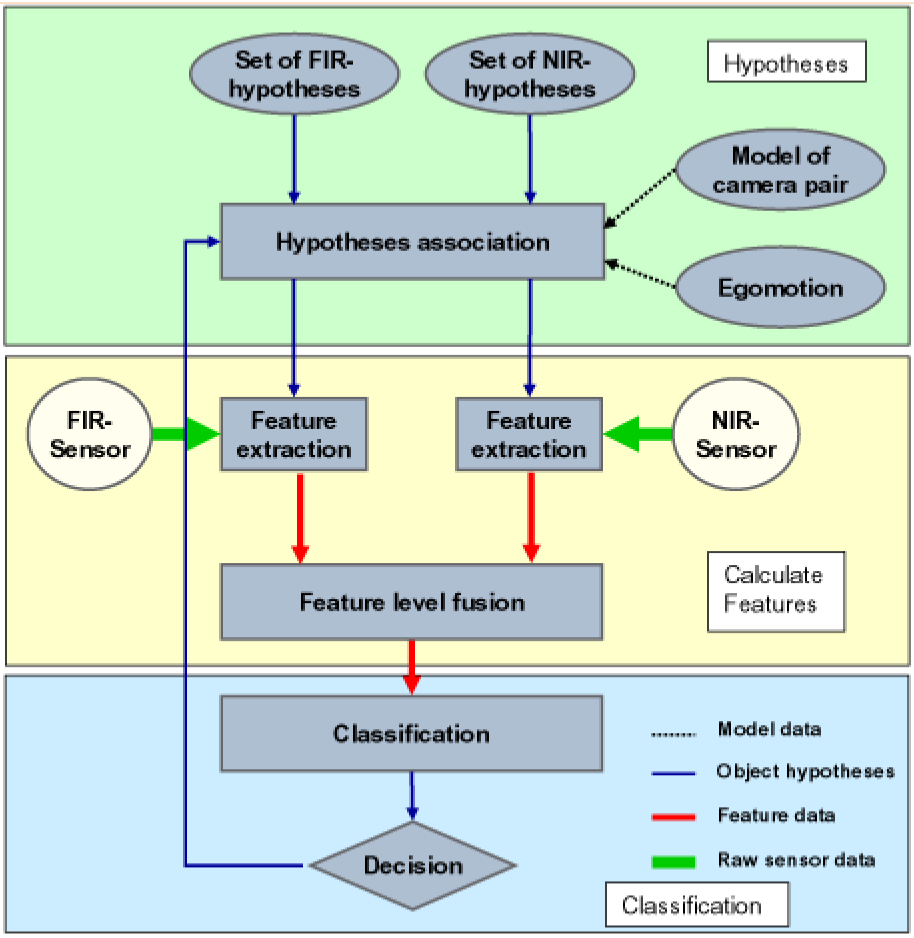


*Figure 4. Sensor fusion architecture within FNIR.*

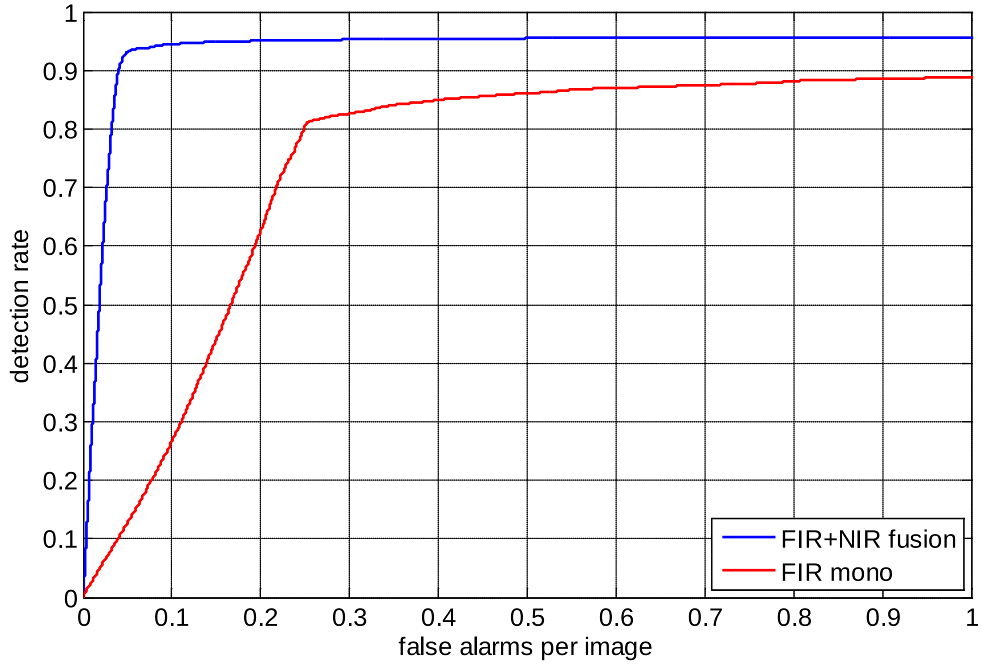


*Figure 5. Evaluation result of comparison between FIR+NIR Fusion (blue) and FIR solo (red)*

The system that was invented as part of the FNIR project is a low cost system with a brilliant night view image on the one hand and a detection performance higher than that of a single sensor Night Vision system on the other hand. The comparison between a fusion classifier and a FIR mono classifier shows, that the detection rate as well as the fraction of missed pedestrians can be significantly improved (Figure 5). The presented classifiers were trained with more than 900 different sequences resulting in more than 160,000 images and over 88,000 pedestrian boxes as ground truth. The test data was an independent set of 96 sequences (38,000 images and 35,000 labels).

Detailed evaluation of classifiers with NIR data fused with FIR data of reduced resolution has proven that the fused system can compensate the sensor degradation in a low cost system with an acceptable performance above a FIR mono system (Figure 6).

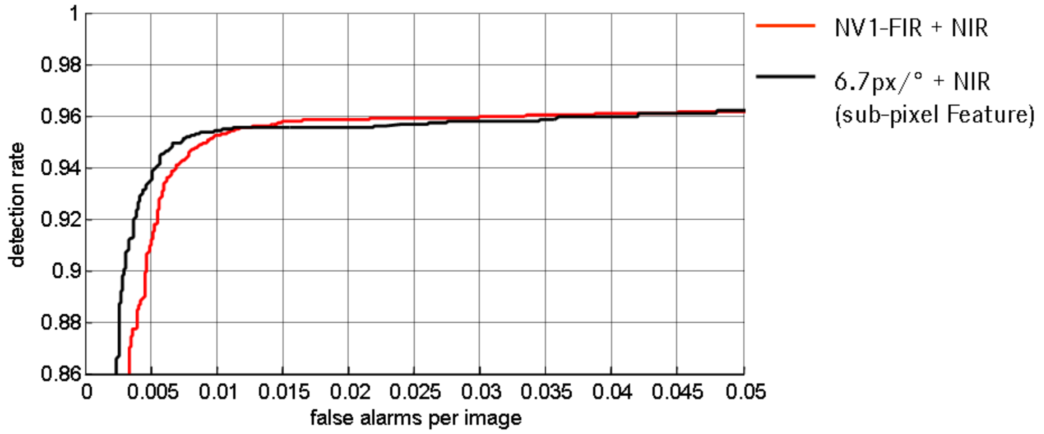


*Figure 6. Evaluation result of comparison between NV1-FIR+NIR Fusion (red curve).and Fusion of reduced FIR resolution with NIR (red curve)*

Reducing the sensor resolution is not the only valuable component for cost reduction. The focus within FNIR also lay on reducing the optics cost, which resulted not only in different relative resolutions but also in different sensitivities. However, the question of how the optics characteristic influences the classifier result was unknown prior to the project. A sufficient amount of training and evaluation data representing sensitivity effects was not available and was not feasible to collect. To overcome this problem, a transfer function was invented that makes the reusability of already existing data possible. For that, pixel-wise registered images from different sensor configurations were used to derive a linear transfer function whose coefficients were estimated using multi linear regression methods (Figure 7). The transfer function was then used to create datasets for training classifiers based on data representing different FIR sensor configurations. The results meet the expectation that the performance of the classifier is directly linked to the sensitivity of the underlying camera. Lower sensitivity results in lower detection performance.

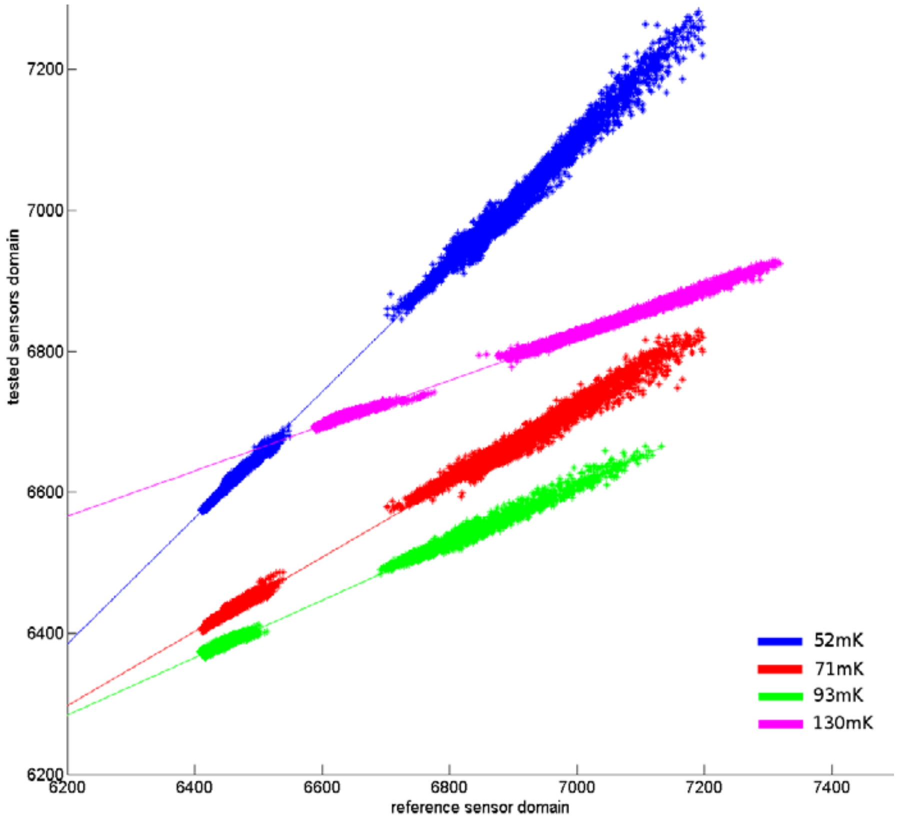


*Figure 7. Transfer function used for simulating data with different sensitivities. The scatter-plot shows gray values of pixel-wise registered images from different sensor configurations, each mapped to the reference sensor. Using that, transfer functions for simulating data with different sensitivities could be derived.*

To verify the modelling of the transfer function, a huge database containing over 750,000 images and over 1.2 million marked pedestrians was installed. Most of the data were recorded within FNIR in a campaign incorporating five sample FIR cameras with five different optics configurations (Figure 8).

*Figure 8. Two examples of FIR (top) and NIR (bottom) images from the measurement campaign that used five different optics configurations in hot weather.*

The comparison of simulated and real data has led to an accurate parameterization of the transfer function. The ability to simulate different sensor configurations makes important contributions to the understanding of the relationship between the sensor and classifier configuration.

Based on this novel approach the impact of sensitivity degradation could be evaluated with classifiers trained on simulated sensor data and tested on the real sensor data recorded in the FNIR project. In Figure 9 the results of classifiers for the 5 different optics configurations are presented which show reduced detection rates and increasing false alarms with decreasing sensitivity of the sensor.

These topics are discussed in greater detail by [Schweiger et al. 2010a, 2010b] and [Franz et al. 2010a, 2010b].

All performed evaluations represent raw detection rates and false alarms per image of the classifiers with no additional heuristics or temporal analysis techniques like tracking applied. By adding a basic temporal constraint of allowing only alarms that occur at least in 2 out of 3 consecutive frames, the false alarm rate can be further reduced. This results in a detection performance of more than 90% at the FNIR projects targeted 0.01 false alarms per image for a NV1-FIR fusion classifier.

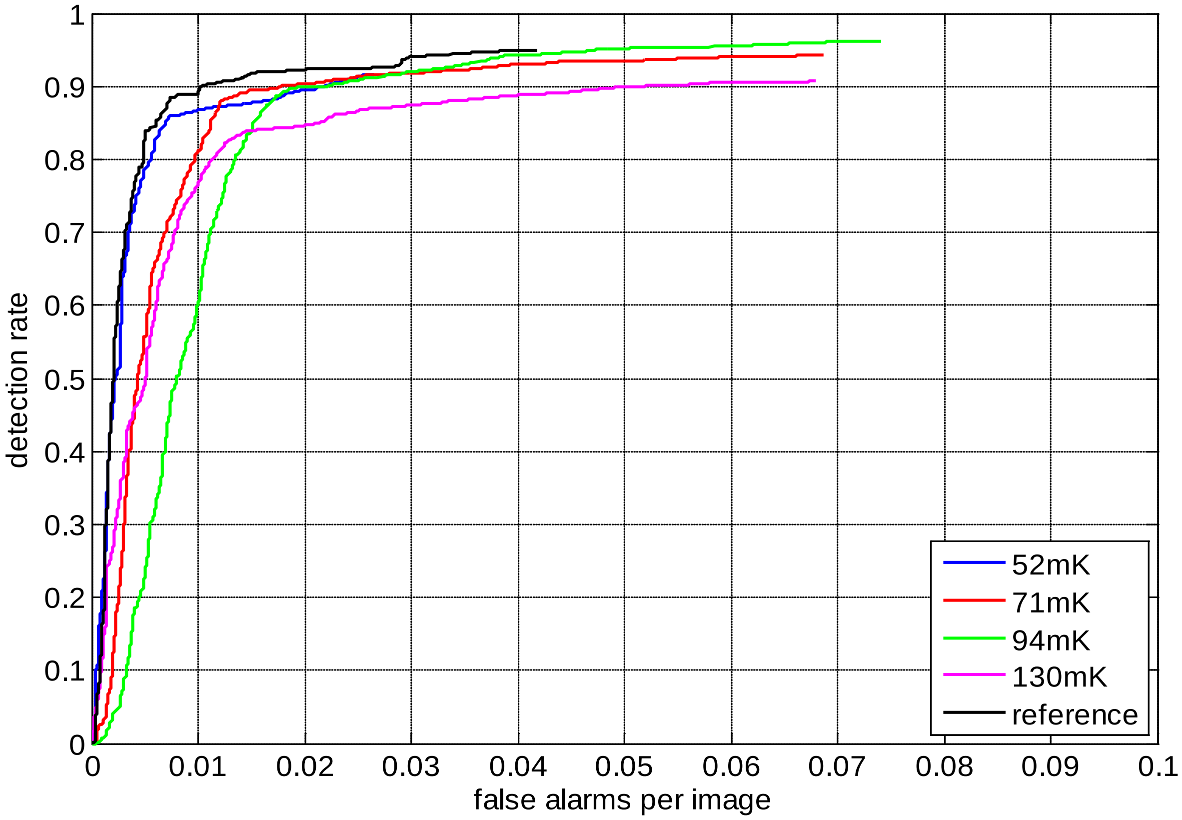


*Figure 9. Result of classifiers trained on simulating data with different sensitivities (42mK reference – 130mK) and evaluated on real sensor data with degraded sensitivity*

## 1.3.2 Results – Test and demonstrator vehicle

The demonstrator vehicle purchased by the project is a Mercedes Benz S350L version that was available for a favourable price through Daimler and has factory installed equipment favourable for dissemination purposes. This vehicle is equipped with a standard Mercedes Benz NIR Night Vision system. The motivation for this is that the NIR camera sensor will be the same as the one currently commercially available in Mercedes Benz S class. However it was reworked to function with the fusion software installed in the demonstration vehicle.

The initial task was to define what and how the demonstrator should show the results. This led to a basic setup shown in Figure 10, a schematic of the system layout, and in Figure 11, an interior picture of the installation. On the left side of Figure 10 are the input signals from the different cameras. These inputs are then connected to electronic control units (ECU) and Autoliv camera link adaptors (ACLA) to control the cameras and give the right video signals to the frame grabbers before they reach the imaging processing computer for sensor fusion and algorithms for pedestrian detection. Finally on the right side is the output to users of the demonstrator vehicle.

The starting point for building the demonstrator vehicle was that it had to be versatile enough to cope with anything the project may generate and not only fulfil what was anticipated at the start of the project. The specification of what and how the demonstrator vehicle should demonstrate the project outcome has been fulfilled with some changes from the original statement of work. This has resulted in a more versatile and a more accurate setup of the demonstrator vehicle. The change from a computer based GUI for the driver to a switch operated interface has made the demonstrator vehicle easier to operate and therefore also safer for the driver. The decision to modify the factory installed NIR camera instead of making a new prototype NIR camera has made it easier to compare results from the fusion algorithms and the commercially available FIR and NIR systems. As the NIR camera used a proprietary interface, we instead had to develop a custom interface to make the image from this camera understandable for a frame grabber in the imaging processing computer. The work of producing such an interface to the frame grabber included capturing and analysis of the bit stream from the installed NIR camera signal through its proprietary interface and making a video signal of the information.

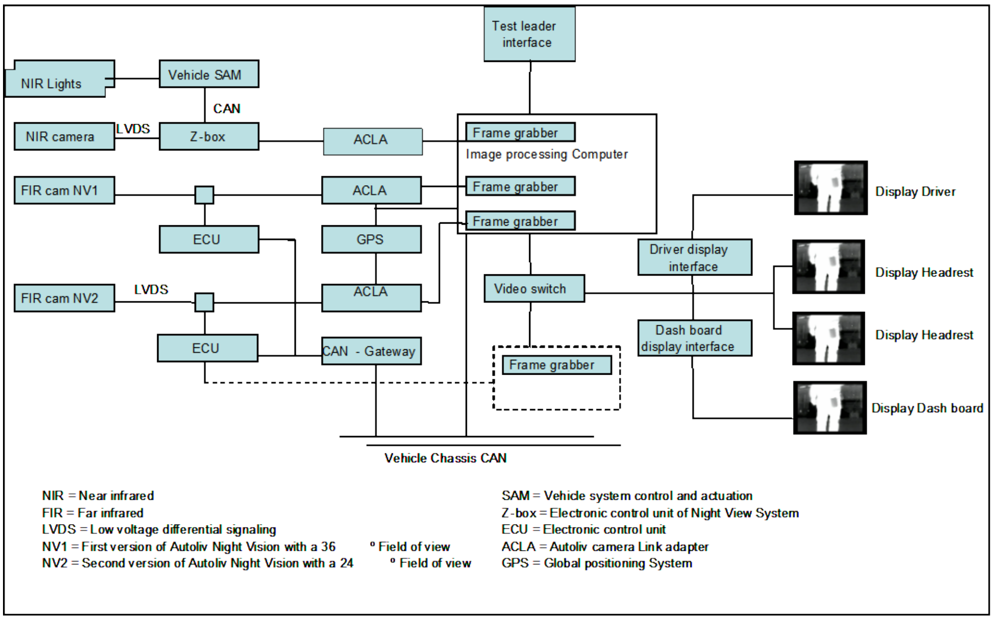


*Figure10 Schematics of installation*

*Figure 11. Interior of  vehicle*

### 1.3.3 Results - FIR system design specification

Based on the FNIR system performance evaluations, the specification for the performance of the FIR camera is a noise equivalent temperature difference (NETD, the smallest detectable temperature difference) of 100-120 mK and a video imaging frame rate of 25-30 images per second. A model for the NETD and the speed of the IR sensor has been used to estimate the performance of uncooled infrared bolometer with pixel pitches of 17x17 $\mu m^2$, 20x20 $\mu m^2$ and 25x25 $\mu m^2$. The calculations suggest that the proposed bolometer design approach in the FNIR project can meet the specifications for arrays with all evaluated bolometer pixel pitches. The calculations also suggest that the bolometer design is very competitive, specifically in anticipation of down-scaling the bolometer pixel pitch in future device generations. The temperature coefficient of resistance of the SiGe bolometer thermistor material is 3-3.5 %/K, which is very competitive. Further increasing the temperature coefficient of resistance will put very high demands on the read out electronics to handle large absolute resistance variations over the expected operating temperature range. To improve the performance of the bolometer arrays further, the main research focus should be on reducing the noise of the bolometer thermistor material rather than increasing the temperature coefficient of resistance. A decreased noise level has the result that smaller sensor signal can be detected.

A chip layout for a 320x240 array with 25 µm pitch is shown in Figure 12. The figure highlights the relative areas for the active pixel array, the getter, the signal chain, the bond ring, and the wire bond pads. The layout was the basis for estimating a cost structure which compared the relative manufacturing costs for detector arrays with different resolutions and pitches. The analysis concluded that the integrated electronics (ROIC), the sensor (MEMS) post processing/packaging and testing dominate this configuration, while only sensor post processing/packaging, and test dominate for smaller chip sizes. At larger chip sizes, the material cost of ROIC becomes more prominent. QVGA with 25 µm pitch is most cost efficient and a larger array or larger pitch will increase the costs significantly while a reduction of the array size and pitch does not gain much in terms of cost. There is a relatively moderate cost reduction when increasing the wafer size to from 150 to 200 mm.

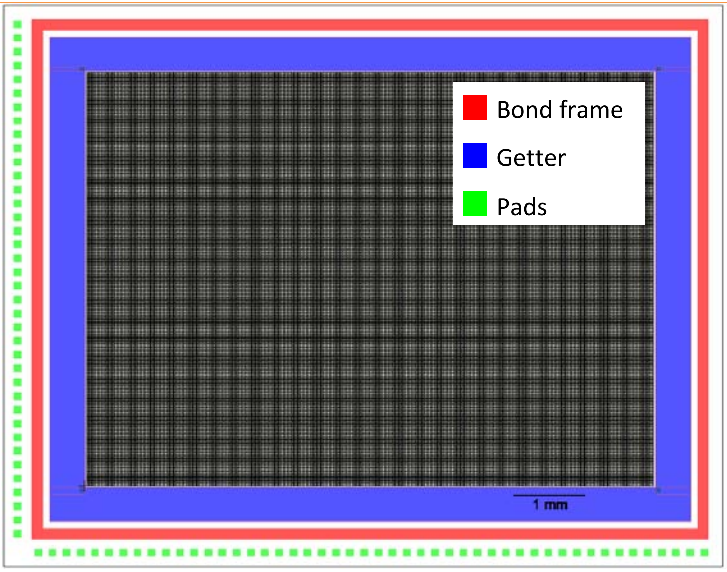


*Figure 12. Chip layout for a 320x240 array with 25 µm pitch*

The preliminary study of the FIR camera specifications for a FNIR system in combination with the NETD performance estimates found that the FIR camera system is likely to require IR optics with f/numbers in the 'intermediate' range of 1.5 to 2. It appears that significant cost reductions can be obtained relative to the Autoliv FIR benchmark system, even with a 2 lens system. The study on the optics shows that a 1 lens system is only possible at an f/number of 2.2. At this f/number however, the cost difference between the 1- and 2-lens solutions is small due to lens dimensions, while the performance of the 2-lens system is far superior to that of the 1-lens system. Thus, the 1-lens design becomes a less attractive solution. Lens manufacturing by moulding promises further cost savings even for classical two-lens systems.

### 1.3.4 Results - Optical material and lens development

Umicore's contribution to the project broke down into 3 main parts:

Design: It was necessary to design the optical system taking into account the requirements of the end user, the manufacturing methods available and the cost of manufacture. The first part of this contribution was an exploration of solution space to determine the possibilities.

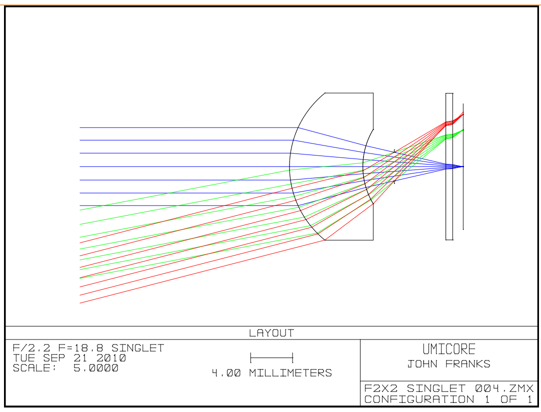


*Figure 13. Example single element solution*

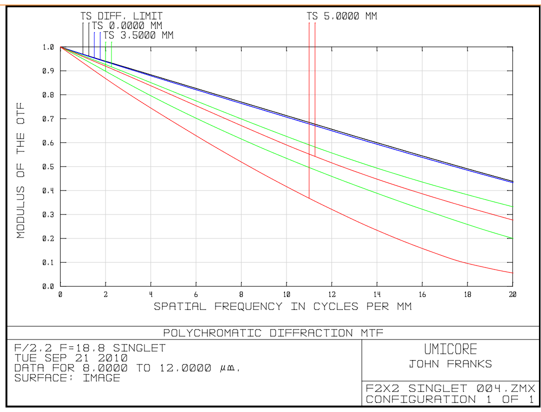


*Figure 14. MTF of single element solution*

Over the course of the project two design studies have been completed. The first study looked into possible 1 and 2 lens solutions against an initial optical system definition. Figures 13 and 14 show an example of a single element solution which demonstrates some of the problems found with a single element solution. It can be seen that the optical resolution described by the Modulation Transfer Function (MTF) is at the lower limits of acceptability. This is for a lens with an f/number of f/2.2. As the f/number increases the optical resolution degrades. The consortium determined that the f/number should be in the range f/1.8 – f/1.0. It was concluded that a 2 lens solution would be necessary. The second design study was undertaken after a refinement to the system definition was agreed by the consortium. This looked in much greater detail at the design space defined and concluded with a cost-benefit matrix to help the consortium in completing the system specification. Figures 15 and 16 show an example of a two element solution from the second study. The additional degrees of freedom created by the second lens allow this design to operate at f/1.1 with a greatly improved resolution.

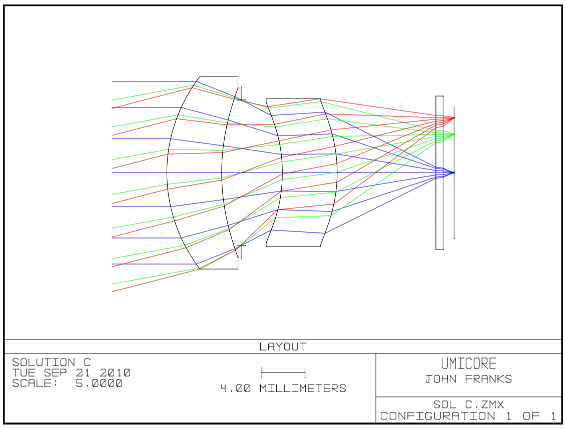


*Figure 15. Example two element solution*

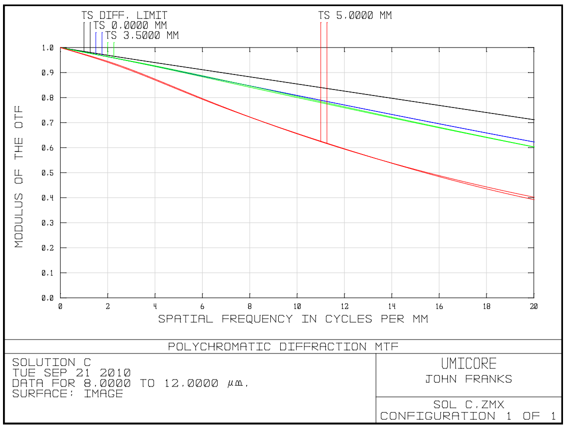


*Figure 16. MTF of two element solution*

Moulding: As this is required to be a low cost system, the second part of Umicore's contribution concentrated on improvements to moulding technologies to enable the realization of the goal of low cost lens assemblies in a low cost system.

The thrust of this part of the project was the improvement of current moulding processes to create low cost manufacturing routes for the design solutions created during the first part of the work package. This involved exploration of improvements to the moulding machinery, improved metrology and improved moulding processes. The initial concepts for low cost moulding routes proved to be unsuitable once it was discovered that a two lens solution was required. This mandated that different approaches were necessary. Significant improvements to moulding techniques and processes were yield as a result of this. Examples of the lenses produced are shown in Figure 17.

*Figure 17. Examples of high volume moulded lenses*

As part of the project Umicore has supplied a set of lens assemblies to enable the trials which were conducted by Daimler. A dedicated design was not selected. However, Umicore has developed a range of standard lenses in parallel with the project utilising the advances in moulding technology yielded by the project. Examples of these lens assemblies are available for use in proving the detector when required.

Coating: The final part of Umicore's contribution was an improvement in the coating technology to design and manufacture a coating that will withstand the aggressive environment seen by automotive Night Vision systems.

This involved improvements to the optical and mechanical properties of the iDLC™ coating. This was done by exploration of alterations to the coating machine, design changes and process improvements. A significant part of the coating sub-project was a real world analysis of the performance in an automotive environment with a view to proving the suitability of iDLC™ on GASIR®, when used as an external window. The results have been used to design a laboratory based test to simulate the real world conditions. Significant improvements have been made to the coating and the real world results show that further work will be necessary before the iDLC™ coating can be used in an automotive environment.

## 1.3.5 Results - Miniature wafer scale high-vacuum packaging

Figure 18 shows a schematic overview of the cap wafer and the ROIC wafer that is bonded to achieve high vacuum levels.

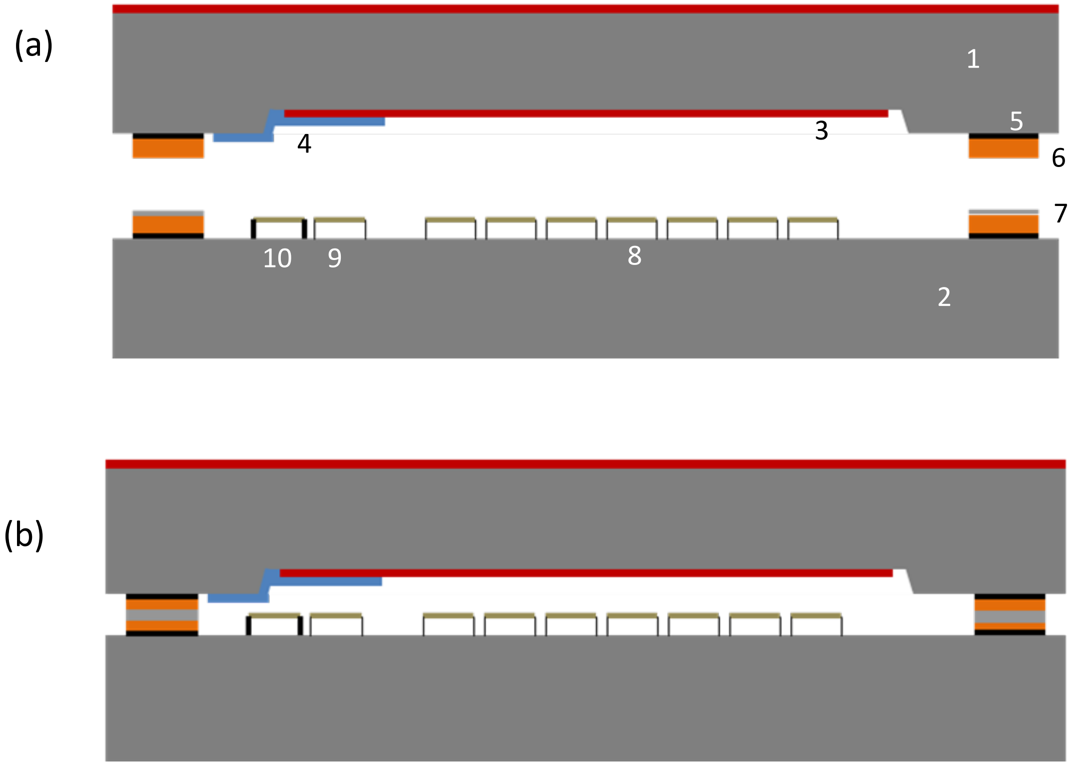


*Figure 18. Schematic view of cap wafer and ROIC layout (a) before, and (b) after bonding. Only one focal plane array shown. 1. Si cap wafer, 2. ROIC, 3. ARC, 4. Getter, 5. Barrier/adhesion layers, 6. Cu bond frame, 7. Cu/Sn bond frame, 8. Active bolometers, 9. Vacuum sensor pixel, 10. Thermally shorted reference pixel.*

The work package has explored Au/Sn and Cu/Sn wafer level bonding technologies for vacuum sealing of the bolometers. Cu/Sn was selected as the most viable process since the initial chip level experiments showed promising results with high-quality Cu/Sn sealing frames. The Cu/Sn material compounds had the potential to tolerate getter activation temperatures, which typically are around 350°C.

The process was also tested on the wafer level at low pressures. Improving the bonding parameters resulted in an enhanced yield and 90-100% is now repeatedly obtained in our fab. Cu/Cu3Sn/Cu stacks with good quality have been observed in bond frames designed with a representative FNIR layout for assembling of 100 mm wafers.

Concepts and designs for vacuum sensors, getters and Anti Reflection Coatings (ARC) were also studied. The target vacuum level in the cavity of ~$10^{-3}$ mbar is assured using a patterned non-evaporable getter with an area of >2 $mm^2$ on the Si cap wafer. A High Durability Anti Reflection (HDAR) coating type is selected for obtaining a ~90% FIR transmittance through the cap wafer, which is required for obtaining high system performance.

The quality of the CuSn sealing frame was investigated by the use of die shear experiments, fracture analyses and rest gas analyses. It was found that the bond strength was typically more than 30 MPa, which is high enough for automotive applications. Many samples had a 3D fracture, which indicates strong interfaces.

Samples were processed in order to qualitatively investigate the hermeticity. Cavities with membranes were fabricated, making it possible to see the membrane deflection when vacuum was achieved in the cavities. Several wafers were bonded using varying bonding processes and different bonding equipment. The very first experiments showed that about 30% of the membranes were deflected but this was enhanced and also wafers with 90-100% deflecting membranes were accomplished. In parallel, elaboration with different bond frame designs has improved the control of Sn flow during wafer level packaging. By dividing the Cu/Sn bond frame into several sub-frames, it is possible to confine most of the molten metal into the spacing. With a proper design, all Sn is reacted forming either $Cu_3Sn$ or $Cu_6Sn_5$ compounds. Thus, there is no melted material during getter activation.

Quantitative measurements of pressure level in the cavities were performed. One important observation was that the samples typically did not show any indication of leakage right after sealing. However, a high partial pressure of Argon (Ar) was found. Residual Ar most likely originated from sputter clean processes prior to film deposition. Several solutions, which will be elaborated in the ICU project (www.icu-eu.com), have been suggested.

## 1.3.6 Results - FIR Detector array

FIR detector including packaging and FIR optics are the key technologies that needed to be developed in order to achieve the reduced cost and improved performance indicated in Figure 2. They were assessed from both a performance and a manufacturability point of view. A schematic illustration of a bolometer used in the FIR detector is shown in Figure 19. The full detector consists of an array of such bolometers, each corresponding to one pixel in the final FIR image.

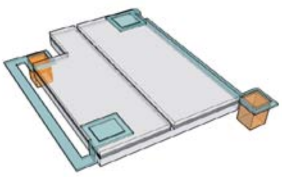

*Figure 19. An illustration showing a bolometer membrane suspended by two legs. Bolometer designs with a pixel pitch down to 17x17 µm have been investigated in the FNIR project.*

A FIR bolometer transforms IR radiation into a resistance change that can be measured and interpreted as an image as illustrated by Figure 20. The transformation is a multi-step process where IR radiation is first absorbed in the bolometer membrane. The absorption efficiency is governed by the fill factor and the design of the pixel cross section. The absorbed radiation results in a temperature change which is related to the pixel heat capacity and thermal conductivity to ambient. Finally, the temperature change results in a resistance change which is determined by the electrical properties of the thermistor material. There are thus several factors which have to be considered simultaneously to optimize the performance of the bolometer: thermistor material design, pixel mass and heat capacity, insulating leg design and means to improve the fill factor.

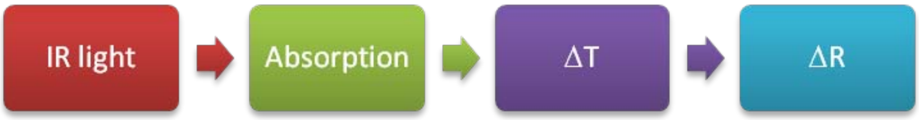


*Figure 20. The multi-step process of converting IR radiation to a resistance change that can be measured and interpreted as an image.*

Thermistor material: A highly sensitive and low noise thermistor material is fundamental to the success of the FNIR concept. A SiGe quantum well structure was chosen since it combines a high temperature coefficient of resistance with very low noise. The objective in the FNIR project was to find the key relationships and limitations between material design parameters and electrical properties. Experimental verification agreeing well with the results of first order quantum mechanical predictions has been found. The upper limit for the Ge fraction was found, above which the performance degrades due to lattice relaxation.

Pixel mass reduction: To achieve high performance, the pixels must be designed to absorb as much of the incoming radiation as possible while at the same time having a small heat capacity. At the outset of the project, it was not fully clear whether it was practically possible with the proposed technology to fulfil these requirements simultaneously or if they were conflicting. The results show that high performance can be obtained, but that the pixel mass must be kept small, even to the point that optical performance is sacrificed.

Insulating legs: Finding a simple, robust and economical technology for the legs that support each bolometer pixel is essential for performance optimization and is linked to the pixel mass reduction effort outlined above. Reducing the size of the insulating legs means that they occupy a correspondingly smaller area in the detector array. This allows a larger area to be used for the bolometer membrane thus improving the performance. Size reduction also leads to a reduced thermal conductance through the legs. This must, however, be tuned in relation to the heat capacity of the pixel to achieve a suitable thermal time constant for the pixel. A sub-micron leg process has been established.

Pixel fill factor: As dimensions shrink, the space occupied by the supporting legs gets proportionally larger if the legs are placed alongside the bolometer membrane with a decreased fill factor as a consequence. Alternative design concepts with a high fill factor even for the small pixel sizes anticipated for low cost applications were studied. A first approach is simply to shrink the leg size in proportion to the pixel pitch reduction. The main challenge will be to perform photo lithography and etch processes with high enough accuracy. The second approach addresses the pixel fill factor issue by adopting a two-level bolometer design where the supporting legs are located under the sensing membrane. The requirements placed on photo lithography and etch processes are slightly relaxed, but the integration process is more complex.

Based on the results of the technology development effort and the pixel design study, prototype sensors have been manufactured and tested on a laboratory scale to demonstrate the feasibility of the bolometer concept for the FNIR application.

### 1.3.7 Results - System Performance Metrics

LiU developed a pair of summary statistics for the quantitative evaluation of system performance, the Metric of Similarity and the Metric of Salience. The two metrics are designed to provide precise and replicable scales for the vertical axis of Figure 2. Both are based on the MaxiMin formulation of the Hausdorff distance (Munkres, 1999) between two sets that may or may not have the same number of elements. In this project, Set S is the output of the Night Vision system - the X locations in the image frame (measured in pixels) where the system indicates it has detected pedestrians. Set G is the ground truth. It is generated by technicians who inspect each frame for pedestrians and define the actual X locations (again in pixels) of every pedestrian they see. Whenever the system fails to highlight a pedestrian (makes an error called a 'miss') and whenever the system highlights a pedestrian where there is none (makes an error called a 'false alarm'), there are different numbers of elements in Sets S and G.

The two metrics address different dimensions of system performance. The Metric of Similarity was designed to be used to assess how well a system matches its ground truth, that is, the relative level of fit or agreement between Sets S and G in a frame. In contrast, the Metric of Salience was designed to be used to infer the level of acceptance of the system by a typical driver. These are two complementary dimensions of system performance.

The difference between the two is illustrated in Figures 21 and 22. Figure 21 is an image frame generated by the FIR system (frame 440 of sequence 17 29 05). Figure 22 is a graph showing the time trace of the two metrics for this sequence. The upper line is the Metric of Similarity. The lower line is the Metric of Salience.

*Figure 21. An image in which the system output is highly similar to the ground truth but misses a salient pedestrian.*

In the image, one pedestrian is occluded behind another. The system highlights only one - there is only one green rectangle. The ground truth shows two - there are two red rectangles. Because the one green rectangle does a good job of identifying where there are pedestrians, the Metric of Similarity indicates a good fit. Its value is 0.99, near the maximum possible value of 1.00. In contrast, the Metric of Salience focuses on the fact that there is a pedestrian here who has not been highlighted by the system. That pedestrian is close to the car and in the road. Its value is much lower, 0.48, indicating that the system has missed a fairly salient pedestrian.

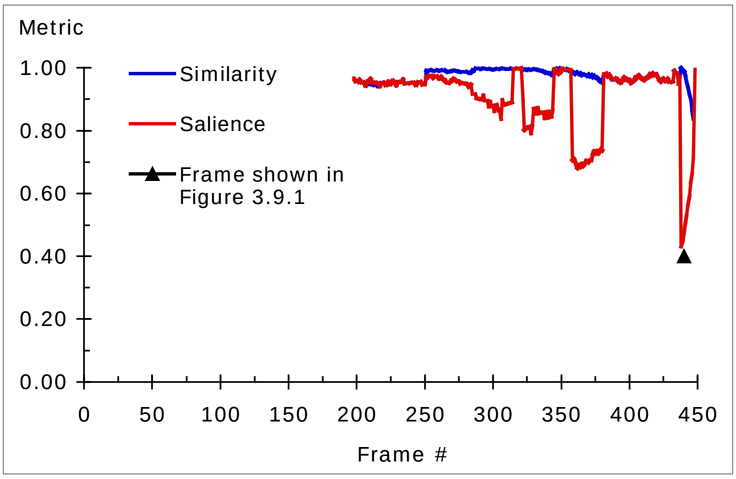


*Figure 22. Graphs of the Metric of Similarity (blue) and the Metric of Salience (red) for the sequence containing the image in Figure 3.10.1. The metrics diverge because they focus on different dimensions of sensor performance.*

The need for a second metric was uncovered by laboratory studies of driver acceptance of system output that were conducted as part of WP7. The central finding was that the typical driver appears quite concerned with failures to highlight a pedestrian in the centre of the road. Accordingly, the Metric of Salience was designed to be used to estimate the relative salience to a typical driver of a pedestrian who is not highlighted by the system.

Figure 21 also illustrates why the summary statistic for a sequence is the minimum value of the metric. The metrics are intended to help designers find when and where system performance might be improved. Low minimum values spotlight sequences that deserve designers' attention.

The two metrics share a common foundation. Both differentiate between 'misses' and 'false alarms', range between 0.0 and 1.0, and can be readily modified to emphasize either a 'miss' or a 'false alarm'. Both apply scaling factors that emphasize nearby pedestrians and pedestrians directly ahead of the sensor (vehicle) over pedestrians who are far away or on either the side of the image. All scaling factors can be readily adjusted by the user.

Both metrics can be used to generate a quantitative appraisal of the performance of the FNIR system relative to the baseline FIR system. The Metric of Similarity provides a purely objective appraisal. The Metric of Salience folds in an element of human subjective analysis.

The metrics have been presented at professional conferences [Smith, 2010; Smith and Wubulikasimu, 2010]. A journal article is being written and will be submitted late in 2010.

## 1.4 Potential industrial impact and use

FNIR was a concept development project employing fusion technology that was driven by European industry and informed by European academic innovation. It has created the foundation for European industry to achieve world leadership in the branch of Intelligent Vehicle systems known as Night Vision Enhancement (NVE). The low cost FIR sensors developed by consortium partners open up a new perspective to environment perception, especially of pedestrians, because the nature of FIR data greatly simplifies the computational task compared to, for example, visible light images. The successful completion of the project has therefore created European industrial exploitation opportunities, which reinforce Europe's industrial strengths. Such opportunities include infrared detector technology, optical components and affordable pedestrian collision avoidance systems.

The development and demonstration of the next generation NVE has the potential to solidify the position of European industry at the forefront of automotive infrared pedestrian detection systems, successfully leveraging the leading position of a European original equipment manufacturer. The combination of reduced cost and improved performance lays the foundation for more widespread adoption of the technology in the full range of passenger (and commercial) vehicles.

Several of the industrial partners are ready, willing, and able to participate in the manufacturing and commercial exploitation of the project results. Autoliv, as a leading supplier of Night Vision Enhancement systems, will assume responsibility for system integration and manufacturing, with Sensonor and Umicore supplying vital and cost efficient components. Daimler, as an OEM, will undertake the vehicle integration and supply to the end users.

There are additional benefits over and beyond the direct benefits of the industrialization of the project results. The sensor material development and packaging development is of direct use in the ongoing commercialization by Sensonor and will benefit other applications as well. Umicore will benefit from advances in design, moulding and coating, which all have active industrial impact within the Umicore group. Our academic partners have gained experience with a leading edge industrial application. For example, the performance metric developed by Linköping University will allow original equipment manufacturers (e.g., Daimler) and suppliers (e.g., Autoliv) to better identify factors that contribute to and/or impair (1) a prototype Infrared NVE system's ability to detect pedestrians and (2) user acceptance of a prototype system. Thus, even the development of metrics contributes to the foundation for a new European industry that can achieve World leadership as the supplier of infrared NVE systems.

## 1.5 Potential Societal implications

Mobility and especially road transport cause major societal problems in the form of accidents, pollution and congestions. Road traffic accidents are perceived as a major societal problem in most, if not all, countries. More than 30,000 lives are lost every year due to road accidents in the European Union only, and the costs are estimated to be about 2 % of its GDP. The destruction and death on our roads should be such an intolerable societal burden that any potential remediation solution should be given serious consideration. The high frequency of accidents during night driving and of pedestrian accidents in twilight and darkness result in a societal need to reduce the accidents in darkness and in particular improve the protection of vulnerable road users. The project therefore focused on pedestrian detection in darkness. The performance increase enabled by the developed technology affords stronger system intervention and increased effectiveness.

If Night Vision systems were widely installed in passenger vehicles, their ability to detect and warn the driver to pedestrians would have an immediate and significant impact on pedestrian safety and, hence, on society as a whole. However, the current technologies to implement a system with the required performance are rather expensive. The efforts of this consortium's partners have greatly advanced the prospect of widespread commercialization and adoption of the novel technology that is the foundation for Night Vision systems. The fusion concept, which in this implementation combine two imaging sensors, allow for an important system cost reduction of the FIR sensor for a given system performance level. The availability of low cost FIR sensors is a prerequisite for enabling FIR based systems to enter the mass market. This cost-reduction enables a penetration of these technologies into the small to medium sized passenger vehicle segments. Higher market penetration generates higher societal impact. Accordingly, the consortium and this project have the potential to have a significant beneficial impact on pedestrian safety and society as a whole.

This beneficial societal impact will be realized if and when the novel system developed for this project becomes a standard part of passenger vehicles. The results will allow policy makers to enact regulation and rating that will promote uptake of this safety enabling technology even further. Significant improvements in safety and comfort of transport can therefore be expected. This beneficial societal impact of the project is in line with the EU plan to halve the number of people killed on our roads. The various components of the system, both hardware and software, contribute to this beneficial impact. While each component contributes by being part of the system, none of the components, when viewed in isolation apart from the system, may have direct societal implications.

## 1.6 FNIR web page

The FNIR web page www.fnir.eu contains information about the consortium, the project, events and achievements, see Figure 23.

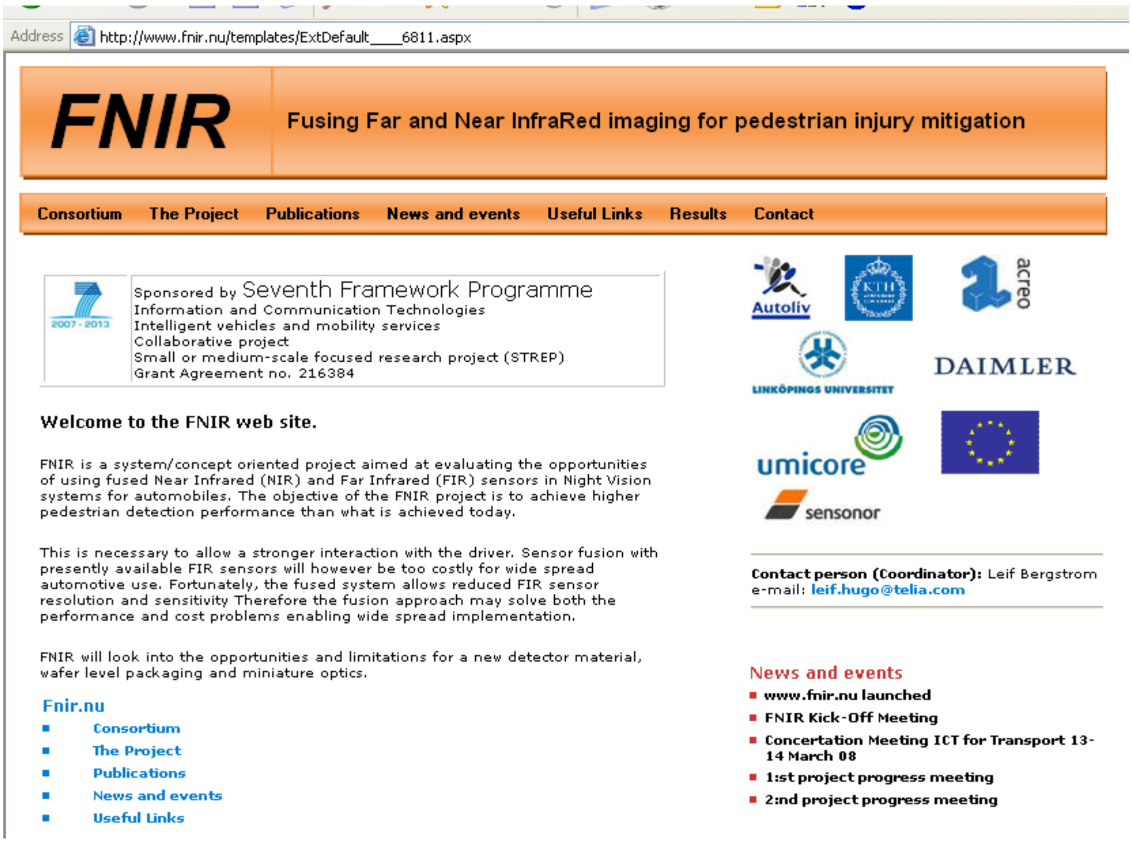


*Figure 23. Snapshot of FNIR project website.*

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# Annex 1. List of acronyms

| | |
|---|---|
| ACLA | Autoliv Camera Link Adapter |
| Ar | Argon |
| ARC | Anti reflective coating |
| CuSn | Copper Tin |
| ECU | Electronic Control Unit |
| EU | European Union |
| FIR | Far Infrared |
| GASIR™ | Umicore optical material trademark |
| GDP | Gross Domestic Product |
| Ge | Germanium |
| GUI | Graphical User Interface |
| HDAR | High Durability Antireflective Coating |
| ICU | Another EU-project |
| iDLC™ | Umicore optical material trademark |
| IR | Infra Red |
| MEMS | Micro Electro Mechanical System |
| NETD | Noise Equivalent Temperature Difference |
| NIR | Near Infra Red |
| NVE | Night Vision Enhancement |
| QVGA | Quarter VGA |
| ROIC | Read Out Integrated Circuit |
| Si | Silicon |
| SiGe | Silicon Germanium |
| WP | Work Package |

## Annex 2. List of figures