WHY ADAS AND AUTONOMOUS VEHICLES NEED THERMAL INFRARED CAMERAS

FLIR

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Introduction

The advent of Advanced Driver Assist Systems (ADAS) and Autonomous Vehicles (AV) will revolutionize how we travel and transport goods by road while improving safety. They have the potential to provide all age groups greater freedom of movement and improve the efficient operation of cars. Simultaneously, they may reduce accident rates by removing human error and the ever-increasing threat of distracted driving.

Humans will be replaced as the decision makers behind the wheel of a car. The ability to sense may be substituted by a suite of sensors that not only replace, but also augment, our current capability to drive in all types of weather and environments. Sensors are advancing, but there is not a one-size-fits-all sensor that makes driving safer. A suite of complementary and orthogonal sensors optimize driving performance across all conditions by providing critical information and redundancy to ensure safety at all time. The typical sensor suite includes radar, light detection and ranging (LIDAR), ultrasound, and visible cameras.

This paper will discuss the necessity, technological value, affordability, and integration details of adding thermal cameras to the sensor suite. Automotive engineers and developers will find it helpful in determining how to better detect and classify humans and other living things in our cluttered driving environment.

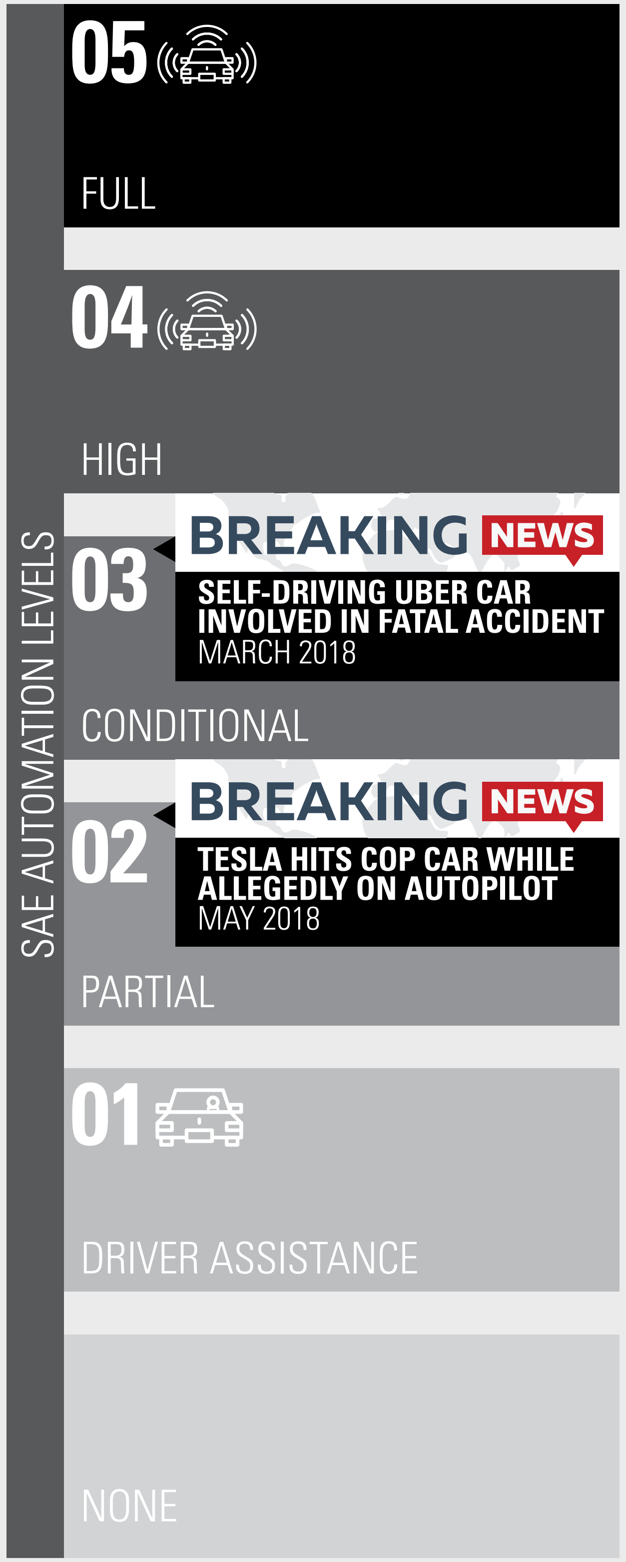

Figure 1. Recent Uber and Tesla accidents show the need for a higher performance ADAS sensor suite in SAE levels 2 and greater.

Why ADAS and Autonomous Vehicles Need Thermal Imaging Sensors

A Challenging Requirement Calls for Advanced Technology

Safe advanced ADAS vehicles and AVs require that sensors deliver scene data adequate for the detection and classification algorithms used to autonomously navigate under all conditions for SAE automation level 5. This is a challenging requirement for automotive engineers and developers.

Visible cameras, sonar, and radar are already in use on production vehicles today at SAE automation level 2. SAE automation levels 3 and 4 test platforms have added LIDAR to their sensor suite. Each of these technologies has strengths and weaknesses. Tragically, as shown in recent Uber and Tesla accidents, the current sensors in SAE automation level 2 and 3 do not adequately detect cars or pedestrians.

The Governors Highway Safety Association states the number of pedestrian fatalities in the U.S. has grown substantially faster than all other traffic deaths in recent years. They now account for a larger proportion of traffic fatalities than they have in the past 33 years.

Pedestrians are especially at risk after dark, which is when 75% of the 5,987 U.S. pedestrian fatalities occurred in 2016. Thermal, or longwave infrared (LWIR), cameras can detect and classify pedestrians in darkness, through most fog conditions, and are unaffected by sun glare, delivering improved situational awareness that results in more robust, reliable, and safe ADAS and AV.

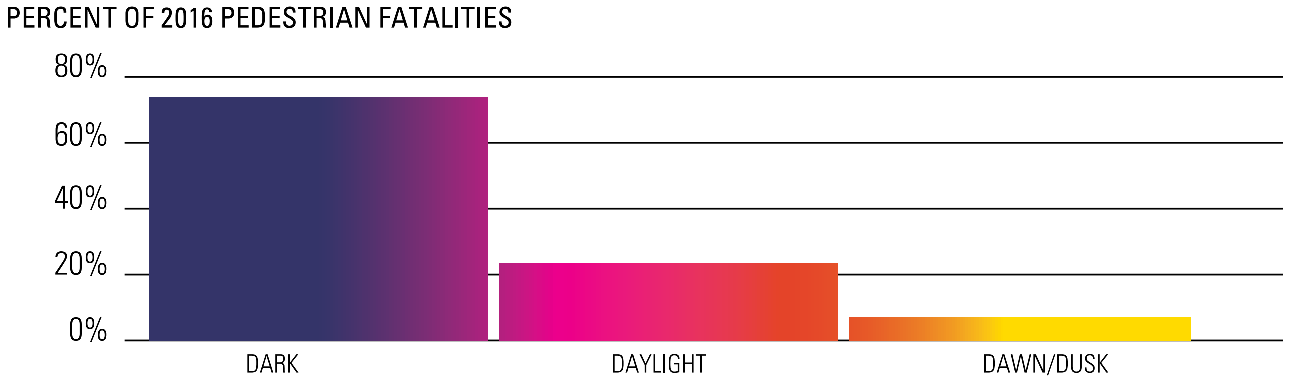

Figure 2. 2016 pedestrian fatalities by light level. Source: Governors Highway Safety Association

Match the Right Technology with the Optimal Application

ADAS and AV platforms use several technologies (Table 1), and the core approach is to detect and subsequently classify objects to determine a course of action. For example, radar and LIDAR systems generate a point-density cloud from the reflections they gather and calculate an object's range and closing speed. To generate the amount of data needed for object classification in a cost-effective and reliable solution, radar and LIDAR are fused with the output from visible and thermal cameras to cover all driving conditions.

SAE International and J3016, Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems, https://web.archive.org/web/20170903105244/https://www.sae.org/misc/pdfs/automated_driving.pdf

Table 1. Detector technologies and application summary

Application	Visible	Thermal	Radar	LIDAR	Ultrasound
Traffic Sign Recognition	X				
Adaptive Cruise Control			X		
Lane Departure Warning	X				
Front Cross Traffic Alert		X	X		
Emergency Brake Assist	X	X	X	X	
Pedestrian/Animal Detection	X	X		X	
Pedestrian/Animal Classification	X	X			
Night Vision		X			
Blind Spot Detection		X	X		X
Rear Collision Warning			X		
Park Assist	X				X
Mapping/Location				X	
Rear Cross Traffic Alert		X	X		X
Rear AEB					X
Collision Avoidance	X	X	X	X	
Surround View	X	X			

Table 1. Detector technologies and their primary roles in ADAS and AV sensor suites.

Classification is challenging for a typical sensor suite in poor lighting conditions, nighttime driving, blinding sun glare, and inclement weather. Thermal sensors overcome these challenges to reliably classify vehicles, people, animals, and other objects in these common driving conditions. Furthermore, thermal cameras perform equally well in daytime driving, offering redundancy for a visible camera.

Low-light visible cameras, coupled with LIDAR and radar, provide baseline nighttime performance, but at ranges beyond approximately 165 feet (50 meters), thermal cameras significantly outperform low-light visible cameras and deliver more consistent imagery in all lighting conditions.

The NTSB Report on the Uber incident in Tempe, Arizona—in which a pedestrian was fatally struck by a developmental, SAE-level-3 autonomous car using LIDAR, radar, and visible sensors—revealed that the pedestrian was first classified as an unknown object, then a car, and then a bicycle before finally being classified as a person. FLIR re-created this accident using a wide field of view (FOV) FLIR ADK™ and a basic classifier. The thermal camera system classified the pedestrian at approximately 280 feet (85.4 meters), more than twice the required "fast-reaction" stopping distance for a human driving at 43 mph (126 feet or 38.4 meters). Additional testing with narrower-FOV thermal cameras has demonstrated pedestrian classification at greater than 200 meters, which is four times farther than typical headlights and visible cameras can typically see.

[3] https://www.ntsb.gov/investigations/AccidentReports/Reports/HWY18MH010-prelim.pdf
[4] http://www.brakingdistances.com

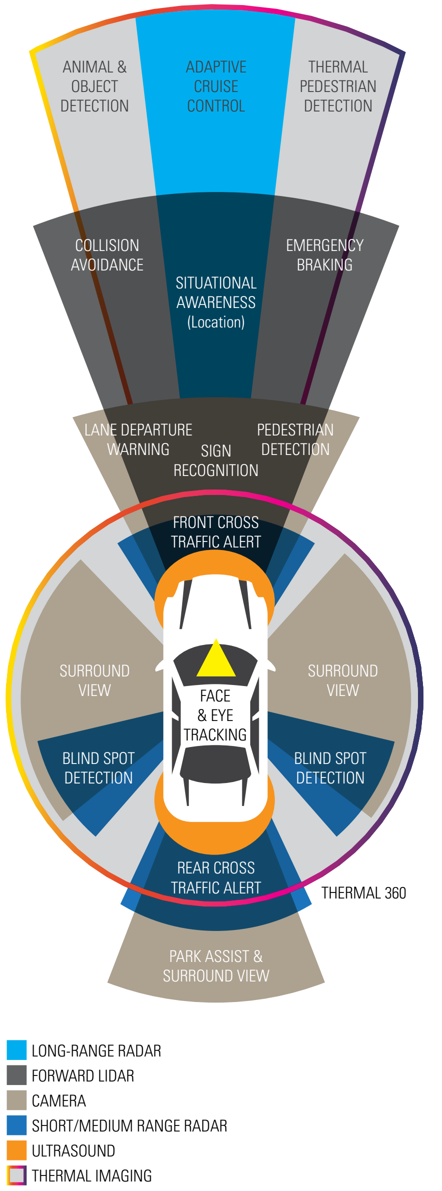

Figure 3. Thermal sensors add reliability and improve performance of the ADAS and AV sensor suites.

Figure 4. A wide-FOV FLIR ADK classified a person at 280 feet, twice the needed stopping distance, in the recreation of an Uber accident in Tempe, Arizona.

“Seeing” Heat Instead of Relying on Light

LWIR thermal sensors are completely passive, a key advantage over visible cameras, LIDAR, and radar. Target reflectivity and atmospheric effects can create variables in sensor performance, particularly at the limits of their operating envelope.

- Visible-light cameras depend on light from the sun, streetlights, or headlights reflected off objects and received by the sensor.
- LIDAR sensors emit laser light energy and process the reflected energy by measuring the flight time of the illumination source.
- Radar emits radio signals and processes the return signal.

Thermal imaging takes advantage of the fact that all objects emit thermal energy and, therefore, eliminates reliance on an illumination source. Figure 5 illustrates how passive sensing benefits thermal over visible sensors in light to moderate fog where a thermal camera can see at least four times farther than a visible camera.

As recent events and our own driving experience demonstrate, it can be challenging to see pedestrians day or night. There are numerous cases where the combination of driving conditions and environment illustrate the need for thermal cameras. In fact, there are times that a thermal camera may be the only detection and classification technology that works.

A radar or LIDAR signal from a pedestrian can be camouflaged by a nearby vehicle’s competing signal. If a pedestrian is crossing between two cars or is partially obstructed by foliage there will be little to no reflected signal to detect the pedestrian. In such cases, as in search and rescue or military applications, thermal cameras can see through light foliage. Because thermal sensors see heat, not visible shapes, they have an advantage over visible cameras in classifying partially occluded people and animals. The heat from a person or animal makes them stand out from a cluttered background or partially obstructing foreground, as shown in Figure 7.

Ready for All Driving Conditions

The primary challenge of ADAS and AV platforms is being prepared for all driving conditions. The road is full of complex, unpredictable situations, and cars must be equipped with cost-effective sensor suites capable of collecting as much information as possible to make the right decision every time. The current standard sensor suite does not completely address the requirements for SAE level 3 and greater.

Figure 7. Thermal cameras see heat, reducing the impact of occlusion on classification of pedestrians.

LIGHT TRANSMISSION THROUGH FOG

FOG CATAGORY	VISUAL	LWIR
Catagory 1	1.22	5.9 - 10.1
Catagory 2	0.62	2.4
Catagory 3	0.305	0.293
Catagory 4	0.092	0.087

COMPARISON OF VISIBLE AND IR IN FOG

Ⓐ VISIBLE LIGHT FROM OBJECT
SCATTERED AND ABSORBED BY FOG

Ⓑ HEADLIGHTS
REFLECTED FROM ACTIVE ILLUMINATION

Ⓒ INFRARED LIGHT
LESS ABSORPTION BY FOG

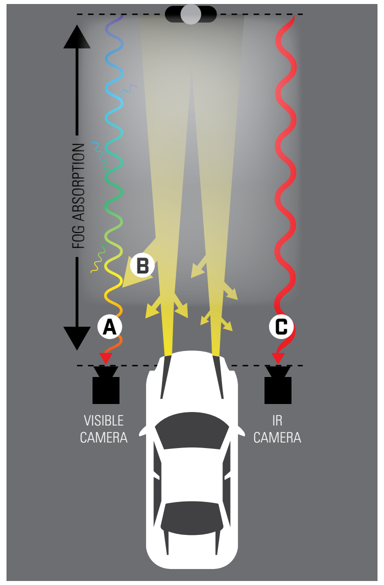

Figure 5. Passive thermal sensing can detect pedestrians from distances four times farther than a visible sensor through light to moderate fog – day or night.

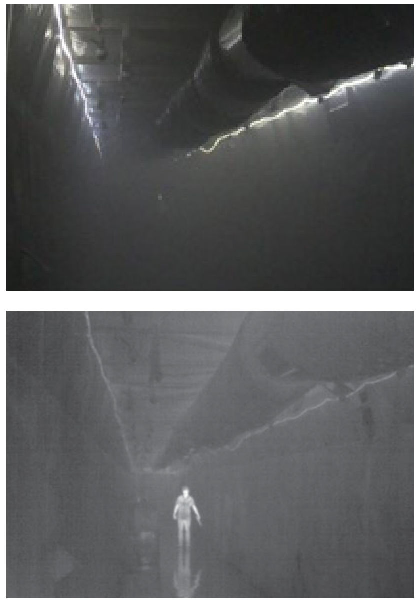

Figure 6. Fog-tunnel testing demonstrates significant visibility improvement with thermal (left) versus visible (right) cameras.

Technical Advantages of Thermal Imaging in ADAS and AV Platforms

Safety Challenges that Require Real Technology Solutions

Until recently, SAE automation level 2 (partial automation) and level 3 (conditional automation) vehicles that drive our roads did not include thermal imaging in the sensor suite.. Although many test vehicles perform admirably under test and ideal conditions, their actual performance must stand up to the rigors of real-life driving conditions.

Sensing Minute Differences in Temperature

Thermal, or LWIR, energy is emitted, reflected, or transmitted by everything that would be on or near a roadway. FLIR thermal imaging cameras are extremely sensitive to differences in temperature as small as 0.05° Celsius. VGA thermal cameras (640 x 512 pixels) can clearly show nearly everything in a scene, even the centerline on a roadway. Figure 4 (a screen capture of video from a FLIR recreation of the Uber accident in Tempe, Arizona) clearly shows roadway surface details such as paint while detecting and classifying the pedestrian at over twice the required “fast-reaction” stopping distance for a human driving at 43 mph (126 feet or 38.4 meters).

“Seeing” Heat Through Fog Instead of Relying on Light

The 2016 AWARE (All Weather All Roads Enhanced) vision project tested a suite of cameras that could potentially enhance vision in challenging-visibility conditions, such as night, fog, rain, and snow. To identify the technologies providing the best all-weather vision, they evaluated the four different bands on the electromagnetic spectrum: visible RGB, near infrared (NIR), short-wave infrared (SWIR), and LWIR, or thermal. The project measured pedestrian detection at various fog densities (Table 2) and formulated the following three conclusions.

- The LWIR camera penetrated fog better than the NIR and SWIR. The visible camera had the lowest fog piercing capability.
- The LWIR camera was the only sensor that detected pedestrians in full darkness. The LWIR camera also proved more resilient to glare caused by oncoming headlamps in the fog.
- Visible RGB, SWIR, and NIR cameras sometimes missed a pedestrian because she/he was hidden by headlamp glare.

Table 2. Fog thickness for pedestrian detection at 25 meters (glare cases not included) indicate LWIR superiority for pedestrian detection in fog.[6]

Camera	Fog Density for Pedestrian Detection
Visible RGB	Moderate (visibility range = 47 ± 10 m)
Extended NIR	High (visibility range = 28 ± 7 m)
Extended SWIR	High (visibility range = 25 ± 3 m)
LWIR	Extreme (visibility range = 15 ± 4 m)

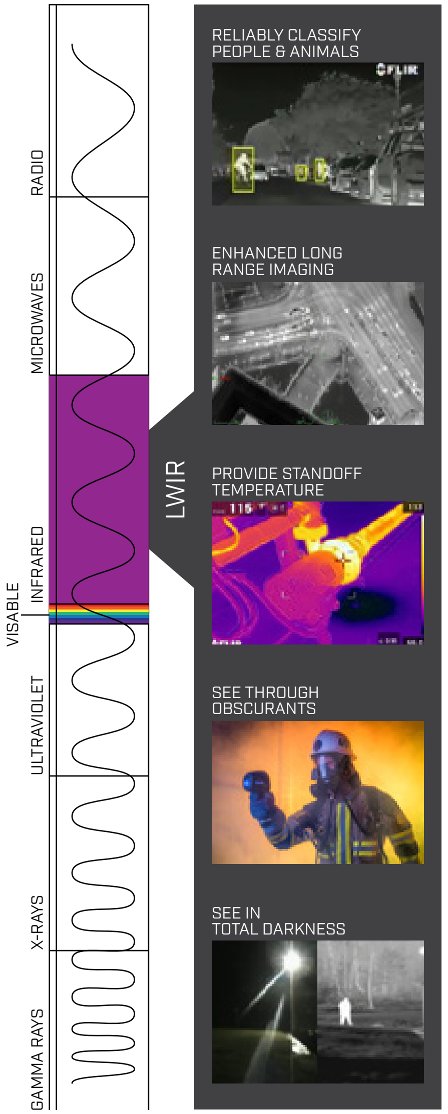

Figure 8. Thermal imagers use infrared energy to detect, classify, and measure temperature from a distance.

On Detection, Classification, and Fields of View

Detection and classification are key performance metrics within ADAS and AV sensor suites. Detection lets a system know that there is an object ahead. Classification determines the class of object (person, dog, bicycle, car, other vehicle, etc.) and indicates the classification confidence level.

In photography and thermal imagers, the field of view (FOV) is that part of a scene that is visible through the camera at a particular position and orientation in space. The narrower the FOV, the farther a camera can see. A wider FOV cannot see as far, but provides a greater angle of view. FOV impacts the distance at which a thermal camera can detect and classify an object, meaning multiple cameras may be required; a narrow FOV sensor to see far ahead of the vehicle on a rural highway, and at a wide FOV sensor for optimal use in city driving.

Current artificial-intelligence-based classification systems typically require a target to fill 20 x 8 pixels to reliably (>90% confidence) classify a given object. For example, to classify a human with reliable confidence, the human needs to be approximately 20 pixels tall as shown in Figure 11. Table 3 includes classification distances for different thermal camera horizontal fields of view and indicates that a FLIR ADK can classify a 6-foot tall human at a distance greater than 600 feet (186 meters) for a narrow FOV lens configuration. Detection, which requires fewer pixels on an object, means that a 6-foot tall human can be detected at greater than 200 meters using the FLIR ADK.

Table 3: Reliable classification distance for FLIR ADK by horizontal FOV – day or night.

FLIR ADK Horizontal FOV	Classification Distance (feet)	Classification Distance (meters)
50	220	67
32	344	105
24	451	138
18	611	186
12.2	898	274

Nicolas Pinchon, M Ibn-Khedher, Olivier Cassignol, A Nicolas, Frédéric Bernardin, et al.. All-weather vision for automotive safety: which spectral band?. SIA Vision 2016 - International Conference Night Drive Tests and Exhibition, Oct 2016, Paris, France. Société des Ingénieurs de l'Automobile - SIA, SIA Vision 2016 - International Conference Night Drive Tests and Exhibition, 7p, 2016. <hal-01406023>

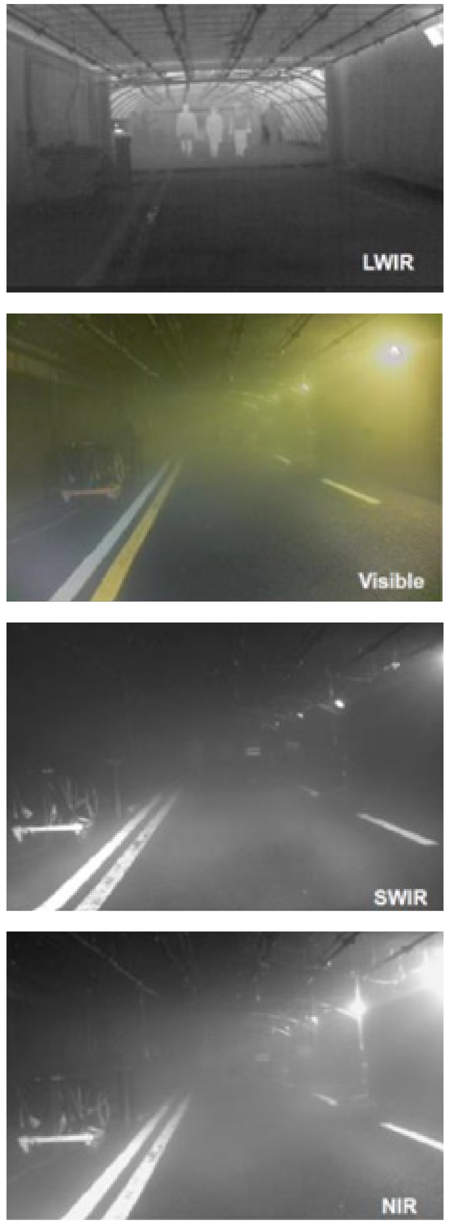

Figure 9. Example images recorded in fog tunnel with thermal (LWIR), visible RGB, short-wave (SWIR), and near (NIR) cameras.

Copyright SIA Vision 2016

Figure 11. Thermal cameras require only 20 x 8 pixels to reliably classify an object.

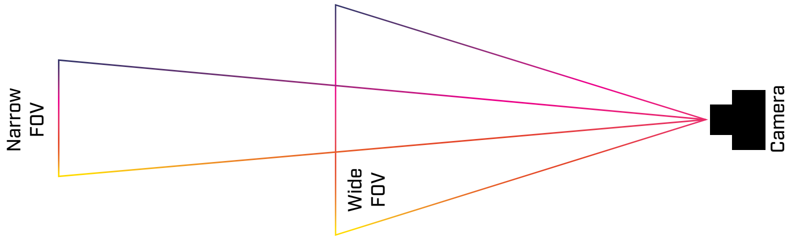

Figure 12. The narrower the horizontal FOV, the farther a thermal camera can "see."

The Pathway to Affordable, Scalable Automotive Integration

Breakthroughs to Affordability

Mass adoption of SAE automation level 3 (conditional automation) and above is dependent on affordable sensor technologies, the computer power required to process the incoming sensor data, and the artificial intelligence needed to execute driving commands that deliver safe and reliable transportation in real-world conditions.

A common misconception is that thermal sensors, with their background in military use, are too expensive for automotive integration. Thanks to advances in thermal imaging technology, improved manufacturing techniques, and increased manufacturing volume, it is becoming possible to mass produce affordable thermal sensors for SAE automation level 2 and higher.

FLIR is focused on the development of cost-effective thermal imaging technology. As the world leader in thermal imaging, FLIR has delivered millions of thermal sensors , including more than 500,000 sensors into driver warning systems installed on several automotive nameplates, including General Motors, Volkswagen, Audi, Peugeot, BMW, and others. Working closely with our tier-one automotive customer, Veoneer, FLIR has driven down the cost of thermal imaging technology for the automotive market as well as other emerging consumer markets, including mobile phones and consumer drones.

Until recently, thermal cameras were measured in thousands of dollars each for VGA resolution or higher. Now they are an order of magnitude lower in price due to volume and technology improvements. FLIR continues to innovate and further reduce camera costs, enabling ADAS and AV developers and engineers to add affordable thermal imaging to their sensor suites.

http://investors.flir.com/news-releases/news-release-details/flir-systems-reaches-one-million-unit-milestone-lepton
www.catphone.com
www.flir.com/uas

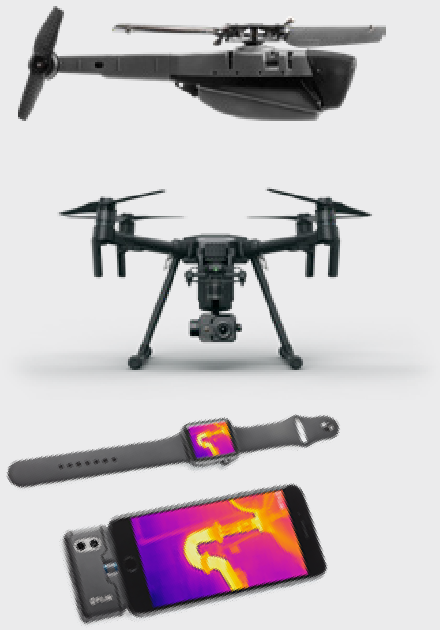

Figure 13: FLIR Thermal Sensors are affordable and integrated in a wide range of consumer, industrial, and military products today

Figure 14: A grill-mounted FLIR thermal sensor integrated by Veoneer provides thermal vision for the BMW X5.

Lowering Costs in the Manufacturing Process

The significant components in a thermal camera include a sensor core (microbolometer), lens, electronics, and case. Fundamentally, the fabrication of thermal imaging sensors is similar to silicon computing hardware. Manufacturing inputs include the silicon wafer, foundry costs, and yield. Per-sensor cost is calculated by dividing total costs by the number of chips available to sell.

Infrared image sensors unfortunately cannot follow Moore's Law. There is a limit to how small an infrared imager sensor's pixel can be made due to a performance tradeoff as the pixel shrinks and approaches the wavelength of interest (LWIR sensors detect 8 to 14 microns wavelength radiation). However, over the past ten years, FLIR has reduced the pixel geometries from 50 x 50 microns to 12 x 12 microns, an 83% reduction in area. This, in combination with wafer-level packaging and increased scale, and process optimization, has enabled FLIR to achieve the lowest costs in the thermal-image sensor market.

What's Driving the Infrared Market?

Maxtech International®, Inc., a specialist in market research in infrared and thermal imaging, provided the data in Figure 15. It includes the estimated global average end-user price and volume for all thermal cameras utilizing uncooled microbolometer technology sold for commercial use. Estimated market data is included from 2003 through 2017 with forecasted amounts for 2018 and beyond. Forecasted units per year include vehicle night vision systems from Veoneer (FLIR thermal sensors), but do not include significant AV adoption, as that will likely start in 2022 or 2023 and must be at a price point of a few hundred dollars.

Figure 15 also does not include price and volume for non-commercial use. The non-commercial (military) market advances technical and manufacturing innovation but is currently not driving significant volumes and price reductions. However, with increased U.S. Department of Defense budgets, new efforts are being made to incorporate uncooled sensors in a wide range of soldier systems. Microbolometer technology is being developed incrementally, which allows for continuing yield improvements, small pixels, larger formats, digital-pixel ROICs, etc.

Infrared has become a mature technology, but continuous ongoing improvements in smaller pixel design and yield improvements at FLIR promise to lower costs still further. Based on current development plans, it is forecasted that an additional two times reduction in cost can be accomplished over the next several years. This compares favorably with the required ten times cost reduction of LIDAR systems necessary to meet OEM cost targets. Adoption of significant volumes of thermal cameras for SAE automation levels 2 and 3 will likely start in 2022 or 2023, with annual growth rates of 200% to 300% through 2030. With the planned improvements and automotive manufacturing scale, thermal cameras will be an affordable component for the ADAS and AV sensor suites.

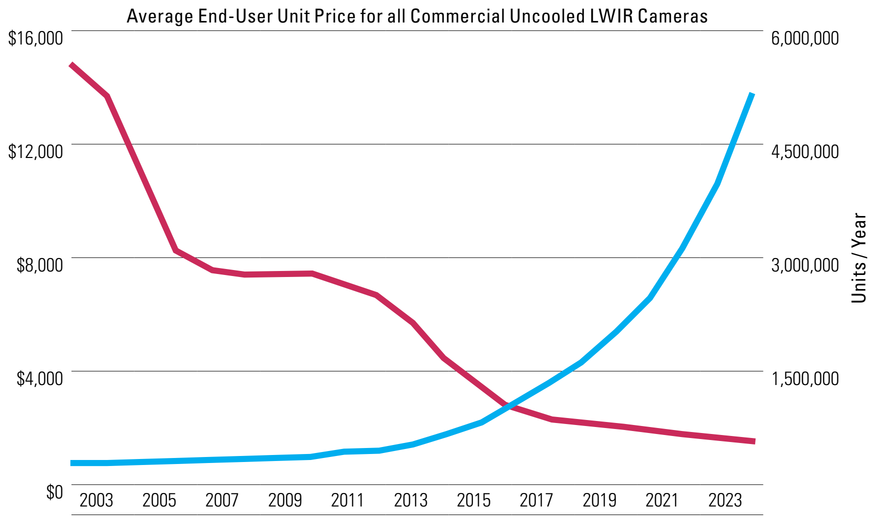

Figure 15. Estimated global average end-user price and volume of thermal cameras. ©Maxtech International®, Inc.

Leading a Developing Market

The ADAS and AV market is in development phase and FLIR is leading the way toward thermal camera adoption. FLIR already manufactures full-rate production thermal sensors for automotive night vision.

As the value proposition of thermal imaging becomes well established and adoption grows, volumes will further increase and drive FLIR thermal imaging systems to price points and increased resolutions that manufacturers can adopt on all autonomous transportation vehicles.

The World Market for Commercial & Dual-Use Infrared Imaging & Infrared Thermometry Equipment (Vol. IRW-C), published by Maxtech International®, Inc., 2018.

Overcoming Technological and Logistical Thermal Imaging Automotive Integration Challenges

Simplifying Integration to Keep Up with Demand

In the rapidly evolving field of autonomous driving technologies, data is key to training and deploying functional hardware that will enable vehicles to navigate in a variety of conditions. Experienced OEMs and bold newcomers are racing to outfit fleets of vehicles with sensors to collect the necessary data to train for various object classifiers and to test their respective systems.

Streamlining Integration with FLIR ADK™

To facilitate a more streamlined integration of thermal imaging, FLIR launched the first automotive development kit in early 2018 and the ADK 2.0 in early 2019. It incorporates FLIR's 640 x 512 resolution Boson™ thermal camera in an IP-67 housing with a heated window for all-weather driving. It includes convenient mounting features and USB, GMSL, and Ethernet interfaces. This enables developers to quickly mount and connect the ADK and record data with an easy-to-use graphical user interface (GUI), all within minutes. The GUI allows for push-button video recording.

The ADK can also be hardware synchronized to other sensors on the platform for developers interested in time-critical operation and real-time sensor fusion. A command-and-control SDK is available in C, C#, and Python for deeper integration with host ADAS and AV platforms.

In addition to the FLIR ADK hardware, GUI, and SDK, FLIR provides developers with a free starter dataset of more than 14,000 annotated thermal images. The dataset includes classification of five groups; people, dogs, cars, bicycles, and other vehicles. It enables developers to become familiar with thermal imagery and to immediately begin training their ADAS and AV computer systems to perform classification and analytics on their thermal data. Additional thermal images are being collected and annotated to expand the FLIR thermal library for exclusive partners.

Table 4: The FLIR thermal starter dataset includes more than 14,000 annotated images for algorithm development.

	Descriptions
Images	>14K total images with >10K from short video segments and random image samples, plus >4K BONUS images from a 140-second video
Frame Annotation Label Totals	10,228 total frames and 9,214 frames with bounding boxes.
	1. Person (28,151)
	2. Car (46,692)
	3. Bicycle (4,457)
	4. Dog (240)
	5. Other Vehicle (2,228)
Video Annotation Label Totals	4,224 total frames and 4,183 frames with bounding boxes.
	1. Person (21,965)
	2. Car (14,013)
	3. Bicycle (1,205)
	4. Dog (0)
	5. Other Vehicle (540)

Figure 16: FLIR thermal sensors can classify pedestrians at distances four times farther than typical headlights.

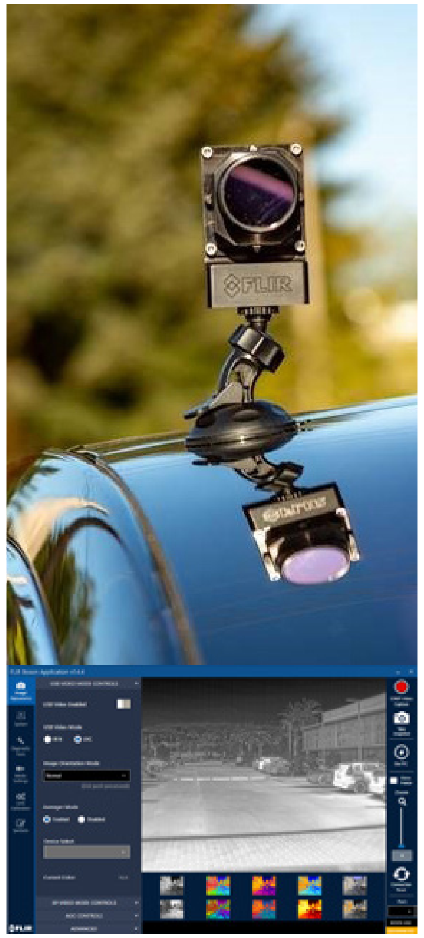

Figure 17. FLIR ADK is a ready-to-use, IP-67-rated thermal camera with a USB Interface and an intuitive GUI.

Everything You Need to Get Started

The ADAS and AV market is still in an early development phase. Thermal sensors will be needed for higher-performing ADAS and AV platforms as the automotive industry moves to SAE levels automation 3 (conditional), 4 (high), and 5 (full). With more than 500,000 thermal sensors on cars, FLIR is leading the way. In addition, the FLIR Boson-based FLIR ADK is available and specifically designed for ADAS developers to integrate into test vehicles. Classification of pedestrians, dogs, cars, bicycles and other vehicles can be started immediately with the use of the free FLIR thermal starter dataset. Together, engineers and developers can leverage the hardware and data with machine learning neural networks to help demonstrate the ability for affordable thermal sensors to make ADAS and AV safer.

For more information about thermal imaging cameras or about this application, please visit www.flir.com/adas

The images displayed may not be representative of the actual resolution of the camera shown. Images for illustrative purposes only.

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