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REVIEW ARTICLE

Infrared detector arrays in the detection, automation and robotics - trends and development perspectives

Abstract

Already in the 1970s, it was predicted that the scale of thermal imaging applications would be limited only by the imagination. It happened thanks to the elaboration of solid-state, Focal Plane Arrays of IR detectors (IR FPA) connected with electronics readouts (ROIC CCD). In the last 20 years, thanks to the appearance of uncooled detectors, and recently also photon detectors in the high operation temperature versions, cameras have become significantly smaller, lower weight, consume lower power and are cheaper. It made them more attractive for civil applications, with optimal adaptation to very different tasks. The aim of this study is to present a brief review of the specifics of non-pure-thermographic markets for these IR detectors. The growing interest of many markets, with more affordable prices of better and better detectors, and the available knowledge base, create good conditions for innovative projects and business programs.

Keywords: IR FPAs, cooled & uncooled detectors, applications, markets.

1. Introduction to fundamentals of use and construction of infrared cameras

It is worth recalling that while our eyes allow us to observe properly illuminated objects using electromagnetic waves of the range of (0.4-0.7) μm, the infrared range covers the area of (0.7–1000) μm. For practical reasons, this area is usually divided into: near infrared NIR (0,7-0,9) μm, shortwave infrared SWIR (0,9-2,5) μm, midwave infrared MWIR (3-5) μm, longwave infrared LWIR (8-12) μm, very longwave infrared VLWIR (12-30) μm. MW and LW ranges coincide with the so-called "atmospheric windows" (outside which the attenuation in the atmosphere is particularly strong).

Generally, we can divide the apparatus with arrays of IR detectors as designed for spectral signals studies (spectrometry) and for utilizing, illustrating or measuring surface temperature distributions (thermal imaging and thermography). Both types can be used in the:

- "active method" - when the original source of the tested signals is an external, especially used system (e.g. laser, lamp, sources of thermal changes extortions as in some NDT methods, etc.),
- "passive method" - when the investigate surface emit radiant signals regardless of the fact of camera use.

By limiting the classification to the most typical and the most common, we can assume that the NIR and SWIR ranges are used in spectrometry and to improve vision in degraded visibility conditions, where the active method is particularly often used. The transition to work in the MW and LW ranges means the possibility of passive work due to the use of ubiquitous temperature radiation. For low temperatures (surroundings, etc.) the main part of the energy is emitted in the LW range (St. Boltzmann law)

Thus, the warmer the surface, the stronger the radiant signal, the greater the variation in temperature on the surface, the more contrasting it is. These are therefore ideal systems for working in conditions of total lack of lighting (night, caves, installations in housings, etc.). Another, often important, advantage of "infrared vision" is the decreasing effect of aerosols (as smoke & haze) scattering (according to Rayleigh' law: the longer the wave, the smaller the disturbance). Thanks to these features, sometimes it is said that we got a kind of "sixth sense"[1].

As a rule, the IRFPA camera consists of the following elements: optical path, sensing element (IRFPA), electronic processing and result generating unit, output path.

The specificity of implementing IR lenses is the need to use special materials that transmit radiant signals well. Typical optical glasses can only be used in NIR cameras. Due to the rapidly decreasing pixel size and the increasing number of pixels in the IRFPAs, the requirements for the MW and LW range lenses are getting higher, more challenging. This can result in an increase of their price. In the face of decreasing cost of IR microbolometers, the percentage share of the cost of lenses in the cost of cameras is growing.

Electronic control, signal processing and final use of IRFPA signals have a very different construction, depending on the tasks performed by the cameras. The rapid development of the technology of microelectronic elements and algorithms for the development of data from imaging devices is very beneficial here.

Up to now, the final form of results has been images on monitors. The tendency of massification and specialization of increasingly cheaper IR cameras results in a very fast developing segment of cameras/systems, whereby using appropriate algorithms, the output information is an appropriate extract of simple data, not the thermal image. These are particularly effective solutions in industrial automation, robotics, smart buildings as well as in road and rail transport.

The proper use of still being discovered potential of such "additional sense", can increase our safety and quality of life.

2. IRFPA

Infrared technology is characterized not only by the width and number of spectral ranges used but also by the large diversity of tasks that devices perform in particular cameras based on FPA. The enormous potential offered by "infrared vision" makes the army the main stimulator and sponsor of technological programs. Thanks to this, the civil sector has been receiving more and more advanced FPA detectors for years.

As breakthrough events in the field of popularization of infrared imaging, there was the emergence of photon detectors in the form of staring arrays, later microbolometers in many times cheaper versions. This has led to the very rapid development of various markets for these detectors. The pressure for ever more and more perfect constructions and simultaneously cheaper in production is constantly being exerted. All of this is the driving force of research on new materials for detectors and new technologies in their production. It is an extremely wide, specialized and dynamic sector of activities in the world. A very good source of knowledge on this topic is the third edition of the compendium published by A. Rogalski [2], as well as many other studies by this author, a multi-annual participant of the TTP conferences.

For a user or even a constructor of infrared cameras, technological details regarding detectors technologies are less important than the ability to compare their features. The analysis of offers indicates the existence of studies thoroughly tested and offered massively by large and proven producers (and a number of others that may not meet these conditions). Below, only basic information on the most popular IR FPA models on the market will be mentioned. Additionally, it will be limited to the most commonly used matrices in cameras for the imaging type applications discussed in the work.

An IR detector is a device that converts the radiant IR energy into the measurable signal (generally electrical in nature). Focusing on detectors for cameras that do not require mechanical scanning operations, there are a line (1-D) and two dimensions (2-D) staring arrays (which let to work without scanning). The linear ones are used when the image of the examined scenery can move along the surface of a sensitive detector (as a result of the movement of the test object or camera, as on production lines or in airplanes, etc.). Currently, due to large quantities of detectors in 2-D matrices and effective information processing, the demand for 1-D types is incomparably smaller. Infrared detectors are typically comprised of arrays of detectors substrates adequately bonded to a CMOS readout integrated circuits (ROIC) and the resulting assembly is called an IR FPA.

A variety of technologies to produce IR FPAs have emerged: pyroelectric and dielectric, Schottky barrier, superlattice, intrinsic, Z-plane ones and microbolometric. Some materials (applied for FPAs fabrication) operate only due to coolers (at cryogenic or low temperatures), and others, (as e.g. resistive amorphous silicon a-Si, and VOx) microbolometers which operate uncooled. The task of coolers is to reduce the level of own noises, especially in photons detectors. This ensures a significant reduction in the noise equivalent power of received radiant signals (increasing sensitivity and Noise Equivalent Temperature Difference - NETD). As a result, these fastest detectors are used in most demanding applications. However, this is at the expense of their Size, Weight And Power consumption (SWAP) and shorter maintenance-free operation times and consequently high or very high price. These disadvantages do not have thermal type detectors (microbolometers), which dominated world markets (now produced in larger volumes than other IR array technologies together).

In general, detector material is primarily selected based on a wavelength of interest, performance criteria, and operating temperature. Common materials used in IR photoelectric (photodiodes and phototransistors) are Si:As blocked impurity bands, InAs, InSb, HgCdTe (shortly: MCT, or CMT). To increase the quality of images, increasing the number of pixels in FPAs is the most efficient way. But to simultaneously achieve a huge reduction in SWAP of cameras (smaller optics) significant decreasing pixels dimensions and HOT detectors is required. Thus, worldwide the pixel scaling effort is to develop very high-density LWIR and MWIR FPAs with pixel dimensions near to the physical limits. As the pixel size is reduced, "bump-bonding", ROIC, signal integrating capacitor and signal to noise ratio become a truly challenging task. Thus, not detecting material but the technology of making this whole assembly becomes a source of limitations. These technologies require over a hundred individual steps/operations. It's one of the elements of their high price (and then the effectiveness and reliability of work in the camera).

For IR FPAs user, here are the most important detector features: spectral characteristic, NETD, Time Constant, Size-Weight-Power data, uniformity of pixels in the matrix and stability of parameters, power supply conditions and the form of output signals as well as resistance to arduous working conditions (temperature, vibration, shocks), aging features data, reliability warranty service and assistance in implementation and of course the price.

Apart from the details of a very large range of current market, it is worth paying attention to the following general features and differences in the current IR FPA (2-D) offer:

- Photon versions: the fastest response times (the highest frequency of images, in the case of the so-called gating, is even several thousand Hz), the highest sensitivity and geometric resolution (number of pixels in the matrix) and thermal (NETD), the ability to match the work in the entire range from VIS to VLW IR (including two-color options), different f-number (where higher value means a smaller lens diameter and vice versa), different types of coolers (JT, Stirling, linear). Currently, there are two competing technologies: HgCdTe material systems and III-V materials (mainly barrier detectors). CdHgTe is the best solution for LW range - with options for MW and SWIR. This detector is typically used in VGA formats (although exist HD MW with 1280×1024 pixels and higher, even). The direction of the world's work is to strive for better solutions in terms of SWAP and price. For example, in France, there are now intensive works on a 7.5µm pitch, 640×512 and a 5 µm pitch 64×152 FPAs. The 7.5 µm pitch IRFPA operating at 110 K displays nonlinearity under 0.1%, a full-well of 3.1 Me- with a 3.8 dynamic range, and NETD of 24 mK [3].
- Thermal / microbolometer versions: their spectral range of work (LW: (8-14) um) perfectly coincides with the band of the highest emission of energy by our environment, and this determines the universality of applications; have the lowest (and still decreasing) price, still decreasing pixel size (now as low as 12 um pixel pitch), a wide range of sizes: the simplest 16×16, and for more detail imaging: 60×80, 80×80, QQVGA (160×120), QVGA (384×288), VGA (640×480), XVGA (1024×780) and (1280×1024); microbolometer pixel pitch has been reduced from 35 µm pixel pitch ten years ago via 25 µm and 17 µm down to 12 µm (due to diffraction, the limit seems to be at 10 µm); typical range NETD of the most sensitive models is (20-40) mK; another the main parameter it's time constant (τ) typically: VOx τ =12 ms; a-Si =10 ms (with the fastest option τ <3 ms for 17 µm arrays [4]).

Assuming that IR cameras are fitted to the tasks, then it's the price (with IR FPA inside) determines the needs of markets. Very good examples are below:

- Great market successes of FLIR company, offering not only detectors but also a whole range of cameras for various applications [5].
- Development of the company Lynred (ULIS) - offering not only the smallest pixels and fastest option on the market, but simultaneously much simpler models as in the case of MICRO80 (80×80, 34 um pixel pitch) series, with digital output, the opportunity to work on a single battery for 5 years, and in the versions with integral lens (90^0 to work in corners or 120^0). Such detectors, fitted to Smart Building needs, may be an attractive option for many other constructions (the manufacturer does not offer cameras) [6].

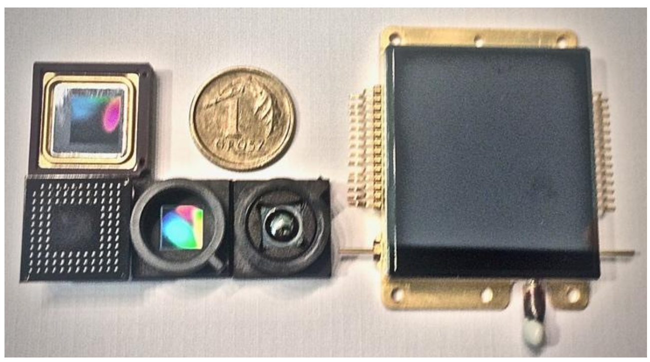

Fig. 1. Microbolometers a-Si: from MICRO80 (80×80 also without and with integrated 120^0or 90^0 lenses) up to PICO 1024 Gen2 (1024 × 768); ULIS production

A peculiar aspect of nearly all FPAs is that raw images tend to be non-uniform. In a perfect device, every pixel would output the same electrical signal if obtain the same number of photons of the appropriate wavelength. In the case of MWIR and LWIR FPAs set of additional disturbances has the source in detecting thermic (own) radiation from the optics and detectors surroundings (thus changing during work, sometimes very significantly). These interferences and nonuniformities make the resulting images worthless, so, therefore, makes the construction of thermal cameras very specific (and different to VIS cameras). Uncooled IR FPAs are particularly sensitive (cooled, photon detectors works in stable temperatures.) These problems are solved programmatically using a mechanical shutter in front of detector or digitally only (based on the appropriate calibration data) [7]. The rules of such corrections depend on the task the camera performs. Especially for radiometric (thermographic) tests, the awareness of these dependencies on the working conditions is very important.

3. The specificity of IR FPA applications

Products and solutions that integrate IR imaging technologies have been around for years, but new ones are appearing all the time. This technology is also garnering increasing interest from academic researchers, who are using it for a wide variety of complex and demanding applications. In this short review, it is only possible to indicate chosen and basic areas of IR FPA applications.

SWIR FPA

Depending on the application there are cooled (cryogenically or thermoelectrically) or uncooled detectors being used. Typical devices are fitted in three groups of applications: a) spectral measurement – spectrometry; b) passive devices for observation and detection; c) passive devices but with active option (with laser or LED illuminator) and continuous or gated reception of reflected incoming signals. Imaging cameras usually detect reflected radiation (but in case of very hot objects their thermal radiation as well). In result, SWIR images are very easy to interpret and recognize through the human eye, thus offer similar identification possibilities. Their typical applications can be broken into several categories: spectroscopy (chemical detection, gas detection, spectrum analysis, sorting, food control, detection of counterfeits), moisture, water and irradiation distributions detection, food and agricultural inspections, better night vision observations (or in hazy air), imaging of IR lasers or IR LED lighting, imaging in poor visibility conditions, 3D imaging (gating method) and hot objects, industrial, thermography.

MWIR FPA

Cooled MWIR cameras have long held a tactical advantage over uncooled cameras in much airborne and ground-based intelligence, surveillance, and reconnaissance use cases. Thus, the army is the main customer for cameras with MWIR FPAs (usually based on InSb or MCT material). These cameras showed to be more effective especially for air defence systems due to better sensitivity for temperature differences and high humidity air – typical conditions for long-range operations. In the civil market, if very fast and sensitive thermography is required, these cameras are a cheaper solution than cooled LWIR cameras. There is a strong advantage of MWIR in comparison to LWIR families of recently offered HOT SWAP, cheaper and high-resolution detectors based on Type II Strained Layer Superlattice (T2SL).

A special group of IR devices is gas detection and imaging cameras. Several gas compounds can be detected simply by selecting interference filters matched to the chosen gas spectral signature. This method shows great potential of multispectral detection for monitoring symmetry of heating inside furnaces [8] but most of the applications there are predictive maintenance programs, e.g. in oil and gas industry, where it can detect dangerous and costly gas leaks. In some cases, even, broadband MW-LW microbolometers can be efficiently applied. Depending on the conditions of such surveys (distance, type of the gas and temperature contrast to the environment) passive or active methods can be used, using microbolometers, even [9, 10, 11].

LWIR FPA

There are cooled and uncooled versions offered in a large range of pixel and detector sizes, sensitivities, maximal frame rate (or time constant), types of coolers, etc. Currently, cooling options form a basis if IR OE (Optoelectronics) systems for aircrafts, tanks, armoured and other vehicles, antiaircraft and rockets defence – where max ranges for DRI (Detection, Recognition, Identification) are extremely important. Majority of these cameras apply MCT detectors as, still, offering the best parameters.

In the military, uncooled FPAs, usually VOx or a-Si microbolometers (which present perfect SWAP features and many times lower price than photon versions), found the biggest applications in personal equipment like viewfinders, binoculars weapon sights and in military vehicles, where it is used for perimeter surveillance, driving assistance, and remotely-operated turrets. This technology is also popular in drones and short-range missiles.

Among civilian application (using the same microbolometers as the army, although often with significant differences in parameters and features) we can find the next groups: surveillance and security, searching for victims, detection of sick people and animals, medical-paramedical-veterinary-biology imaging, non-destructive-testing, audits of buildings, constructions and different installations, industrial inspection and machine vision, petrochemical processes and furnaces, preventive and predictive maintenance in factories, firefighting, gas detection, outdoor and leisure activities, smart buildings, transportation, imaging from the air, penetration of caves and dangerous places plus connected devices, as: “smart” glasses, thermal goggles, smartphones, and digital cameras.

4. IR FPA in detection, monitoring and robotics

It is obvious that robotics is currently developing at an extremely fast pace. In addition to the use of numerous new products in the field of components and sensors, unusual driving forces are brought by Artificial Intelligence, telecommunications networks and other elements of the so-called IoT (Internet of Things) and IIoT (Industrial IoT). The dynamics of this development are shown in many studies. ROBOTS (flagship publication of the IEEE - the world's largest technical professional organization for the advancement of technology) deserves a special recommendation [12]. Thermal vision in robotics expands and makes applications of robots (and drones, which are de facto mobile robots) more attractive. Supplementing cameras with computer vision allows these robots to see what's around them and make decisions based on what they perceive. Additionally, new technologies such as deep learning are allowing robots to interpret these images and learn new things on the fly.

A drone is a popular name of an unmanned aerial vehicle (UAV) – i.e. aircraft without a human pilot on board. The basic programs of various specialized UAVs were created more than 20 years ago, as a result of the army's needs. In the army, UAVs are a component of an unmanned aircraft system (UAS); which include a UAV, a ground-based controller, and a system of communication between the two. The flight of UAVs may operate with various degrees of autonomy: either under remote control by a human operator or autonomously by onboard computers [13].

For many years, drones have been commonly used for military reconnaissance, as artillery support and civil defence. At the moment the main family of drones (UAV) consists of such groups as big (e.g. combat), small, miniature and micro ones – with different drives. Special thermal cameras (and others) are offered for each of these types. Combat UAV (UCAV) solutions are responsible not only for recognition but also for firing missiles or releasing bombs at a target. It’s worth to mention as only the United States, Israel, China, Iran, Italy, India, Pakistan, Russia, Turkey, and Poland [14] are known to have manufactured operational UCAV as of 2019.

As in the case of thermal imaging cameras, civilian drone markets appeared soon after the military ones and are growing very fast (from professional missions to toys in supermarkets). IR cameras (mainly uncooled LW but SWIR, as well) work as basic sensors or accompanying to other sensors and elements of drones' heads. What's particularly important, is that the viewpoint chosen for a thermal measurement can be identified immediately and can be used to rapidly and accurately determine the area to be covered and pinpoint searched items or any anomalies.

The effectiveness of research using drones radically increases based on the properly selected software. A great example is the extensive forest research report. Coincident RGB and thermal imagery from a UAV platform were collected of both a standalone tree and a relatively dense forest in Swiss Alps [15]. These methods demonstrate important implications for modeling of various uses and have wide application for effective thermal measurements of remote environmental landscapes [16]. Another example of the importance of appropriate algorithms leads e.g. the use of a thermal camera as efficient and unique support for drone navigation (presented at our conference) [17].

Among the most efficient applications of worldwide use of drones with thermal cameras are (in addition to the military) e.g.: agricultural, fire safety and fighting, law enforcement and peacekeeping, surveillance and rescue – particularly in very difficult to get to areas, buried objects detection, documenting damages, aerial and archeological photography, buildings and various installations (electric, heating, transport, machining, fuel and gas) auditing and inspections, solar power plant inspections, livestock and wildlife monitoring, traffic safety monitoring and management, as well as recognition of caves and areas dangerous for people, etc.

Increasingly cheaper cameras and better software are the main driving forces behind the innovations and new niches in the world market for drone applications.

5. The spectrum of IR FPA applications

SWIR FPAs are of growing popularity and create emerging and prospective markets. This waveband has some special characteristics that make it a helpful band for detecting. Output images (although without "natural colors") often are similar to visible, making identification of objects personalities possible - because the source of signals is reflected light (visible-like). There are a few features which decide as modern IR FPA are of particular interest of army: in low-visibility often longer DRI then using VIS and NIR devices; perfect co-operation with eye-safe lasers (>1,4 μm) applied as illuminators or target indicators. In the case of applying "active mode" with gated and regulated input of reflected laser radiation systems of such type can even provide 3D images of the distant, and obscured objects. SWIR OE systems are efficient to support landing operations of planes and navigation of vehicles and ships.

There is a growing interest in the civilian sector, as well. This applies to both spectrometry, single and multi-band imaging and multi or hyperspectral imaging (VI-NIR-SWIR). Typical applications of SWIR FPA equipment include, in the:

- Surveillance & Security (hidden target detection and identification, seeing gases, explosives detection)
- Industry (process control, plastics sorting, fill level monitoring, silicon inspection, moisture detection)
- Agriculture (irrigation and moisture monitoring, crop health monitoring, food sorting, vegetation)
- Other: mineral detection, paintings research and falsifications detection, perimeter protection.

MWIR and LWIR: Thermal imaging is now used in a broad range of applications and offers technical characteristics that meet the specific needs of different markets. The basic ones are presented in the tables, below.

DEFENCE

Desired capabilities	Uses	Technical characteristics
- Night vision and in all weather conditions - Accurate images - Fast response - Shock resistance - Very high DRI - Low SWAP - V. long MTBF	- Military surveillance drones - Integration in military vehicle sights - Night driving assistance - Infantry equipment (clip-on, binoculars, TWS)	- Spatial resolution of QVGA - XVGA - Thermal resolution < 50 mK - Can withstand in challenging environments - Array operability > 99.5%

TRANSPORTATION

Desired capabilities	Uses	Technical characteristics
- Night and bad visibility support - Fast response - Vibration and acceleration resistance - Fitted DRI	- At night and day, in the fog and smoke - Aviation and UAV - Road and rail vehicles, and ships - Observation and obstacle detection in all weather conditions	- Image frequency 60 Hz or higher - Long MTBF - Withstanding in challenging environments - Diamond-like anti- reflection coatings

SURVEILANCE

Desired capabilities	Uses	Technical characteristics
- High image quality - Day/Night vision in all weather conditions	- Video surveillance of buildings /plants, fence & perimeter protection, border/urban - Detection of intruders - Detection of the sick in the crowd	- Spatial resolution: 60-80×80 - XVGA - Thermal res. <0.06° - Frame rate: up to 50 Hz (or higher) - Array operability > 99.5%

FIREFIGHTING

Desired capabilities	Uses	Technical characteristics
- The basic thermometric features - Ability to work in challenging environments	- Moving in the dark and smoke - Assisting in the search for victims - Identification of fires and fire hazards	- QQVGA, QVGA - SWAP features - Switching speed - Auto settings - High scene dynamics > 300°C

THERMOGRAPHY

Desired capabilities	Uses	Technical characteristics
- Known and good radiometric features, settings flexibility, fitted to task software - Versality - Machine vision (high-frame-rate)	- Energy audits - Predicative and preventive surveys - Industrial, medical, veterinary, breeding inspections - NDT (passive,active) - Support in R&D	Depending on task.: - FPA&pixels sizes - FOV: fixed, zoom - NETD, frame rate - Temperature scaling & reporting - Location (fixed handheld), power

OUTDOOR

Desired capabilities	**Uses**	**Technical characteristics**
- Enhanced vision in many activities - Handheld, fixed or mobile UAVs, cars - Simplicity of use and recording	- Studies of nocturnal activity of animals and birds - Daytime more precise hunting and looking for victims - New: games, activities	- Format from QQVGA to VGA - Smaller optics and lower cost: 12 um pixel pitch - Frame rate: 30 Hz for smooth images

The increasingly popular and future-thinking use of IR cameras in robotics and drones does not have separate tables, because both are already being used in all of these groups.

PARTICULARLY NEW AND MASSIVE MARKETS FOR IR FPA

In recent years, new classes of potentially massive IR FPAs camera applications have appeared. One is a new application that has just been created: Smart Buildings which are the central pieces of the Smart Cities. Particularly uncooled thermal sensors offer uniquely important features for these purposes as e.g.: work in the absence of light, detection, and differentiation of adults, children, and animals. And, additionally, unlike VIS, NIR and SWIR cameras, small resolution LW thermal devices ensure anonymity and privacy compliance.

SMART BUILDINGS, SMART CITIES

Applications	Tasks, results	**Suggested features**
A. Buildings monitoring and automation (networks of indoor sensors- with algorithms instead of monitors)	- More efficient management - Upswing occupant comfort and convenience - Optimization of energy consumption (electricity and heat; offices etc) - Greater occupant's safety	- Low price, simple use, maintenance-free, integral lenses, digital output, very long MTBF, low power consumption - arrays sizes start from 16×16 but optimal are 80×80 (as modules for corners: 90° or for central: 120° -with integral lenses)
B. City security	- Rescue actions and detection of the sick persons in the crowd - Monitoring of urban technical networks - Support for police and other municipal services	Various imaging IR cameras (SW-LW+ gas detection units): depending on the task, place of montage, level of autonomy.

With the aim to accelerate required transformation, in 2012 in Europe SBA (Smart Buildings Alliance) has been created. SBA has 170 organizations representative of all the trades relating to the Building sector and Smart City stakeholders, with an aim to conceive and define "Smart Buildings". It's a very open and active organization where all the construction industry is involved: cities, developers, specifiers, builders, installers, integrators, equipment manufacturers, utilities, telecom, IT & Network, start-up, banking & insurance [18]. Chosen European producers of IR FPA joined SBA, to better respond for specific of these needs, and to co-operate in creating new technical and legal regulations [19].

AUTOMOTIVE APPLICATIONS

The automotive market will be a powerful challenge for camera suppliers. Preparations of one of the world's leading producers (ULIS, with 2nd place after the USA), made a few years ago, are shown in the table below

Function	Conditions & requirements	Proposed IR FPA
<u>SAFETY</u>:	Day – Night – Smoke – Fog <u>"Images or their extracts"</u>	Maybe VGA (ATTO640?)
AEB - VRU	Detection range: > 100 m	PICO 384P
FCW	Detection range: > 100 m	PICO 384P
HBA	Detection range: > 200 m	PICO 384P
BSD	Detection range: > 200 m	PICO 384P
Rear Camera	Detection range: > 10 m	MICRO80P
<u>MONITORING</u>:	<u>"Only images extracts "</u>	
OCS – SBR	Occupancy Classification	MICRO80P
Battery/Engine	2D Temp. measurements with 0,1K accuracy	MICRO80P
<u>COMFORT</u>:	<u>"Only images extracts "</u>	
HVAC	2D Temp. measurements with 0,1K accuracy	MICRO80P
HMI	Human to Machine Interface Gesture recognition	MICRO80P

Where:
AEB – Autonomous Emergency Breaking
VRU - Vulnerable Road Users
FCW – Forward Collision Warning
HBA- Hydraulic Break Assist
BSD – Blind Spot Detection
RC – Rear Camera
Battery / Engine
OCS - Occupant Classification Systems
SBR - Super Barrier Rectifiers
HVAC - Heating Ventilation and Air Conditioning
HMI – Human Machine Interface

HELTHCARE

Use in healthcare is also expanding. Here are a few examples of innovations leveraging thermal imaging that will improve our day-to-day lives: early detection of breast cancer, preventive care for diabetes, monitoring of patients with respiratory issues, monitoring of seriously ill in hospitals, health monitoring in public places and prevention of infections as well as veterinary and monitoring of our animals.

CONCLUDING

Thermal imaging is a technology driving the innovations we will use every day. A rich array of thermal application possibilities (although far incomplete) discussed in this short review shows that the future of IR FPA and imagers is very bright indeed.

6. Markets and trends

For several decades the United States dominated the global market with the support of major research and development programs run by DARPA (Defense Advanced Research Projects Agency). Today, however, the global market is more balanced. According to the data presented lastly, the US represents around 54% of the market by value vs. 46% for the rest of the world. Political instability in certain parts of the world and the rise of terrorism have spurred governments around the world to make sure that their armed and police forces have the latest equipment.

Based on data from the last report [20]: SWIR industry was valued at USD 161 Million for the year 2018. Shortwave Infrared (SWIR) Industry is further expected to grow at a CAGR of 9.99% from 2018 to reach USD 284 billion by the year 2025. European region holds the major industry share whereas Asia Pacific region is considered as the fastest growing industry in the forecasted period. It is observed that developing countries from an emerging Asia Pacific Industry are anticipated to grow strongly in the next 5 years. Progression in SWIR sensors is one of the essential drivers for developing an enthusiasm for areas like ordinary reconnaissance imaging and headways in a hyper ghastly imaging application. Further size-decrease of these cameras is expected (due to new detectors). The main markets will be shared by the army and emerging civilian applications (automotive, surveillance, agriculture, chemical, and food industries).

According to different sources, the compound annual growth rate of the thermal imaging market is somewhere between 8% and 10% for defence and between 10% and 20% for surveillance. The global thermal imaging market is expected to grow by 7.18% from 2018 to 2023 (from $5.16 billion to $7.3 billion). It's worth to add, as the Asia-Pacific region should be a major growth driver with strong demand from the security industry. [21, 22].

Presently, the thermal imaging market is dominated by well-established market players. Some of the market leaders are FLIR Systems, BAE Systems, Leonardo DRS, L3, ULIS, Lockheed Martin, Elbit Systems, Raytheon, Sofradir, Jenoptik, Safran, Thales, Guide Infrared, and Zhejiang Dali. To stay on the top of the global market, most of them, leverage partnerships, joint projects, acquisitions, new product developments, product launches, and other agreements to increase their share of the global thermal imaging market. In 2017 the market saw around 20 mergers and acquisitions. It's worth to note, as in June 2019, two European the biggest IRFPAs producers: Sofradir and ULIS, merged to form LYNRED [23].

In the case of fastest and the most sensitive i.e. photon IRFPAs, therefore deeply cooled, the main market was, is and will be the army and borders protection. The percentage share of MW and LW cooled cameras produced on the civil market (such as specialized thermographic cameras or cameras for gas detection in the air) is gradually decreasing in favour of more and more perfect, and much cheaper microbolometer cameras. This tendency may slow down only the massaging of detectors in really HOT and SWAP versions, especially when they will be significantly cheaper.

Simultaneously, for the uncooled IRFPA producers, there is a multi-million chance in terms of the scale of the market's needs. For example, the number of firefighters in the world reaches 37 million, and the number of hunters is 6.7 million in the US and 11.2 million in Europe. This new market in Europe is worth about €16 billion per year and in the United States €26 billion. In the example of the ULIS company: the main products sold on this market are viewfinders (35%), monoculars (51%), and clip-ons (14%). Half of the thermal sensors are QVGA and 38% are VGA. US and China producers probably have a similar situation and sales successes. Personal Vision Systems (PVS), including portable monoculars and binoculars for consumer outdoor leisure, law enforcement and border control. The PVS segment is seen as significantly contributing to the growing global infrared market, expected to reach 30% annual unit growth between 2018-2024, according to the Yole Development report on 'Uncooled Infrared Imagers [24].

Another, relatively new but of growing importance is the market for robots and drones. Among different models, only for security robot the global market in 2017, was valued at USD 1.946 billion and is expected to register a **CAGR of** about 3.11% during 2018-2023. [25]

This market is booming, but as it has not yet reached maturity, it is difficult to measure. The most widely-accepted forecasts indicate that by 2022 this high-potential market could be worth $15billion and demand is only expected to grow. Here is forecasted growth by the year 2022 in specific areas: "Farming" 36%; "Transportation" 81%; "Construction and civil engineering" 103%; "Civil defence and firefighting" 110%; in the "Oil & Gas industry" 126% [26].

Based on chosen data presented by ULIS, the growth rate for 2018-2023 could be forecasted as follows: MILITARY 16%, THERMOGRAPHY 16%, SURVEILLANCE 20%, FIREFIGHTING 23%, and LEASURE 30%. Volume forecast for uncooled IR detectors shows as in 2023 this number will be more than doubled in comparison to 2018 (when world production reached 1 600 000 pieces). Impressive growth since 2010, when the total number of IR uncooled detectors in the world was 270 000 [22].

Thus, when we add future potential, mass applications in transport, automotive and smartphones, a huge, complex and very expensive task is seen before the world of manufacturers of uncooled IRFPAs. The largest of them are already implementing adequate programs [27]. Signalized here state, results in a continuous process of improving the offers and reducing the prices of IR detectors at the same time. The companies that offer various specialized solutions, especially those offering application of this unique "sixth sense" in intelligent buildings, networks IoT and IIoT, can also take advantage of this dynamically developing and prospective market.

It's worth to remember, as different countries have different rules for importing and exporting thermal imaging sensors (both military and dual-use). This is a major issue that must be taken into consideration. In the United States, thermal imagers and their components may be subject to ITAR (International Traffic in Arms Regulations), enforced by the US Department of Defence, or EAR (Export Administration Regulations), enforced by the US Department of Commerce. These regulations require the identification of the final user. The real issue is that they are extra-territorial, which means that they must also be followed by companies outside the US. Many European manufacturers use US-made electronic components in their products. Therefore, in the case of IR cameras, these devices are subject to the US regulations, giving the United States the ability to restrict export sales of these cameras to other countries. Similarly limiting exports may be so-called "blacklists" of clients of Israeli companies. For this reason, it can be advantageous to use, in Poland, components manufactured in Europe, as export final devices have to follow Polish, i.e. EU law.

7. A few conclusions for newcomers to the thermal imaging business

Currently, the majority of thermal imaging cameras are very easy to use. In the case of seeing images only, interpretation is significantly simpler than in the case of temperature measuring thermographic ones. It's worth to remember as these are subjective type investigations. To execute valuable radiometric survey' operator has to accurately correct exit results for emissivity, reflection, background and atmospheric influence for instance. Otherwise, he might draw false conclusions. Thus, acquiring adequate knowledge is strongly recommended.

As our (every two years since 1992) TTP conferences proved, in Poland, we have a number of laboratories and teams experienced in unique research projects, constructions and IR cameras testing. They are active in the exchange and collection of knowledge and when required, they are supported by the detectors or cameras manufacturers. Therefore, for many national firms particularly worth to be considered is to maintain their capacity for innovation through research based on set up of adequate partnerships with technology research teams, and institutions.

In this review, I tried to show how fast infrared imaging technology is developing and how big the innovative potential is. If it proves to be a stimulant for the development of own implementations based on IR cameras, there are four ways to go about it:

1. to hire a specialized external company,
2. to create a solution based on the purchase of a typical IR camera from a wide market (EU, USA, China, Israel, and others),

3. to create a camera from ready OEM modules, "blocks" (lens, IR FPA assembly with matching electronics, own or external software).
4. to buy objective lenses and IR detector and elaborate all the rest alone (for optimizing the solution, ensuring uniqueness and secrecy and creating own niche on the market, as well).

Intentionally, issues of thermography were almost omitted, here. However, various collections of hundreds of presentations of the past 15 TTP conferences are available (through the Organizational Comm.) but above all, significant book collection wrote by leading specialists in the Polish thermographic community are on the market and in libraries [References II].

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