Thermal Imaging Camera Technology

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Introduction

I thought a brief document on thermal imaging cameras might be of interest to some forum members and may also answer some common questions on the topic. This document is deliberately high level and does not dive deeply into topics such as detector materials and the detailed characteristics of such.

This document is dynamic and I shall likely amend and add to it in the future. This is effectively a first release that will improve as and when I have the time. Much has been written from memory so minor errors may exist within it. These will be corrected in future versions.

Are you sitting comfortably ? Then let us begin..........

Thermal imaging is a relatively recent invention in terms of practical and portable solutions. It is very similar in principle to a common CCD camera in that a lens system illuminates a sensor/detector system that converts E.M. spectrum energy into a form that can be processed using electronics. The electronic element of the system corrects errors in the captured data and processes the resulting data into an image that is either stored in digital data format or on a display. The significant difference in the system is that the scene that the lens system and sensor/detector processes is at the thermal energy wavelengths of the E.M. spectrum.

The major component parts of a thermal camera are as follows:

1. The Optical Block
2. The Detector Block
3. Image Processing Block
4. System Controller Block
5. Image Output Block
6. Power Supply Block

As will be seen, each block can comprise very different technologies and will have different component parts within it.

The Cooled detector years Circa 1960's onwards

The earliest thermal imaging cameras used semiconductor detectors that were only useable for thermal imaging when cooled to very low temperatures. Above such low temperatures their characteristics rendered them useless for such a task.

Cooled Detector formats

Single Pixel

The detector could be a single pixel that is presented with the thermal scene via a lens structure and scanning mirrors or prisms. A raster scan is created using two axis of movement.

Linear Pixel array

A number of pixels can be arranged in a vertical stack that provides the vertical resolution. The array is presented with the thermal image from a lens system and scanning mirror. Only one axis of movement is used in this format and this creates the horizontal scan.

Focal plane array

The focal plane array is an X-Y matrix of pixels that receive the thermal image via a lens assembly. The matrix is read out in a manner to suite the image processing electronics and so is very versatile. Such arrays are also often described as staring arrays.

Detector Cooling Methods

Liquid Nitrogen cooler.

In this cooler design a small vacuum flask called a DEWAR is filled with Liquid Nitrogen. In the wall of the DEWAR the detector element is positioned such that it is cooled by the Liquid Nitrogen. The detector operates at temperatures as low as -200C The advantage of Liquid Nitrogen is its relatively easy availability in industry. The significant disadvantages include, safety of handling, inability to invert the camera and the limited run time due to liquid Nitrogen evaporation. Such cooling technology was often practical for fixed industrial installations but was impractical in many portable deployments. At the time, however, there was little choice and liquid Nitrogen was essential to good low noise thermal imaging. A late example of the 'state of the art' in Liquid Nitrogen cooled thermal cameras was the AGEMA 880.

Argon Gas cooler

Argon gas coolers comprised of a high pressure bottle of Argon gas that could vent through a Venturi heat exchanger that was connected to the detector assembly. The rapid gas expansion through the Venturi created a very low temperature capable of cooling the detector to a temperature suitable for thermal imaging. The advantage of this system over Liquid Nitrogen cooling is that the camera can be operated at virtually any angle. The disadvantages include an inferior cooling temperature and a limited run time set by the capacity of the Argon gas bottle. Such Gas expansion based systems were to be found in Hughes hand held thermal imaging cameras and in some airborne thermal camera installations.

Stirling mechanical cooler

The Stirling engine is well known for converting thermal energy into mechanical movement, hence the term 'engine'. In that configuration gas expansion and contraction act upon pistons to move the crank shaft. The 'charge' used is usually air at atmospheric pressure. Adding Helium to the charge improves performance significantly.

The Stirling mechanical cooler is a different configuration that uses the same principles as the Stirling engine but its crank shaft is driven by a motor and the charge is usually Ultra Pure Helium at a pressure of around 40 atmospheres within the sealed cooler enclosure. As the electric motor rotates the crank, the two pistons operate and whilst one cylinder head heats up, the other cools down significantly. This may not seem that impressive until it is realised that the cooling side cylinder head is lowered to -196C from an ambient of around 25C, almost that of Liquid Nitrogen. Sadly the design has very little thermal load capacity and so measures have to be taken to minimise the load on the cooled cylinder head. A 'Cold Finger' connects the cooled cylinder head to the rear of the detector die. The whole cooling cylinder and detector die are enclosed in a vacuum Dewar to insulate them from ambient temperatures that would increase the thermal load on the cooler. The cooler has two operating states, initial cool down and maintenance cooling. When the cooler is first switched on, its controller drives the motor at high RPM to provide an initial boosted cool to operating temperature from ambient. Once at operating temperature the controller reduces the motor RPM to a speed that enables the cooler to maintain the low cold finger temperature. Initial cool down of a thermal camera Stirling cooler can take between 5 and 15 minutes. During that time, no thermal image is created. A Stirling cooler that takes significantly longer than specified to drop into maintenance cooling mode is likely nearing the end of its operational life and needs a rebuild and re-gas with Helium. Such is a very expensive service operation.

The advantages of the Stirling cooler over the Liquid Nitrogen and Argon gas coolers is that the cooler will run for as long as power is supplied to it and the camera may be operated in any orientation. The cooler does have an operational life between services of between 2,000 and 10,000 run-hours depending upon model, so it can be expensive to maintain It also has the disadvantage of being quite noisy, making it a poor choice for covert observation, as needed in some military scenarios..

Common examples of a Stirling cooled thermal camera are the AGEMA PM550 and Inframetrics PM280 cameras. The Liquid Nitrogen cooled AGEMA 880 could be upgraded to a Stirling Cooler at significant cost. This upgrade was carried out at AGEMA and involved the fitting of a new detector/cooler assembly and recalibration of the camera. Stirling cooled cameras are still manufactured and used in the military, laboratories and industry as they provide the lowest noise imaging and greatest sensitivity.

Peltier Element 'stack'

The Stirling cooler has the advantage of electric cooling but the disadvantage of mechanical moving parts and high pressure Helium gas in its design. In the thermal imaging industry there was a desire to find a cooler that used electricity but that had no moving parts. The Peltier element is a semiconductor device that appeared to meet this criteria. Sadly its efficiency and cooling differential across it s hot and cold plates was inadequate for the task. The solution to the problem was a Peltier 'stack' which comprised a number of Peltier stages joined together, each providing a temperature differential lower than its previous stage. As such it could step the final output temperature down to the approx -70C required by the detector element used. It should be stated that the Peltier 'stack' design is far more complex than just bonding a number of individual coolers together. The inefficiency of the individual Peltier cooler stages must be considered. This means that the detector Peltier element is quite small, but each successive stage is of a larger size than that feeding heat to it. The cooler is normally housed inside a vacuum Dewar to lower the heat loading on it by ambient temperatures. The major advantage of the Peltier element cooler is long operating life running from electricity with no gases or moving parts needed. The disadvantage is the high current needs of the multiple Peltier element cooling stages. Such high current consumption can limit portable operation when running on compact batteries. An example of a Peltier element cooled thermal camera is the AGEMA 400. This camera looked like a large VHS camcorder and was very popular in its time.

The Uncooled detector years Circa 1990's onwards

Few of the cooled thermal cameras were found to be that convenient for portable use and the Military wanted a thermal camera that did not require expensive or bulky cooling systems. New technology was developed and the most convenient technology has continued in production to this day.

The Pyro-Electric Vidicon

Some older members of the readership may remember the Vidicon television camera tube that was to be found in television and CCTV cameras. The simplest description of this thermionic valve era device is a sensitive target face that is scanned in a raster pattern by an electron beam emitted from an electron gun at the rear of the tube. The raster scan is created by H and V deflection coils placed around the tube. The target incorporates a signal output line that is very high impedance. When a thermal scene is presented to the thermally sensitive target material the raster scan translates the image to a changing signal amplitude at the target output. This high impedance signal is passed to an amplifier and then processed by the video electronics that follow. The Pyro-electric Vidicon based camera basically uses typical television camera technology. There is an additional requirement however. A motorised chopper wheel is placed in front of the target to create the required change in the target material. The chopper wheel is synchronised to the raster scan timing. The chopper wheel did introduce an unwelcome mechanical element to the imaging solution but, in general, the motors used were high quality and long lived. GEC Marconi (EEV) developed the Pyro-electric Vidicon camera to good effect and the P4428 camera was issued to the British and US Navy's for use as a fire fighting camera on board warships after lessons learnt from the 1982 Falkland Islands Conflict.

The Barium Strontium Titanate (BST) array

The BST array was the first commercially used detector array that did not need cooling. The ceramic detector pixels provide a variable charge output to the read out electronics proportionate to the level of thermal energy to which they are exposed. When an X-Y array of the BST pixels are read out, the complete thermal scene may be reconstructed. The BST array requires a motorised chopper wheel for the same reason as the Pyro-electric Vidicon tube. A change is needed in the scene to 'reset' the pixels ready for the next image capture. The chopper wheel is synchronised to the read out electronics and is generally reliable. Sadly BST detector array technology had a weak point and that was its relatively limited dynamic range of around 50C. To overcome this limitation manufacturers often incorporated some form of motorised or manual iris in the lens assembly. This behaves in the same fashion as the iris of a conventional camera and controls the amount of energy to which the detector array is exposed.

The BST array is usually deployed with a thermal stabiliser attached to it to maintain an optimum operating temperature of around 32C. The thermal stabiliser of choice is the Peltier element. In this scenario, only a single stage Peltier element is needed and it does not reside in a Dewar. As such it is a far less complex and power hungry solution to that of the multi-stage Peltier cooler described earlier. Many Fire Brigades throughout the world were equipped with BST based thermal cameras. Well known models of such cameras are the GEC Marconi (EEV) ARGUS 2 and Talisman WASP.

BST technology appeared to be the solution that the military and industry had been looking for and further research was paid for in the USA by the DoD to develop the technology further. That was all to change however......

The Microbolometer array

The 'new boy on the block' was the Vanadium Oxide (VOx) Microbolometer. This is a component that varies its resistance with temperature. The array of tiny Microbolometers pixels are read by the read-out electronics as variations in the resistance of each pixel. A thermal scene can thus be recreated by the video processing electronics. The Microbolometer requires neither temperature stabilisation, nor the mechanical chopper wheel, and so presents an advantage over the BST technology. It also has a far greater dynamic range and so the need for an iris is removed. The Microbolometer die is not the most thermally stable of detectors however, and its output will drift with time. To address this drift, a solenoid operated Flat Field Correction flag is employed. Early Microbolometers produced inferior images to those of BST arrays. The image contained significant levels of noise in the early generations of Microbolometer based cameras. A battle between the two technologies ensued and only one could win the valuable US military contracts for thermal imaging cameras. The US DoD invested in both technology streams to establish which offered them the best solution for their needs. It was eventually decided to pursue the development of the Microbolometer and DoD ceased funding BST development. Sadly this effectively removed most of the essential funding from BST technology development and it fell out of favour with the OEM's as a result. The military applications for the Microbolometer arrays ensured rapid development of that technology. The result was large reductions in the noise levels and far cleaner thermal images. Some cameras operate with a Peltier thermal stabiliser whilst others do not. Interestingly, the focus was on improving the image noise content and general clarity, rather than an increase in resolution .The military applications for thermal imaging technology lead to tight controls over the production and distribution of such capable technology.

Another version of the Microbolometer is based on Amorphous Silicon (A-Si) pixels and is also a very capable detector array. A-Si detector pixels have a more predictable drift pattern and rate and this has lead to A-Si based Microbolometer cameras that do not require the Flat Field Correction (FFC) shutter. Dynamic offset tables are used in its place.

In recent years the Microbolometer based camera technology has become more available to the general public of countries not deemed to be a threat to NATO. Strictly speaking, any decent quality thermal camera capable of producing a 60fps real 320x240 pixel image is capable of high end military applications and so subject to strictly controlled distribution. The lower frame rate cameras producing less than 9fps are less strictly controlled.

The Thermopile array

The thermopile detector technology is commonly found in IR non-contact thermometers. In this role it is more than suitable, but as a thermal camera detector it has historically had drawbacks that limited its usefulness. The thermopile array was developed into a thermal imaging role by a company called Irysis who wanted to build affordable thermal imaging cameras for industry, schools and some scientific roles. The thermopile has quite a slow thermal response making it only suitable for lower frame rate cameras. An imaging array would also require a mechanical chopper wheel for the same reasons that such is needed in the case of BST detector arrays. In order to offer an affordable solution, Irisys developed low pixel count, low resolution detector arrays. The commonly available arrays were 15x15, 16x16 and 32x32 pixels. Whilst the pixel counts appears unsuitable for a thermal imaging camera, the clever use of interpolation resulted in useable images.
In recent years higher resolution thermopile detector arrays have been developed. They remain on the periphery of the thermal imaging camera marketplace however and no high resolution thermopile based cameras are known to be available at this time.

Camera Resolution

Camera resolution can be an emotive and hot topic when discussing thermal cameras. Some people, new to the technology, are disappointed at what they consider the "cheap webcam" resolution that is available and the "high cost of cameras". Those who have worked in the industry understand why this is the case. The technology has advanced greatly in recent years but there remain technological limitations and high development costs for improving camera resolution significantly.

Scanning thermal cameras

The X-Y raster scanning thermal camera uses a pair of mirrors or Germanium prisms to create the image raster that is read by the single pixel detector. The resolution is determined by the scanning step rate of the mirror/prism drive system. These cameras usually produce around 128 lines in the image equating to around 128 x 128 pixel resolution. Frame rates can be quite low for this technology due to the mechanical limitation inherent in such a design.

Linear row detector array X axis scanning thermal camera

The linear detector array is stacked vertically and this forms the vertical resolution of the camera. The X axis scanning mirror is driven by a galvanometer which is an analogue drive system. The vertical resolution of the camera is normally around 128 pixels and the equivalent horizontal resolution is about the same or slightly higher for an uneven aspect ratio such as 4:3. Frame rates are limited by the mirror drive system in these cameras and can be quite low as a result.

Focal Plane Array (FPA)

Focal plane arrays contain a number of pixels arrange in an X-Y matrix that is read but read out electronics. Both BST and Microbolometer detectors are examples of an FPA detector. These are also called staring arrays. The challenge with these FPA's is the construction of a die that contains acceptable numbers of dead pixels. The pixels can be complex to manufacture and there will normally be a certain number of malformed or 'out of tolerance' pixels. These are dealt with in the image processing stages of the camera via the dead pixel map.

The difficulty in manufacturing high quality, high performance detector arrays should not be underestimated. These are very different technology to visible light CCD and CMOS FPA's found in common digital cameras. The detector elements need to be thermally isolated from the substrate and of thermal low density for a fast response, yet remain relatively robust.

The difficulties in the manufacture of such detectors has meant that common resolutions were 160x120 and 320x240 pixels. Top of the line Industrial thermal cameras still had only 320x240 (QVGA) pixels because that was adequate for the tasks for which they were intended. For potential buyers and users, it is important to re-align resolution expectations when dealing with thermal imaging cameras. They are not the same as visible light cameras, and the detector technology does not make increases in pixel count an easy process for the manufacturers. In recent years 640x480 (VGA) resolution cameras have become more available, but often at a significant cost premium. Higher resolutions are available but these are often limited to very high end industrial, scientific or military uses where such resolution is justified. It is worth bearing in mind that 320x240 pixel detector arrays have been adequate for the majority of thermal imaging applications for more than two decades.

The frame rate of the BST and microbolometer arrays is limited only by the response time of the detector pixels. Both technologies are capable of 60 frames per second with 100 frames per second used for higher speed thermography. High frame rates are beneficial when the camera is recording fast moving objects or when it is being panned across a scene quickly. Cameras limited to less than 9 frames per second are still very capable in most applications including imaging moving targets or slow panning of the camera. A 9fps camera should not be discounted from a buying shortlist due to the lower frame rate alone unless the intended role definitely requires the faster frame rates. Theoretically a camera with a 9fps core provides ample opportunity for greater image processing in the increased 'dead' time between frames.

Optical Block lens materials

A thermal imaging camera needs decent optics if it is to produce a good quality image. Poor optics can ruin the image produced by even the most sophisticated imaging arrays.

Germanium

The original default choice of material for thermal camera lenses was, and likely still is, Germanium. Germanium is a metal and a single crystal of this metal has to be grown to dimensions large enough for the lens. The lens blank is cut from the large crystal and a single diamond lathe used to shape the lens element before polishing. The lens is carefully polished and then an Anti-Reflective coating is applied that sets the optical pass-band of the element. Germanium lenses are both expensive to grow and to machine. the current scrap value of Germanium is around £1 per gram ($1.50 per g) . Germanium does have an undesirable physical characteristic that must be considered when it is used in a radiometric thermal camera application. Germanium's transmission reduces with an increase in physical temperature. The effect becomes more pronounced once the lens temperature passes 60C and is very noticeable at 100C. To counter this well documented effect, thermal cameras employ temperature sensors in the lens assembly in order to apply corrections to any radiometric measurements taken. In most applications the effect is of little consequence but in specialist applications such as blast furnace monitoring, the lens needs to be protected from heat as well as physical damage. To this end, such cameras often operate from within special protective housings with forced air or water cooling.

Chalcogenide Glass optimised for thermal camera lens applications

Chalcogenide glass IR lenses have been under development for some time. Early experiments proved promising but there was a problem with the sintering process that resulted in micro fractures throughout the material. Such fractures degraded the materials performance. The material appears to have been perfected now with several manufacturers of thermal camera optics manufacturing them. A well known brand is GASIR. the material offers the significant advantage of being mouldable. This permits mass production and significant unit cost savings over Germanium. For this good reason this lens material is common in modern 'affordable' thermal cameras such as the FLIR Ex series.

Zinc Sulphide (ZnS) and (Zinc Selenide) ZnSe

ZnS and ZnSe are viable alternatives to Germanium optical elements in some applications. The two materials are optically and thermally transparent with a yellow tint. Anti reflective coatings may be applied to reduce the normally very wide pass-band properties of the materials. A disadvantage of the material is the lower refractive index and its relative softness. It is easily scratched unless a hardened protective coating is applied.

IR transmissive plastic Polymers

IR transmissive plastic Polymers relatively transparent at thermal wavelengths and may be used to make Fresnel lenses for thermal camera applications. The Fresnel lenses produce image issues that have yet to be fully addressed and so prevents the construction of a completely IR Polymer based lens assembly. If a suitable lens design made from IR Polymer can be constructed, it offers the potential for truly cheap thermal imaging camera lenses as the material is intrinsically cheap and easily moulded.

Gallium Arsenide (GaAs)

Gallium Arsenide is used in the production of some CO2 laser systems that operate at similar wavelengths to LWIR thermal cameras. This material is also capable of being used in thermal camera optical systems and has been used to good effect as a close-up auxiliary lens. I have yet to see a GaAs lens in a commercial thermal camera however.

Silicon

Lenses can be constructed of silicon and this opens up the possibility to fabricate lenses on Silicon chip fabrication lines using lithography techniques. Silicon is not normally a good choice of material for Long Wave thermal imaging cameras due to its mainly Short Wave passband characteristics. If the lens is constructed of a thin enough layer of silicon, it will operate reasonably well at Long Wave in applications that are tolerant of its less than ideal passband. An example of a Silicon lense used in a thermal camera is the FLIR ONE Generation 2 that uses a LEPTON 3 core. The Microbolometer detector is a Long Wave device, yet its lens is made from silicon.

Other exotic materials

There are other materials that may be used to create thermal camera lens elements but these often have undesirable characteristics, such as being hazardous, very fragile or hydroscopic.

Why do thermal cameras cost so much money ?

There are many reasons why thermal camera technology costs more than conventional visible light imaging technology. Some are listed below:

1. Thermal cameras are a niche technology only recently made freely available

2. Thermal camera production and sales are minute compared to conventional visible light digital cameras

3. The materials used in thermal cameras are far more exotic than conventional visible light cameras and produced in far lower volumes.

4. Exotic thermal lens materials are significantly more expensive than even high quality conventional glass optics.

5. The detector assembly used in a thermal camera is a relatively low yield product and low volume when compared to visible light CCD and CMOS detector arrays.

6. There are very few manufacturers of thermal cameras and cores, as such they can, to a degree, control the market and retail prices of thermal cameras.

7. Ongoing thermal camera development is very costly and manufacturers wish to recover their investment before a new technology replaces their current product lines.

8. Historically, thermal imaging has been so expensive that it was the preserve of the Military, Industry and Scientific users who had sizeable Capital purchase budgets. New consumer grade thermal cameras are actually sold at bargain prices when compared to previous Industrial grade cameras. This has been made possible by new cheaper methods of Microbolometer production, Chalcogenide Glass lenses and a more mass production approach to marketing.

9. Thermal imaging remains a specialist market that is insignificant when compared to that of visible light cameras and mobile phones. As such its products will always tend to be sold at premium prices.

Q. Are all thermal cameras of the same resolution created equal ?

A. The short answer is "NO"

A thermal camera comprises many components that eventually produce the thermal scene image. Cost cutting in any or all of these components can degrade the quality of the image produced. This is no different to visible light cameras. However, as thermal cameras are usually of relatively low resolution, a degraded image may not be as noticeable as on higher resolution visible light cameras. Thermal camera manufacturers take advantage of this fact.

1. Lower quality optics of smaller apertures, less than ideal material and fixed focus will present the detector with an image inferior to a well designed, larger aperture Germanium manual focus lens. That is just physics at work.

2. A Microbolometer array may come in many forms. The most expensive are high precision, low dead pixel count arrays of significant size. The die sits within a gold plated metal vacuum module with a Germanium window at the front of the module, and a Peltier temperature stabiliser attached to the rear of the die. Lower cost Microbolometers come as a compact sandwhich of materials containing the Microbolometer pixel elements in a tiny vacuum space and often have no temperature stabilisation. Such Microbolometers are built down to a price yet remain quite expensive due to the low yield rates and complexity of manufacture. it is nor reasonable to expect a low budget simplified Microbolometer to perform as well as a high budget precision manufactured large array. That is just a simple fact of life. Small precision arrays are available, such as those from ULIS, but they cannot be described as budget priced.

3. The Microbolometer can be a most unruly device and image processing is required to create a good quality image from it. Dead pixel maps, Non Uniformity Correction, Flat Field Correction and noise reduction algorithms are all used in teh industry to create the desired quality of image. Whilst Dead Pixel Maps, NUC and FFC are reasonable simple processes, the noise reduction algorithms are often complex and propriatary to a manufacturer. These Algorithms can make the difference between an 'OK' camera image and a 'Great' camera image. An example of this is the FLIR PM 5xx and 6xx series of professional thermal cameras. the PM570 was FLIR's first Microbolometer thermal camera. It produced good images but they contained more noise than the cooled detector array PM550 that preceded it. A generation 2 Microbolometer was developed with a lower internal noise level and more sophisticated noise reduction algorithms. This was fitted in the PM 575 camera. Following that FLIR developed a generation 3 Microbolometer that was again improved and the noise reduction algorithms were even more refined. The improvements in the noise reduction algorithms occurred over several years of production and with great financial investment in the cameras firmware. A new company to the thermal camera industry would be unlikely to be able to get teh noise reduction algorithms perfected on their first attempt unless assisted by a more

knowledgeable manufacturer such as FLIR. This situation may be changing however as modern DSP systems and adaptive noise processing algorithms may prove highly effective in new thermal camera designs.

4. Power supplies is an area that is sometimes neglected badly in a design that is built down to a price. The Microbolometer is an analogue device that passes its data to an Analogue to Digital Converter. If the power supply to the analogue stages is of poor design and suffers noise contamination from digital supply rails or circuits, the image quality can be degraded requiring more sophisticated image processing in later stages. Thermal camera power supplies should be split into analogue and digit supplies as per best practice when dealing with sensitive analogue circuits.

5. Temperature monitoring systems are needed in thermal cameras to feed data into the image processing and measurement stages of the camera. Where Germanium lenses are in use, it is important to capture the temperature of the lens so that any offsets may be applied to measurements taken. The chassis temperature is another important variable to capture as this can directly affect the detector array accuracy. especially in cameras that do not have thermal stabilisers fitted to the detector. The temperature of the detector array is an essential to accurate radiometric measurements as such directly affects such measurements. There are normally at least two 'on-die' temperature sensors on a detector die or in close proximity to it. Finally, on Microbolometer based cameras the FFC flag is used to create the flat field correction table. Knowing the real temperature of the flag is of benefit to this correction process. A temperature sensor is often attached to the flag or very near to it and captures this data. Cost reduced thermal cameras will often remove some of the temperature monitoring nodes and rely upon just the Microbolometer sensors and one chassis sensor.

It is not reasonable to expect a sub $5000 'budget' thermal camera to perform as well as a $50K industrial thermal camera. That is not to say that a sub $5000 thermal camera cannot produce more than acceptable images for most non-specialist applications. There are cameras coming onto the market that cost far less than $5000 yet produce perfectly respectable images for many applications. Examples of these 'budget' cameras are the Opgal Therm-App and the i3 Thermal Expert. The high quality Microbolometers and optics used in these camera have been carefully chosen to provide the best possible image at the price point, and much of the processing is carried out on a powerful host mobile phone, further reducing the BoM.

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