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Thermal endoscope based on cost-effective LWIR camera cores

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ABSTRACT

The implementation of a thermal endoscope based on the LWIR camera cores Lepton and a custom miniaturized electronics is reported. The sensor and the PCB can be inserted into a cylindrical protective case of diameter down to 15mm, inox tube or plastic, 3D printable envelope, with an optical window in Germanium. Two PCBs were developed for assembling the endoscope in two different schemes, to enable frontal or lateral thermal vision setup. The thermal endoscope unit is controlled by a Raspberry external unit. The Infrared Vision Software is provided for controlling the acquisition of thermal frames, and for the thermographic calculation of the object temperature from the input parameters on object surface emissivity and environment. In general, the device enables to perform thermography in applications in which traditional larger equipment cannot be employed, as nondestructive diagnostics in confined space in the engineering field. The thermal endoscope was designed with dimensions also compatible for robotic-assisted/traditional minimally-invasive surgery.

Specifications table

Hardware name	Thermal Endoscope System (TES)
Subject area	• Nondestructive Testing (NDT) • Engineering and Material Science
Hardware type	• Imaging tools • Measuring physical properties and in-lab sensors • Field measurements and sensors • Electrical engineering and computer science
Closest commercial analog	The "thermal imaging borescope" Vividia is available in commerce (order 10 k US$), https://www.oasisscientific.com/store/c43/Thermal_Imaging_Borescopes.html. The submitted hardware is low cost (ten times less), in a rigid envelope of smaller diameter, suitable for robotic-surgery applications. The software acquire the raw camera data with access to sensors function to allow scientific thermal post-processing.

(*continued on next page*)

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2468-0672/

Open source license	CERN-OHL-S
Cost of hardware	Approx. 600 €
Source file repository	https://doi.org/10.5281/zenodo.5643580

1. Hardware in context

Infrared (IR) thermography [1] is an important nondestructive technique with applications in different fields, ranging from engineering to industry, from bio-medicine to emergency relief, up to heritage conservation, as extensively reviewed in [2–6]. The technique is based on the use of proper imaging systems for the acquisition of the thermal radiation that every body at a given temperature emits; from this radiation, knowing the thermal emissivity, it is possible to calculate the temperature of the body. A thermal camera, therefore, is a calibrated device that provides, in non-contact way, a 2D map of the temperature field on the object surface. For measuring objects around room temperature ($\sim$ 300K), uncooled Long Wave Infrared (LWIR) sensors with spectral sensitivity in the range from 8μm to 15μm are typically used.

The thermal cameras available on the market include portable medium-sized devices for on field measurements, up to more recent and compact devices suitable for machine vision and drone applications [7]. Recent advances in sensor technology has lead to the availability of small and cost-effective LWIR camera cores, mounting uncooled microbolometers [8], allowing researchers to prototype thermal vision systems tailored to very peculiar applications and specific environments, such as the endoscopic thermal inspection proposed in this paper.

When developing our project since 2016 [9–12] the state-of-the-art technology did not report imaging devices for endoscopic thermography. A commercial device was more recently introduced, i.e., the thermal boroscope Vividia [13] (by Oasis Scientific), which has a flexible arm with diameter of 17mm or 18.5mm mounting LWIR sensors of 80x60 or 160x120 pixel, respectively. Such devices designed for industrial inspection are rather expensive (order of 10 k US$). A few projects on thermal endoscope can be found in scientific literature, mainly based on different sensor technologies: the pioneering work by Matsuura [14], who developed a 6mm diameter device based on an optical fiber bundle, but with a coarse spatial resolution; more recently, the Worcester project [15], which developed the endoscopic device for the da Vinci surgical robot, with a squared 14mm x 14mm head mounting a small LWIR camera of 160x120 pixel resolution; and the medical endoscope developed by Ohara [16], based on a thermopile 32x32 array, nosier and with lower resolution than the microbolometers, but with more compact dimensions (14mm diameter) for the use in surgical laparoscopic environment. The cost of the prototypes [14–16] is not declared.

In this paper we report the concept and the construction of a thermal endoscopic system based on cost-effective camera cores, starting from the smallest LWIR radiometric sensors available on the market. The goal was to miniaturize the electronics to reduce the size of the thermal endoscope as much as possible, in order to make the tool compatible with laparoscopic and robotic-assisted minimally-invasive surgery. Among the advanced intraoperative imaging methods for laparoscopy anatomy navigation [17], thermal endoscopy is a potentially powerful adjunct allowing the spatio-temporal monitoring of the temperature in the anatomic structures. The need for studying thermal injuries during electrosurgery in laparoscopy has driven this interdisciplinary research and the development of the proposed thermal endoscope [10]. In the field of engineering and nondestructive testing the thermal endoscope can be potentially useful for condition monitoring applications [4], allowing to perform thermography in peculiar setups characterized by difficult to access spaces and cavities; an example is the inspection of electrical components in equipment.

2. Hardware description

The Thermal Endoscope System is a customized thermal imaging device, designed starting from the new family of compact thermal camera cores launched in the market (year 2014) by FLIR, Lepton® [8]. The development of the thermal endoscope device was particularly challenging due to the compactness requirement: specific sensors had to be selected, and *ad hoc* design of the case, the electronics, and the control unit was required. The thermal camera core is the FLIR Lepton [8] (order of the cost 150 €), with the specifications in Table 1. It mounts an uncooled bolometer that is sensitive in the spectral range 8μm to 14μm with a Noise Equivalent Temperature Difference (NDTE) of $\pm$ 50mK, allowing the measurement of a temperature range -10°C to 140°C with an acquisition frame rate of 8.6Hz. Low cost thermal camera cores mount fixed-focus lenses (silicon or calcogenide). The lens of the Lepton family is a f/1.1 silicon doublet, the depth of field is 10cm to infinity for the 2.x model and 28cm to infinity for the 3.x model.

The LWIR spectral band, the NDTE, and the frame rate were retained suitable for real time monitoring of the temperature in typical nondestructive testing applications, especially on delicate materials, e.g., artworks and biological samples, where there are neither high temperatures nor large and fast temperature gradients. The other spectral range employed in thermography, the Mid Wave Infrared (MWIR) band from 3μm to 5μm, is needed to inspect objects at high temperatures. However, MWIR technology is very expensive, often based on cooled sensors, and small compact camera cores are not available nowadays.

Table 1
Comparison of the nominal characteristics of the small-size LWIR camera core.

Features	Lepton 2.0 and 2.5	Lepton 3.0 and 3.5	Micro Core	Mosaic Core
Resolution pixels	80×60	160×120	200×150	200×150 or 320×240
Pixel pitch [μm]	17	12	12	12
Size [mm] (L×W×H)	11.7×10.5×6.4 and 12.7×11.5×6.8	12.7×11.5×6.8	8×11×8	10×20×21 or 23×20×21
Dynamic Range [°C]	-10 to 450	-10 to 450	-20 to 300	-40 to 330
Spectral Range [μm]	8 to 14	8 to 14	7.8 to 14	7.8 to 14
Horizontal Field of View	51°	57°	61°	15° to 105°
Thermal Sensitivity [mK]	< 50	< 50	< 100	< 100
Frame Rate [Hz]	8.6	8.7	< 9	< 9 or up to 32
Pixel depth	8/14-bit	8/14-bit	16/32-bit	16/32-bit
Operating Power [mW]	150	150	300	300
Control Interface	I2C	I2C	USB	USB
Video Interface	SPI	SPI	USB	USB
Radiometric	No/Yes(2.5)	No/Yes(3.5)	Yes	Yes
Producer	FLIR	FLIR	Seek Thermal	Seek Thermal

Table 1 compares the small-sized LWIR camera cores available on the market, depicted in Fig. 1. Lepton 2.x and Lepton 3.x differ in the size of the sensor, both available with radiometric capability. An alternative technology is Seek Thermal (presented in December 2019) that embeds two low-cost and compact OEM camera cores, the Micro Core™ and the Mosaic Core™. All these sensors are potentially good candidates for developing a thermal endoscope with a good resolution. Some restrictions on the dimensions might be imposed in specific applications, such as for example laparoscopic surgery with access points (trocar) that have 15mm diameter.

As the primary objective was to develop a compact system with the best characteristics for endoscopic applications, the dimensions of the thermal probe comprehensive of both camera core and electronics had to be kept as small as possible by customizing a miniaturized electronics. In fact, the commercial breakout boards and interface card kit for the above thermal sensors have dimensions and shape not suitable for an endoscope.

The developed endoscope has a cylindrical casing with an external diameter of 15mm and 16mm for the version with the shutter. The system was designed with frontal or lateral aperture, for different image acquisition setups. As proof of concept, we created the thermal endoscope with rigid and flexible casing, using plastic and/or metal material, according to the needs. The prototypes are shown in Fig. 2.

The list below summarizes the main characteristics of the thermal endoscope:

- The device allows endoscopic thermography, which is a novel nondestructive testing tool. The main application is thermal monitoring in laparoscopic electrosurgery.
- The small size of the final device suits applications in different fields where larger traditional thermography equipment would be impossible to use, e.g., thermal testing for fault detection and condition monitoring in difficult to access spaces. The device could be potentially useful for diagnostics in heritage science.
- The endoscope records the thermal radiation in a 2D map in real-time, enabling spatio-temporal monitoring.
- Recorded data can be easily sent to and viewed in a computer such as Raspberry Pi 3 using the developed Infrared Vision Software.

Design files

(a) Lepton® (b) Micro Core™ (c) Mosaic Core™

Fig. 1. Small-sized LWIR camera cores. Pictures are not in scale.

Fig. 2. Thermal Endoscope System prototypes assembled, for frontal and lateral vision.

2.1. Miniaturized breakout board

To reduce the size of the breakout board as much as possible and allow to embed both camera core and electronics in the endoscope, two solutions were specifically designed and implemented. The first solution included two printed circuit boards (PCB) connected to each other, one orthogonal to the other, with the infrared sensor soldered on the first component and the electronics on the other, as shown in Fig. 3(a). The second solution involved the development of a single miniaturized breakout board along the length that is not constrained by the internal diameter of the endoscope, with the infrared sensor positioned next to the electronic components, as shown in Fig. 3(b).

The schematics of the fabricated PCBs are available in the repository zenodo.org, under the GNU GPL open source license.

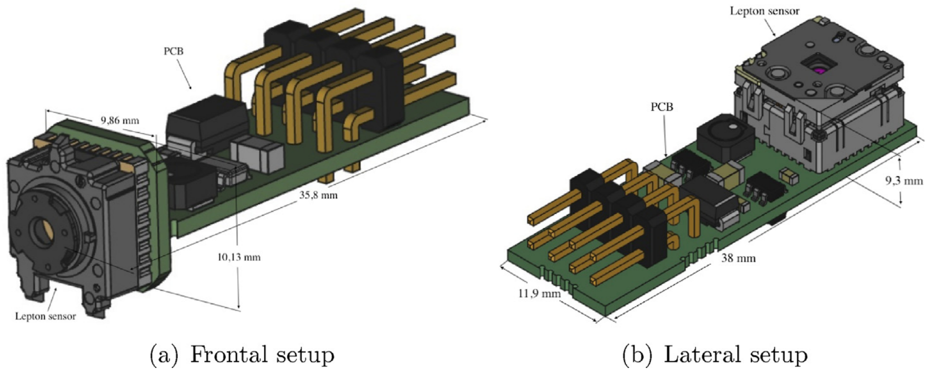


Fig. 3. CAD of the breakout board and infrared sensor connected in a different scheme: (a) for frontal acquisition, on the longitudinal axis of the endoscope; (b) for lateral acquisition.

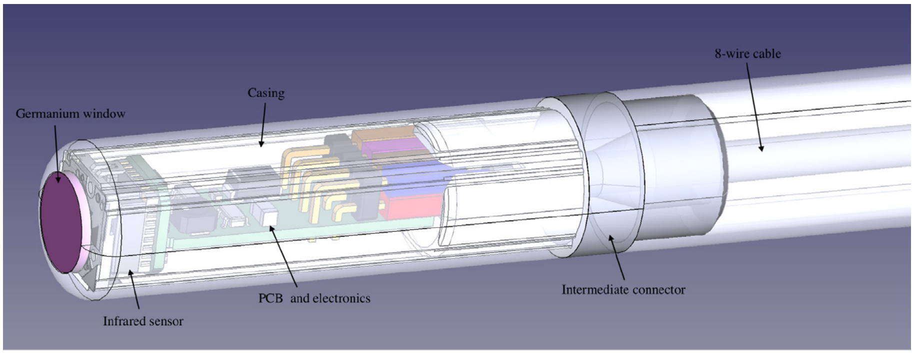
2.2. Casing structure

The envelope structures were designed and built with also the function of supporting the internal positioning of the electronics with mounted the Lepton camera, and the additional optical window. This latter was designed of a material optically transparent in the LWIR range, in the specific, the endoscope mounts a Germanium (Ge) of 10mm diameter from Edmund Optics.

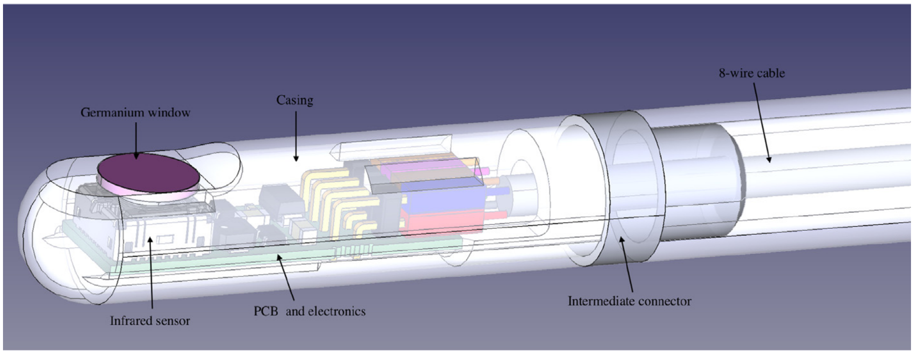
Fig. 4 shows the sketch of the two different assembling schemes for the thermal endoscope, with frontal or lateral vision.

The casing can be made of different materials depending on the application field and the budget available. For medical use, stainless steel or titanium should be used, while for nondestructive testing in engineering, plastics can be used to lower the costs. The 3D printing of the casing was not the best solution because the production of the cylindrical structure by additive manufacturing caused a lower robustness and an uneven surface finish. Moreover, the standard 3D printers were limited regarding the maximum size of the printed object, and the final cost was higher than some pre-fabricated products. Conversely, a very effective and less expensive solution was the 3D printing of the customized supports designed for positioning the components, i.e. the electronics, the sensor, and the optical Ge window.

The endoscope casing is 3D printable from the CAD files available in the repository zenodo.org.



(a) Frontal setup



(b) Lateral setup

Fig. 4. CAD of the prototype assembling. The core with the infrared sensor mounted on the PCB is positioned inside the support casing.

2.3. Optical window

The optical window for the endoscope was chosen on the basis of the nominal transmission of the substrates in the LWIR region and considering the suitability of their thermal properties for the laparoscopic humid environment. Hazardous and delicate materials were not suitable; attention should be paid to the presence of coating, unknown materials, that is used to improve the performance. Looking at the available commercial components, a trade-off among cost and performance needs to be considered. For this proof-of-concept of a thermal endoscope the coated Ge window (about one hundred euro) is a suitable compromise.

3. Design files summary

Design filename	File type	Open source license	Location of the file
Frontal endoscope break-out board	CAD (.FCStd)	CERN-OHL-S	zenodo.org
Lateral endoscope break-out board	CAD (.FCStd)	CERN-OHL-S	zenodo.org
Frontal endoscope casing	CAD (.STEP)	CERN-OHL-S	zenodo.org
Lateral endoscope casing	CAD (.STEP)	CERN-OHL-S	zenodo.org
Pin-out diagram	.png	CERN-OHL-S	zenodo.org
Infrared Vision Software	C++ (.exe)	BSD-2-Clause “Simplified”	zenodo.org
User Guide	(.txt)	BSD-2-Clause ”Simplified”	zenodo.org

Bill of materials

- The *Frontal break-out board* is the schematics of the miniaturized PCB for mounting the camera with frontal vision.
- The *Lateral break-out board* is the schematics of the miniaturized PCB for mounting the camera with lateral vision.

- The *Frontal endoscope casing* is the technical drawing of the casing with the frontal aperture for the Ge window.
- The *Lateral endoscope casing* is the technical drawing of the casing with the lateral aperture for the Ge window
- The *Pin-out diagram* is the connection scheme for the miniaturized break-out board and the Lepton type LWIR sensor.
- The *Infrared Vision Software* is the developed software for controlling the camera and acquiring the thermograms.
- *User Guide* is a comprehensive manual of the thermal endoscope system.

4. Bill of materials summary

ID	Component	Number	Cost per unit (Euro)	Source of materials	Material type
c1	Kit Raspberry Pi 3 B	1	99.27	rs-online	Electronics
c2	Micro SD memory, 32 Gb	1	11.38	rs-online	Electronics
c3	Germanium window ø 10 mm	1	113	edmundoptics	Optics
c4	Tube ø 15mm or 16mm	1	20	ebay	Acrylic/Metal
c5	Lepton core	1	150	FLIR	LWIR sensor
c6	Custom Breakout Board	1	50	pcbway	PCB electronics
c7	8-wire cable	1	9.49	amazon.com	Electronics
c8	Pin Header Connector	1	10.58	amazon.com	Electronics
c9	8-pin Plug Metal GX16 Connector	1	9.99	amazon.com	Electronics
c10	Raspberry Pi LCD Touch Screen	1	56.47	rs-online	Electronics

5. Build instructions

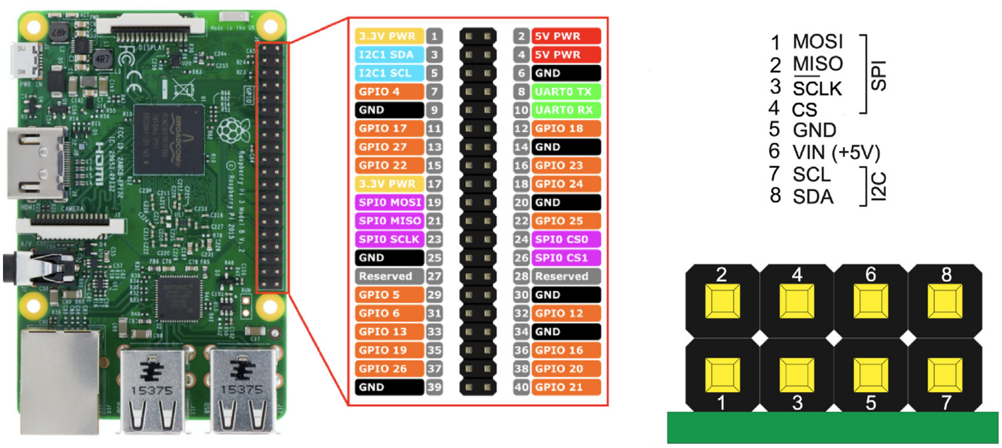
5.1. Hardware assembly

The assembly of the PCB and the sensor can be made according to the drawing in Fig. 3. The assembly of the lateral endoscope only requires to insert the Lepton sensor in the socket, while manual soldering is necessary in the frontal endoscope setup.

Next step consists in passing the 8-wire cable inside the tubular casing, through the hole in the intermediate connector, and connecting one side to the pins on the PCB, the other side to the pins on the Raspberry as described below. Finally, the endoscopic core is inserted inside the endoscope casing and the germanium window positioned (see Fig. 4).

5.2. Connecting to Raspberry Pi

The miniaturized break-out board pins can be connected to devices supporting SPI (Serial Peripheral Interface) and I2C (Inter Integrated Circuit) protocols with enough processing power. In Fig. 5 and Table 2 we give the pin-out schematics



(a) Raspberry Pi 3 (b) Lepton PCB

Fig. 5. Pinouts description of the components.

Table 2
Pinouts connection between Lepton PCB and Raspberry Pi.

GPIO Raspberry Pi 3	Lepton PCB
19 SPI0 MOSI	1 MOSI
21 SPI0 MISO	2 MISO
23 SPI0 SCLK	3 SCLK
26 SPI0 CS1	4 CS
6 GND	5 GND
4 PWR (+5V)	6 VIN (+5V)
5 I2C1 SCL	7 SCL
3 I2C1 SDA	8 SDA

for connecting the endoscope to the Raspberry Pi 3. The Pi 3 is a single board computer, which has a 64-bit, 1.2 GHz quad-core ARM Cortex-A53 processor. The board is equipped with 1 GB RAM and a 40-pin GPIO that allow to exchange data and control other devices via SPI and I2C. The Lepton uses the SPI protocol for the streaming of the acquired raw thermal data, while the I2C protocol is used for accessing the specific camera function, for example the shuttering for flat-fielding calibration.

5.3. Configuration

To enable the SPI and I2C protocols, the Raspberry Pi should be set as explained in the *User Guide*. Download the *Infrared Vision Software* (.exe file) from the repository, and before launching it, check that the execute permission is granted to the user. After the configurations and permission have been set, it is possible to run the program.

6. Operation instructions

Once the endoscope is assembled and connected to the Raspberry, it is possible to run the Infrared Vision Software for real-time acquisition and visualization of thermal images. Before carrying out the measurements, it is recommended to wait a few minutes after running the program for the sensor to reach the working temperature.

6.1. The Infrared Vision Software

The Infrared Vision Software is implemented in C++ through the use of the Qt Creator platform. The software allows the user to control the acquisition of the thermal frames with the endoscope as well as to set the parameters required in standard thermography measurements, described later (Section 6.2).

The thermal maps are visualized in real-time, with the possibility of selecting the range of temperatures and optimizing the colormap to the dynamics of the target object. The maximum and minimum temperature of the framed scene are plotted over time. The user interface is shown in Fig. 6, the main functions of the software are listed below.

`REC`. It records the raw data or, only for Lepton X.5, also the temperature (Kelvin) as a series of frames, writing a `.bin` file and a separate `.txt` file with the metadata.
`Photo`. It grabs the single thermal frame, and saves it in `.png` format.
`LUT`. The LookUp Table function allows to set and to lock the range of temperature for the visualization of the thermal sequence, i.e., the colormap. The user interactively operates on the colorbar.
`FFC`. The Flat-Field Correction function allows the user to trigger manually the in–house flat-fielding operation, based on shuttering, to compensate for temperature variation, pixel-to-pixel non uniformity, lens effects.
`Environment Settings`. To set the experimental parameters for a precise temperature measurement. These parameters are needed for the temperature conversion calculus of the raw data.

To record a thermal dataset, optionally enter the name of the file (`File names`) and press the `REC` button. The physical meaning of the thermal signal acquired by the camera is detailed below.

The Lepton sensors equipped with shutter perform the flat-field correction automatically, every 3 min or if camera temperature variation exceeds 1.5°C [18]. The `FFC` button allows to perform this operation manually.

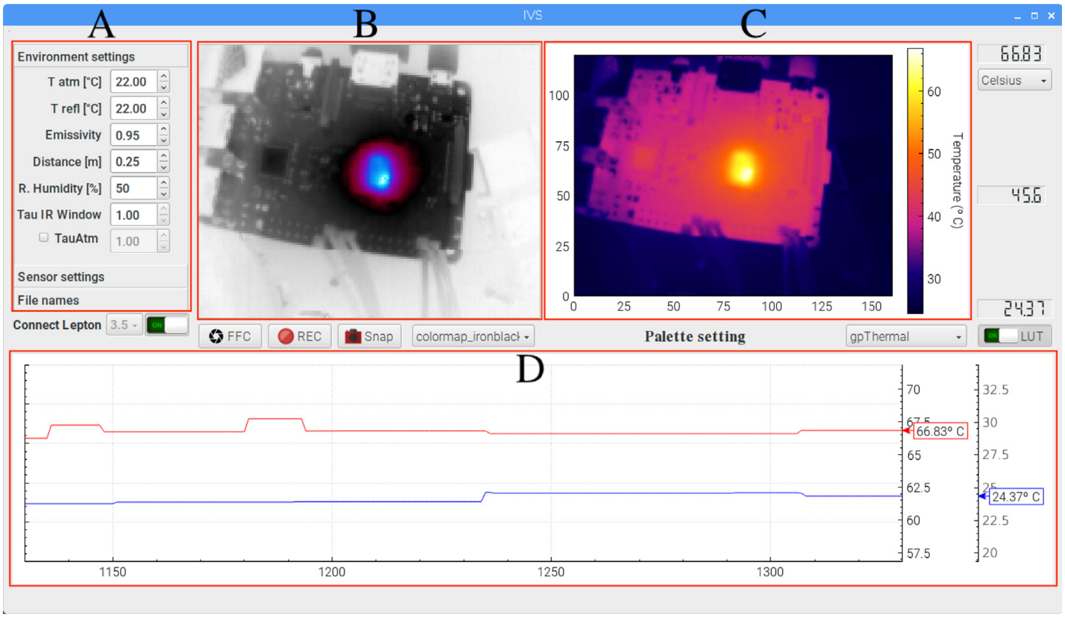


Fig. 6. Infrared Vision Software user interface. [A] Setting parameters; [B] raw data camera output; the thermal image [C] is interpolated to improve the vision, it allows to zoom and set the colormap; temperature range and mean are indicated, T_{max} and T_{min} are plotted over time [D].

6.2. The thermographic measurement

During a measurement, the thermal endoscope collects a total amount of LWIR radiation, schematized in Fig. 7, which includes the following contributions [1]:

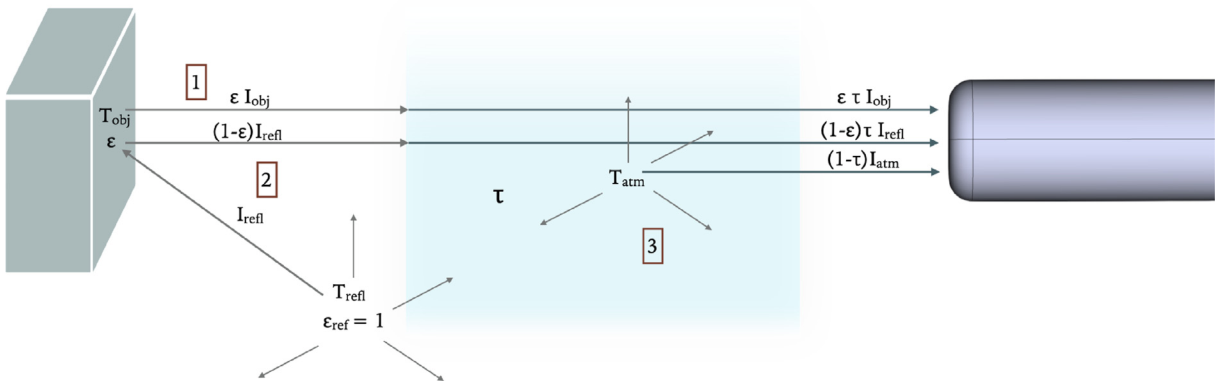


Fig. 7. Sketch of a thermographic measurement in real-environment: the total signal collected by the camera comes from object emission [1], object reflections [2], and atmosphere emission [3].

1. emission from the object, related to its temperature T_{obj} and dependent on surface emissivity ε. It is computed as $\tau\varepsilon I(T_{obj})$, where τ is the medium transmissivity, and the function $I(T)$ comes from the calibration of the camera, i.e., the radiation collected from a blackbody radiator.
2. emission from environment sources reflected by the object. It is computed from the reflectivity $(1-\varepsilon)$ and an effective environment temperature, called the reflected temperature T_{ref}, therefore $\tau(1-\varepsilon)I(T_{ref})$.
3. emission from the atmosphere, computed as $(1-\tau)I(T_{atm})$.

The parameters $\varepsilon, T_{ref}, T_{atm}$, distance, and relative humidity must be input for the specific experiment (`Environment Settings`); the transmission coefficient τ is calculated by the software using the FLIR formula available in [19]. These parameters affect the calculation of the object temperature from raw thermal data. The accuracy in raw to temperature conversion depends on the calibration of the camera, provided by the manufacturer. The calibration of a thermal camera requires adequate equipment to perform measurements in controlled conditions of certified blackbody radiators.

6.3. Thermal emissivity of materials

The surface of a target object has a specific thermal emissivity that varies with the materials, the surface roughness, as well as the temperature of the object and the radiation wavelength. The emissivity coefficients of common materials, including human tissues, are reported in Table 3. Many other materials can be found in the online Engineering ToolBox (2003) [20].

Table 3
Emissivity of some common materials ($T = 300$K) in the LWIR range.

Materials	Emissivity (ε)
Black body	1
Skin, human	0.95–0.98
Burnt skin	0.97
Human bone	0.96
Plaster	0.98
Black Silicone Paint	0.93
Plant leaves	0.96
Water	0.95–0.96
White paper	0.93
Asphalt	0.93
Concrete	0.85
Wood	0.8–0.95
Aluminum Foil	0.04
Silver Polished	0.02–0.03

7. Validation

7.1. Thermal endoscope applications: surgery context

Electrosurgical devices used in laparoscopic surgery exploit the passage of alternate radiofrequency current in the tissues to obtain cutting and coagulation. Unfortunately, excessive accumulation of heat in the region surrounding the electrosurgery site may cause an irreversible damage to the tissues. Cell death is instantaneous above a temperature of 60°C. When using the electrosurgical unit it is essential for the surgeon to keep the temperature below the threshold of damage in the unwanted regions; however, minimal heat dispersion in tissues adjacent to the surgery site is inevitable. For this reason, monitoring the temperature distribution in real time is important.

The thermal endoscope, configured with the Lepton 2 sensor and the coated Ge window, has been evaluated for possible surgical applications in the laparoscopic CO2-rich environment with the instrument inserted into a surgical trocar of 15mm in diameter. Fig. 8 shows the spectral sensibility of the sensor in relation to the transmittance of Ge window and the environment. An experimental model of artificial pneumoperitoneum was built, operating in controlled CO2 atmosphere, constant temperature and pressure, and the thermal endoscope was tested as a tool for monitoring the thermal effects of electrosurgery (Fig. 9(a)). Thanks to the 2D mapping of the surface, the device allowed to evaluate in real time the diffusion of heat to the tissues to prevent possible thermal damage (Fig. 9(b)).

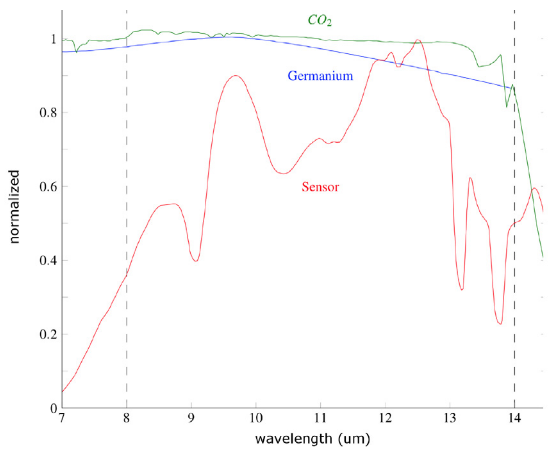
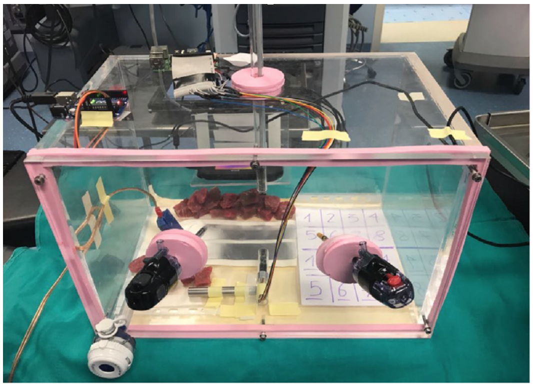
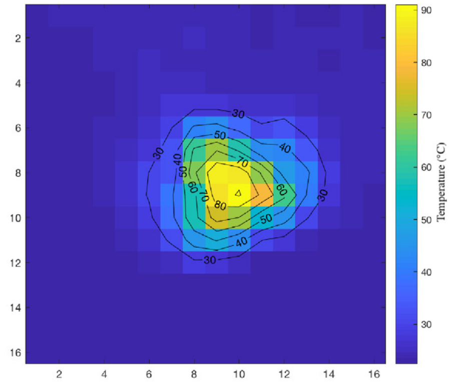


Fig. 8. Nominal spectral sensitivity of the sensor, transmittance of the coated Ge window, and transmittance of CO2 environment.



(a) Laparoscopy simulator [10].



(b) Contour of thermal injury area.

Fig. 9. Experimental setup and example of thermal distribution map (detail) obtained with the endoscope during electrosurgery in an artificial model.

Besides the desirable in-process application during surgery, thermal analysis could be important in the optimization of the electrosurgery procedures using laboratory mannequins. For further details see the publications [10,11], in which the developed thermal endoscope was effectively used to investigate the effect of thermal spread during bipolar cauterizing in an artificial model. This preliminary study showed that the area of thermal distribution is related with the delivered energy, the histopathological analysis showed a correlation between necrotic area and the area of energy delivered.

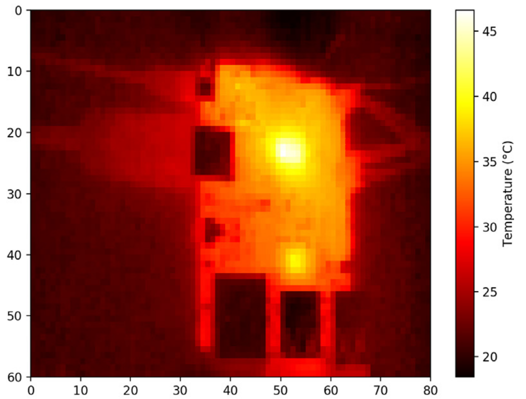
7.2. Further thermal endoscope applications: versatile scene and confined space measurements

In the field of nondestructive testing, the thermal endoscope is particularly suitable for performing measurements in cases where a versatile positioning of the camera is necessary, such as the thermography of small 3D objects and/or in confined and difficult to access spaces. An example is the diagnostics of laboratory instrumentation, e.g., the monitoring of the temperature distribution in electronic parts for identifying the spots of overheating. On-field diagnostics can be easily performed without the need to disassemble the inspected device.

The example of the electrical circuit in Fig. 10 shows that the device is suitable for thermal monitoring in such specific cases; the passive measurement can be performed in difficult to access spaces, compatible with the diameter of the endoscope head (down to 15mm). The device is not designed for close-up imaging; however, since the hyperfocal distance is in the order of centimeters, measurements of a versatile scene at small working distances are possible.

The plot in Fig. 11 reports the thermal depth on field analysis for the endoscope Lepton cores, computed following [21]. In case of nondestructive application, where the constraint of the diameter is not mandatory as in the laparoscopy application, the configuration with the Lepton 3 sensor allows better resolution.

(a) Thermal endoscope



(b) Thermogram

Fig. 10. Diagnostics of electronic circuits.

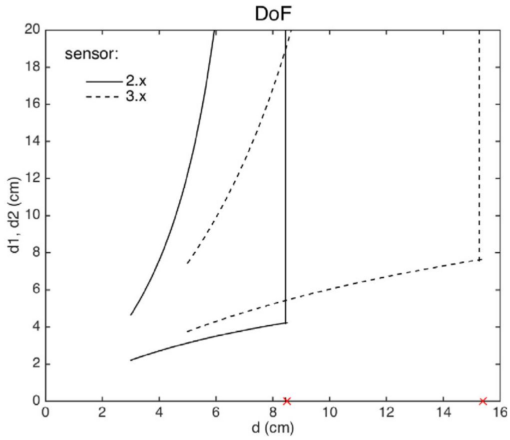


Fig. 11. Depth of field calculation for the Lepton thermal cores, with the lens characteristics in Table 1. The near and far borders (d1 and d2) are plotted against the distance of sharp focus, down about to one third the hyperfocal distance (red cross markers), at which the far distance d2 becomes infinity.

8. Final remarks on the thermal endoscope

We designed a low-cost thermal endoscope suitable for the laparoscopy environment and demonstrated the feasibility in an experimental electrosurgery study. The enclosing case can be built in surgical stainless steel, with dimensions compatible with surgical trocars (15mm). The PCB is miniaturized with the option of lateral/on-axis vision. The protective window of the prototype is in Ge, which is suitable for Lab testing and allows to contain the cost, but diamond-based windows (costly, 2 k euro) are available for the use in clinical applications. The provided software allows controlling the Lepton core. The raw data to temperature conversion takes into account the effect of the optical chain, including the transmission of the protective window and the CO2-rich atmosphere of the laparoscopic environment.

The thermal endoscope can be also used for nondestructive testing in non medical field, e.g., engineering and heritage science. Some considerations can be done for further research and improvements, which were not within the aim of this report:

- A joint use of thermal and visible vision, besides improving the endoscopic navigation and the referencing of the thermal maps, will enable an efficient correction of the thermal emissivity [22]. The last issue is especially important in the industrial field, where materials of variegate thermal emissivity are present.
- The device can be engineered for the clinical use, with a study of the bio-compatibility of the materials used for the cylindrical case and the protective optical window.
- The endoscope can be used for active thermography by designing suitable excitation hardware. The application could be of interest in the nondestructive field, e.g., material inspection and structural analysis, from engineering to cultural heritage.

Ethics statements

This work did not involve the use of human or animal subjects.

CRediT authorship contribution statement

Dumitru Scutelnic: Investigation, Software, Data curation, Writing - original draft. **Giacomo Marchioro:** Investigation, Software, Data curation. **Salvatore Siracusano:** Conceptualization, Methodology. **Paolo Fiorini:** Conceptualization, Methodology. **Riccardo Muradore:** Conceptualization, Methodology, Writing - review & editing. **Claudia Daffara:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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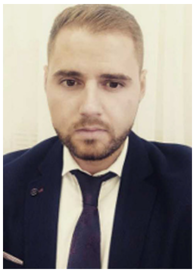

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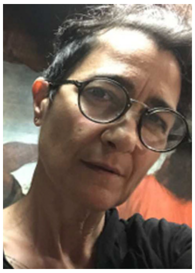

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