Uncooled MWIR PbSe technology outperforms CMOS in RT closed-loop control and monitoring of laser processing

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Abstract: We report novel findings in the field of real time closed-loop control and monitoring of laser processing. Using a novel coaxial multispectral imaging system, we compare the performance of uncooled MWIR PbSe sensors to visible CMOS sensors. Comparison is performed in two different tasks: closed-loop control of laser cladding and monitoring of laser welding. In both cases, PbSe imagers show a clear advantage in terms of reliability and accuracy as for the performance achieved using the same state-of-the-art processing algorithms on images acquired simultaneously during the same laser processing trials.
OCIS codes: (150.5495) Process Monitoring and Control; (110.3080) Infrared Imaging; (140.3390) Laser materials processing;

1. Introduction

Coaxial imaging of the melt pool in laser processing has enabled a number of approaches to real time closed-loop control and monitoring of different laser processing applications. CMOS technology has dominated this research area with most relevant works appearing during the last decade. As a result, the few imaging commercial systems available for this purpose are mostly based on CMOS sensors. However, these sensors present a number of issues that seriously limit their performance in practical settings. Firstly, they are sensitive only to wavelengths under 1 µm hardly seeing thermal emission from bodies at temperatures under 900ºC, thus being blind to typical cooling processes (e.g. in laser cladding). Secondly, they suffer much in the presence of reflections and bright [1] from projections or powder, due to their high sensitivity (in the visible range). Moreover, radiance increases much faster with body temperature in the visible range at process temperatures than in the IR. As a result, a very limited dynamic range is available for process observation. The images acquired are practically binary with little information about actual heat distribution in space.

In the last years novel uncooled PbSe imagers that work in the MWIR spectral range (1-5 µm wavelength) have appeared[1] with the potential to being game changers in this field. Being sensitive in the MWIR means that these sensors can see radiance emitted at much lower temperatures -down to 100ºC- and they can make a better use of their dynamic range, even at high temperatures. Otherwise, these sensors are really fast with some models featuring up to 10 kHz acquisition rates. Due to these features, uncooled MWIR sensors have been proposed for their use in the observation of different industrial processes [1] - [4]. Their limitation appears to be a low spatial resolution with latest models featuring 128x128 pixels, still far from reaching the Mpx capability of visible range sensors.

In this work, we report on a systematic comparison of performance of CMOS and PbSe technology at work. Using a novel coaxial multispectral imaging approach (Figure 1), we compare the performance of image-based control and monitoring algorithms when fed with images acquired with uncooled MWIR PbSe sensors to that achieved by visible CMOS sensors. The comparison is tackled in the context of real time monitoring of laser welding and closed-loop control of laser metal deposition, performed independently at Fraunhofer ILT and AIMEN laser applications center. Results from both cases consistently rank PbSe clearly over CMOS, finding no advantage from the higher spatial resolution capability of the last one. Moreover, both scenarios provide complementary information on the advantages of uncooled MWIR sensors and valuable insights for the development of novel approaches to RT closed-loop control and monitoring of laser processing.

2. Real-Time monitoring of laser welding

In the welding case, the goal of the monitoring system is the detection and identification of relevant defects (e.g. false friend, no seam, open pore, seam width exceeded) in real time. With this aim, a battery of feature extraction methods was designed and implemented. Such features were extracted from images acquired by a CMOS and two

[1] http://www.niteurope.com/portfolio-item/catalogo-de-productos/?lang=en

PbSe sensors working at different spectral bands. Besides measuring prediction accuracy, an analysis was made in order to determine the relative contribution of features to the predictive capability of the system.

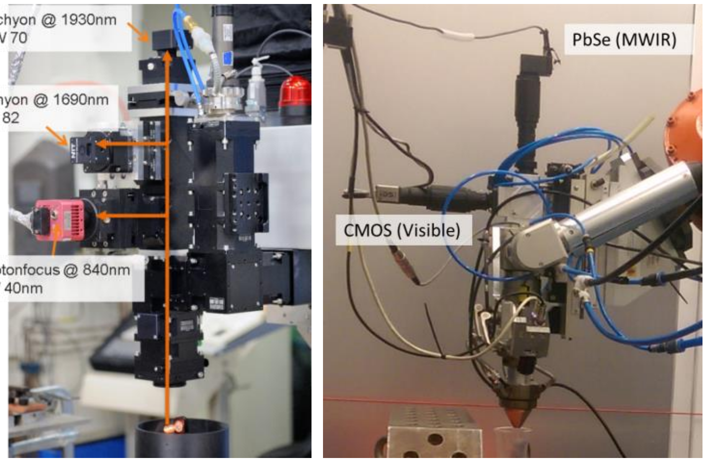

Figure 1 Coaxial setups for multispectral imaging for RT monitoring of laser welding at Fraunhofer ILT (left) and for closed-loop control of laser metal deposition at AIMEN laser applications center (right)

Figure 2 illustrates the outcome of this benchmarking effort. The most important features are extracted from MWIR images, with the best features from the visible-NIR range appearing at the bottom of this rank of best 46 features.

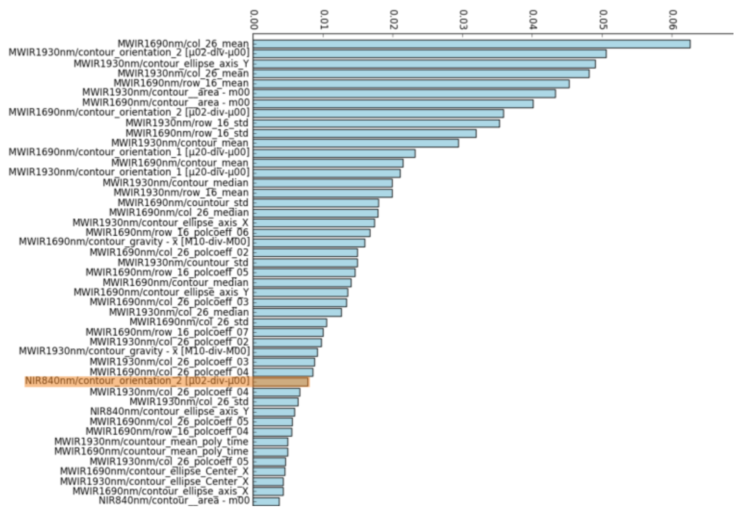

Figure 2 46 top tesults of benchmarking 40 features extracted from images acquired with two MWIR (PbSe) and one visible-NIR (CMOS) sensors observing the same welding track. The top performing CMOS feature is highlighted.

3. Real-time closed loop control of laser metal deposition

For this analysis, we have used functions available in OpenLMD[2] to perform multispectral process monitoring and closed-loop control of a laser cladding process [5].

Looking at the images acquired (Figure 3), we can see the problems of visible range images -acquired with the CMOS sensor- to capture the spatial distribution of heat. Since radiance increases sharply with temperature in the visible range, the image reaches saturation at the boundary of the melt pool and gives practically no response outside. Otherwise, MWIR images can handle the distribution of temperatures with the available dynamic range.

We also look at the measured values of melt pool width and height, widely recognized as suitable reference signals for closed-loop control of laser power in a cladding process. Comparing variability in measurements of width and height of the melt pool using the same algorithms on different sequences acquired from the same clad tracks, we find that the relative variability ($2\sigma/\mu$) observed from visible range images is systematically about 15% for width and 17% for height, while the same values measured in MWIR images go down to 7% and 9% respectively. This

[2] http://openlmd.github.io/

difference is also reflected in the magnitude and frequency of single peaks in the signals that are not apparently linked to the real dimension of the melt pool. This means that the additional spatial resolution available in the images from the visible range does not add anything but noise compared to the images acquired in the MWIR range.

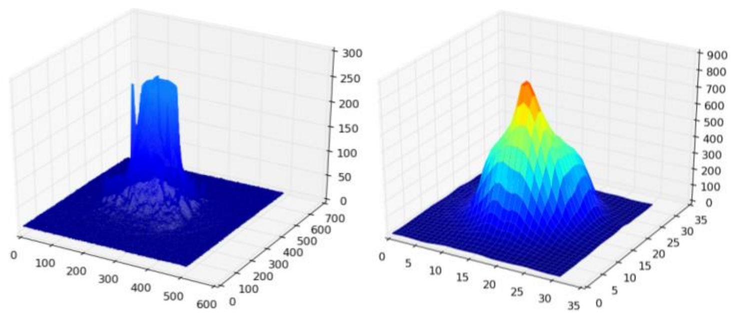

Figure 3 Distribution of digital levels delivered by a CMOS sensor (left) normalized to 255, compared to a PbSe sensor (right) normalized to 1024, when observing the melt pool through the same optical path at the same time.

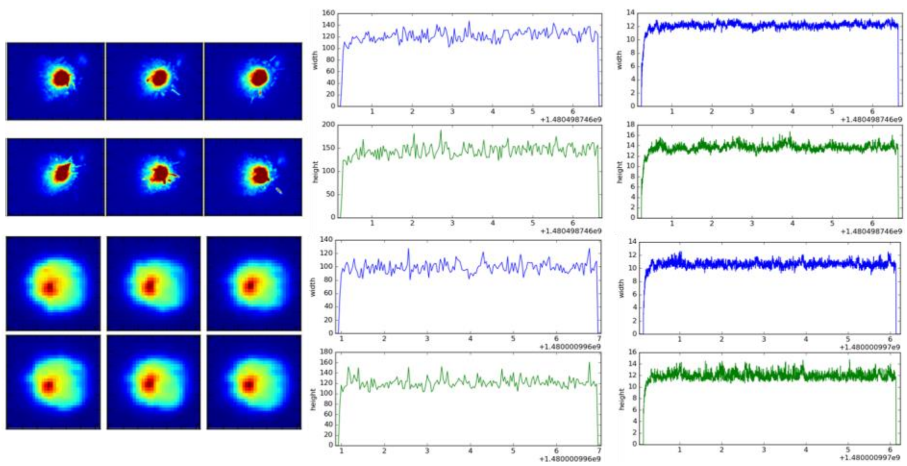

Figure 4 Examples of 6 frames acquired by a CMOS sensor (left top) and the corresponding frames simultaneously acquired by a PbSe FPA (left bottom) and measures of height and width of the melt pool against time extracted from CMOS images (center) and PbSe images (right) using the same algorithms on two image sequences of the same clad track. CMOS shows far less stable.

4. Conclusions

We have shown evidence of clear advantages of uncooled MWIR PbSe technology compared to CMOS in the visible range for image-based monitoring and control of laser processing. MWIR images capture better the spatial distribution of heat and do not suffer from noise related to reflections or bright. Overall, PbSe sensor technology enables strong improvements in the accuracy and reliability of monitoring and closed-loop control of laser processing, compared to systems based on CMOS.

5. Acknowledgments

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6. References

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[5]. Jorge Rodríguez-Araújo, Antón García-Díaz OpenLMD, multimodal monitoring and control of LMD processing,*SPIE Photonics West* 2017.

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System specifications

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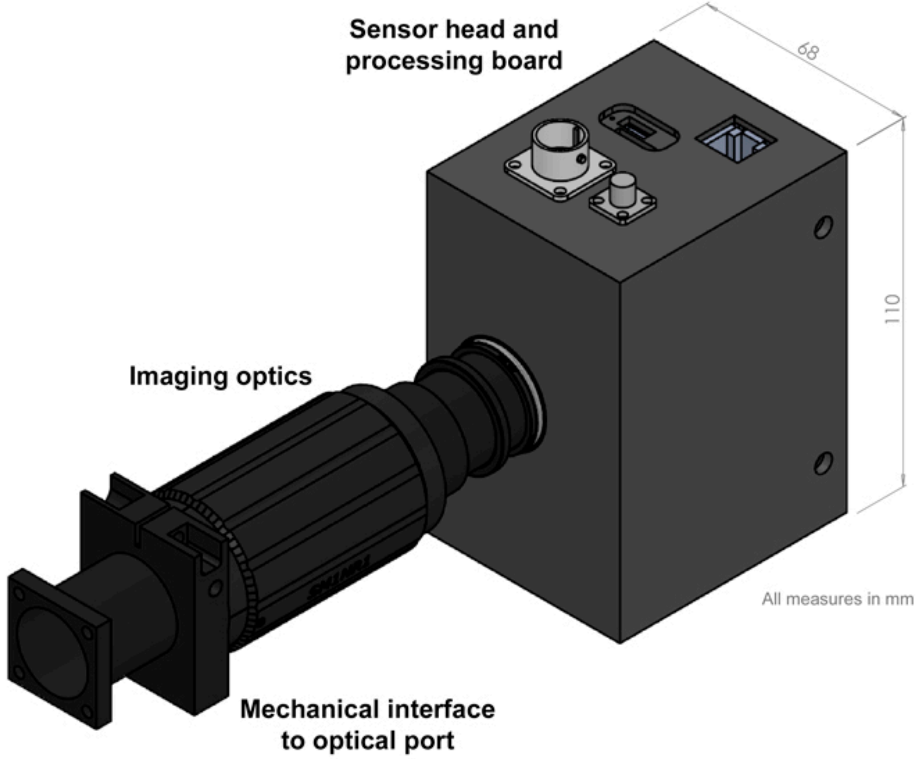
General information

Description	System for closed-loop control of the laser power applied to metal Laser Additive Manufacturing processes such as LMD (Laser Melt Deposition) or cladding, through the real-time on-axis infrared monitoring of the melt-pool, to maintain its geometrical parameters during the complete process
Components	Sensor head with real-time processing electronics and connectors Imaging lens Mechanical interface to the optical port in laser head Software for system configuration Metal plate for optical calibration
Process compatibility	Continuous LMD process (Laser Melt Deposition) Discrete cladding processes (Tracks)
Optical compatibility	For the correct operation of the control system, it's necessary that the optical components installed inside the laser head allow the transmission of infrared signal (above 1.1 um) from the process area to the optical port installed in the laser head. The system is not compatible with lenses type BK7 installed in the optical path.
Material compatibility	Steel powder Stainless steel powder Stellite powder Others
Laser power control unit requirements	Analog signal control, 0 VDC – 10 VDC

CLAMIR - Control for LAM process with Infrared imaging



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Hardware

General specifications

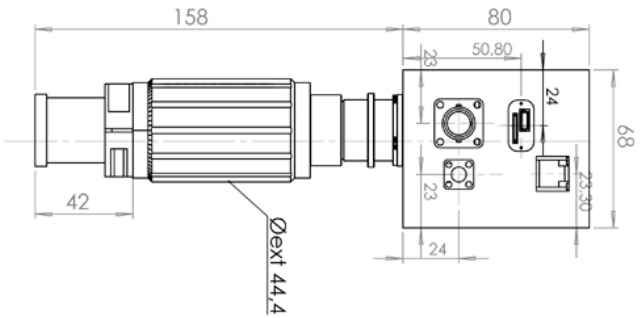
Dimensions (mm)	Sensor / processing head: 80 mm x 68 mm x 110 mm Imaging lens: 116 mm length, 44.4 mm diameter (max) Mechanical interface to laser head: 40 mm x 40 mm x 42 mm
Weight	1 kg
Power supply	5 VDC
Power	Less than 20 W

Infrared camera

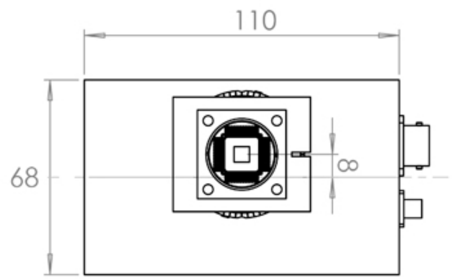
FPA material	VPD PbSe
Resolution	32×32 (total: 1024 pixels)
Pixel size	135 um x 135 um
Spectral response	MWIR (1 – 5 um)
Response time (typ)	10 us
Frame rate	1000 images per second
Bit depth	10 bits

CLAMIR - Control for LAM process with Infrared imaging

Dimensions of the system



All measures in mm



Front view
All measures in mm

CLAMIR – Dimensions (top and front view)

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Hardware

Imaging lens

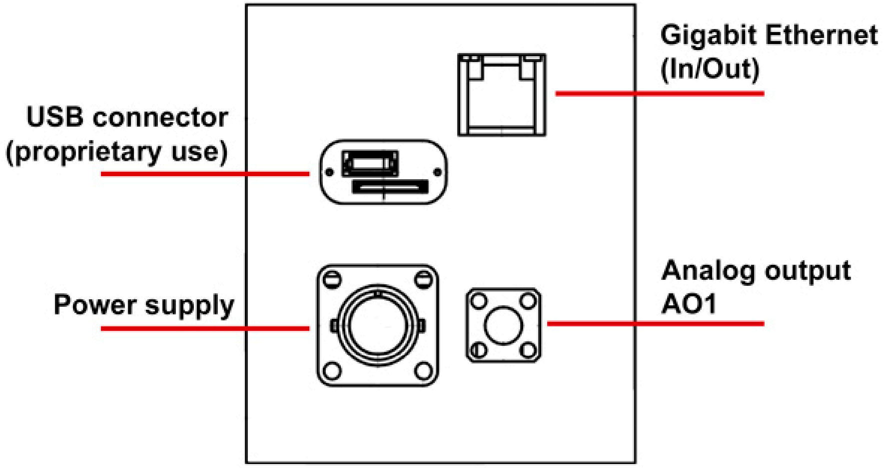
General specifications	Embedded, non-dettachable
Material	CaF_2
Focal length	100 mm
Focus	Manual focus mechanism
Mechanical interface	Adaptable to the laser head
Field of View	Dependent on the optical system installed in the laser head and diameter of the noozle
Resolution per pixel (iFoR)	Dependent on the optical system installed in the laser head and diameter of the noozle

Interfaces

Laser power control	Analog signal, 0 – 10 VDC BNC-type connector
Communication interface	Gigabit Ethernet (RJ-45)
IP address	Configurable

CLAMIR - Control for LAM process with Infrared imaging

System connections



CLAMIR – Interface connections

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Software

Description

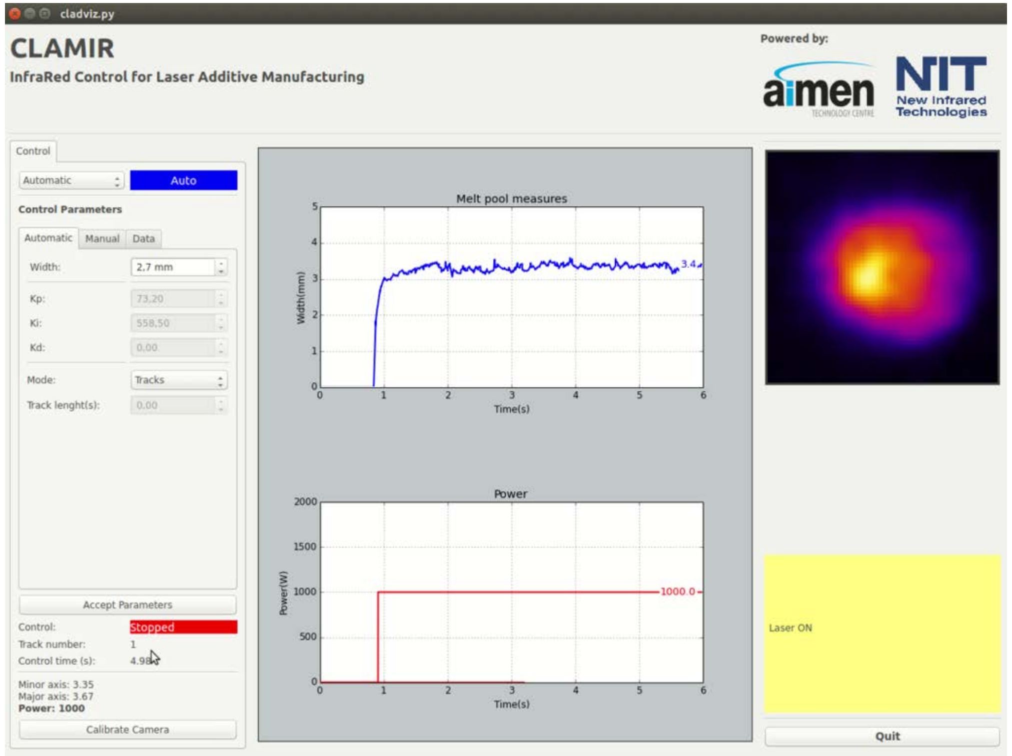
Software	CLAMIR control SW v.1.0 (embedded in Linux virtual machine)
Minimum requirements	PC with processor i5 RAM memory: 8 GB Hard disk available: 1 GB O.S.: Windows 7
Additional components required	VMWare Workstation Player

Process control

Process control	Selectable modes: Automatic, Manual
Process configuration	Selectable modes: Tracks, Continuous
Control parameters	Initial laser power Track length (Tracks mode)
Indicators	Melt pool width Laser power Infrared image Laser status

Other functions

Calibration of infrared camera	On demand (not allowed during automatic process control)
Data record	Under implementation



CLAMIR – Automatic mode with constant laser power

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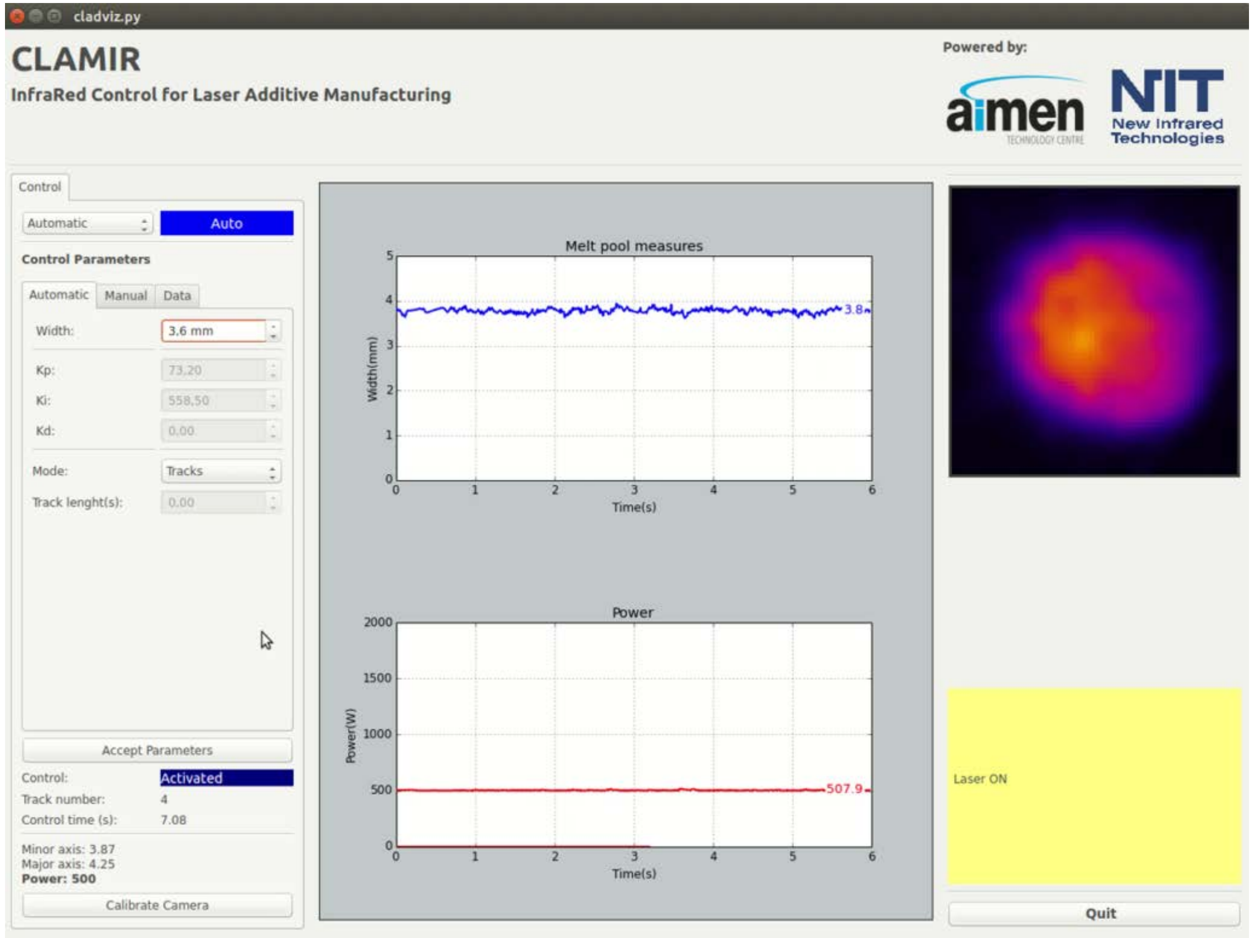
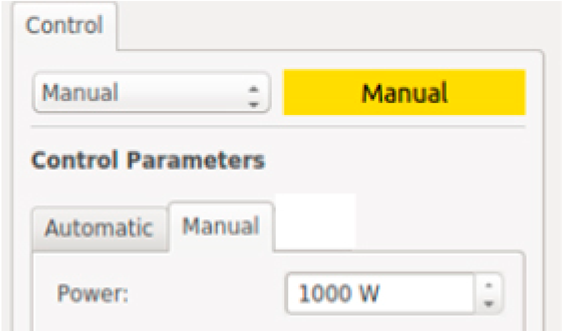
Software screenshots

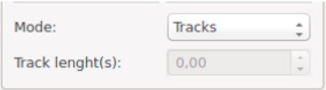


CLAMIR – Automatic process control



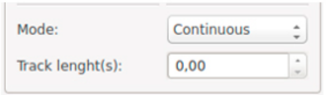
CLAMIR – Manual control of the laser power

Single tracks mode



Using this mode the S/W will automatically detect the beginning and end of each track.

Continuous mode



Using this mode the S/W will automatically detect the beginning of the process.

CLAMIR – Selection of process mode

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