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## An AR based Digital Twin for Laser based manufacturing process monitoring

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### Abstract

In the modern manufacturing era, monitoring systems evolve towards sophistication and complexity, introducing numerous challenges in the feasibility, the assembly, the efficiency, and the integration of process monitoring devices on the relative equipment. The current work introduces a novel digital AR based digital twin framework, enabling real-time information analysis and advanced data visualization of monitoring performance on process monitoring systems. The main goal of the current research is to provide a dynamic AR environment, capable of simulating the main system's functionalities, minimizing the configuration time, cost, and inaccuracies. The case study introduced regards the configuration of optics for thermal emissions capturing from laser based processes, while the coexistence with other aspects of monitoring, such as in the case of Remote Laser Welding is considered. The usability of the tool is shown and visualization issues encountered are presented.

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**Keywords:** Monitoring Systems; Augmented Reality; Design; Digital Twin

### 1. Introduction

In modern machining, manufacturers utilize laser processes as a thermal-energy-based method that increases the industrial productivity, flexibility and effectiveness [1]. Although laser processing, has been promising in various industrial applications, it provides numerous challenges especially when it comes to the process monitoring and control. Industries spend a massive amount of time and resources towards the quality assessment and control, in a pursuit of delivering high-quality products, while at the same time maintaining low cost and fast response to the market. Process modeling and simulation is utilized, in order to resolve those challenges and provide insight and direction, in advance, over the process results [2].

Additionally, the emergence of technologies and digitalization that takes place into the modern process, allows manufacturers to obtain knowledge upon the process status

seamlessly, and thus rapidly take the right decisions for the future. Quite similarly, the digital twin (DT) concept introduces a virtual model of a process, product or service, promising into robust analysis of data and monitoring of systems, to head off problems before they even occur. Despite the variations on the definitions and applications of a digital twin, within the current study, this concept was simply used as a standalone digital system working independent of the actual environment, in order to simulate and display some of its physical principles and functionalities [3], in real time and in real space (mixed reality).

Different information technologies have been used, supporting the visualization and interaction with those digital manufacturing tools, by means of enabling process engineers, to participate during the process, take actions and monitor information in real-time. Augmented Reality tends to evolve more and more towards that direction, as it

provides an advanced level of visualizations and mobility to the users [4]. AR technologies enable the coexistence of digital and physical objects within a single immersive environment and enable holograms to be projected upon the real-world in a way that keeps the user's interference with the surrounding environment.

To this end, considering the industrial requirements for accurate process monitoring systems, this paper aims in the provision of a DT application that supports the design phase of a monitoring system, using the latest novelties of Augmented Reality. The proposed tool support the configuration and preview of the monitoring system, by means of choosing those components, that more accurately capture all the spectrum of condition indicators, in the lowest cost and minimum setup time possible. Aiming into supporting the multi-spectral thermal camera monitoring techniques, the proposed approach, models the main components of the monitoring system i.e. IR-cameras, laser beams, workpiece, mirrors & filters; and projected within an AR environment, where different physical characteristics of the system are simulated and displayed to the user. The DT environment will enable numerous solution alternatives to be foreseen and tested on the real machine space reducing cost and time on the actual setup of the monitoring modules, by checking interaction with actual surroundings.

## 2. Literature Review

In today's research and manufacturing communities, massive effort has been put into controlling the quality of laser processes. Different simulation techniques have been used in order to improve cost, time, quality etc. through mapping and analyzing the performance indicators of the laser processes [2]. The DT concept as already indicated, is one of the key methodologies in this field [3]. The complexity though of thermal process feature identification, as well as the high computational demand in the optimization of the system, has limited the existing solutions into reducing the model down to a manageable level of parameters. To this end manufacturers rely on high-quality monitoring and control, to provide a flexible and sustainable manufacturing system [5], operating in an automated way, free of errors and defects [6].

Designing and implementing the monitoring system itself is a challenging task, requiring time and resources that frequently needs to be repeated when dealing with a slightly different laser case or machine [7]. Most of those approaches, introduce differences upon the modeling of the heating source and interaction between the laser and the material [8], aiming to provide feedback to the machine within a recurrent endless loop of information exchange. Optical monitoring is mainly used [9], since it provides a valuable source of information to the model, with considerably low cost. This methodology includes mapping the thermal radiation emitted by the workpiece in real-time, and information transmission to the process control interface, working in parallel with the actual process [10]. In this process, the efficiency of the monitoring setup as well as the components' selection actively effect the desired process output [11]. An interesting

challenge to those methodologies, is the identification of the optimal configuration of the equipment, that will be the basis in the following diagnostic operations [12], while control systems will then take place into maintaining a high-quality process outcome [13]. This tasks includes the selection of the thermal camera device, filters or/ and other lenses that will be used as well as the setup upon the actual machine [14].

Augmented Reality has been proven valuable in those cases where more realistic visualization is required between different components of a system [15]. In this paper this technology has been adapted into supporting the design phase of a monitoring system, in order to decrease the time for selection and setup of the equipment. Thus, feedback upon the usability, feasibility and performance of a monitoring system [16], can then be provided, allowing the user to choose the optimal solution without having the need to conduct any physical demonstration experiments.

## 3. Proposed Digital Twin Methodology

The proposed methodology aims to provide an realistic understanding of the interactions between the monitoring system components, within an environment highly interactable by the user. As such, the modeling methodology focuses on reconstructing the main monitoring devices and equipment i.e. the thermal cameras, filters / lenses, workpiece, laser source; in a digital AR environment, where the user can immerse and interact, without cutting off the actual machining space. The interaction with real space is really important in such cases.

The modelling has been based on introducing discrete elements (nodes) with different properties and functionalities, where there can be added together in creating different digital objects (components). Further on, radiation has been also modeled up to a specific level that enabled interaction between the different nodes of the system. The following table describes all important information that took place into the modeling methodology of the system.

Table 1. Main variables used for modelling methodology and a brief description

Symbol	Description
$\omega_0$	Initial amplitude of the radiation
$\omega(z)$	The amplitude of the radiation in distance $z$
$T$	Approximate absolute temperature of a node for a process
$\lambda$	Wavelength of radiation
$E_{b,\lambda}(\lambda, T)$	Power of radiation energy, for a blackbody at wavelength $\lambda$ for a specific absolute temperature $T$
$\tau(\lambda)$	Transmissivity of a node per wavelength unit.
$\alpha(\lambda)$	Absorption of a node per wavelength unit.
$\rho(\lambda)$	Reflectivity of a node per wavelength unit.
$C_1$	$3.74177 \cdot 3 \cdot 10^8$ [W mm <sup>4</sup> / m <sup>2</sup> ]
$C_2$	$1.43878 \cdot 3 \cdot 10^4$ [mm K]

The radiation modelling has been based on featuring the geometrical characteristics of its propagation throughout the

$\mathbb{R}^3$  space, as well as its spectrum. As such, the radiation has been defined within the system as an object that starts from a specific point and moves along the Z-direction of its pose until it finds a digital collider. The wavelength characteristics are defined by the source that instantiates the radiation in the digital space, whereas the propagation has been considered to be similar to a Gaussian beam [17], at which the amplitude at a specific distance from its origin is defined as  $\omega(z)$  given by the following equation:

$$\omega(z) = \omega_0 \sqrt{1 + \frac{z^2 \lambda^2}{\pi \omega_0^2}} \quad (1)$$

Further on, the nodes of the system have been proposed in order to define any digital monitoring component by giving different properties to it. The properties that have been added within each node have been based on defining the different sources, filters, workpiece and IR sensors. To this end, *temperature* has been added to define the average temperature that the workpiece is planned to be processed with. This property will enable the identification of the radiation spectrum required to be captured throughout the process without requiring thermal-energy modeling for the different components. *Transform* has been defined to support the special definition of the node in manner of the position/rotation, from its parent object. *Transmission* has been defined in order to identify the bandwidth of wavelengths that this objects transmits radiation. *Reflection* is responsible for defining the bandwidth of wavelengths at which the specific node reflects the radiation. *Absorption* defines the different levels, that the specific node can absorb radiation over a specific wavelength, and this property has been found useful for characterizing the IR-sensors. *Damage threshold* has been also added to characterize the wavelength at which the node will be damaged, since this is a valuable property for the definition of the filters.

Finally, the construction of a digital monitoring component has been performed by adding different nodes within the same entity called *digital component (object)*; additional properties of the component is the *mesh* that has been created to provide a set of different triangles between the nodes, useful for visualization and interaction purposes.

Moreover, each node contained a list of input radiation and output radiation objects that have been responsible for providing the different interactions within the system. The input radiation is always formed from one of the output radiations of another node that has been propagated throughout the surface of the triangle that this node is included. Each time that such an incident occurs, radiation objects alters parent objects, moving from the transmitter to the receiver.

On the other hand, output radiation is created from three different ways: (a) reflection of an input radiation based on the *angle of incident (AOI)*, (b) transmission of an input radiation, and (c) emission of radiation either due to the average temperature that this object will have during the simulating the process, or because of a standard defined  $\epsilon(\lambda)$  formula (in case of a laser source). (a, b) are based on the properties  $\tau$ ,  $\rho$  of the node and the output radiation created has the same characteristics with the input, whereas (c) on the other hand, totally depends on the temperature that the object will averagely have during the process, which is a

static predefined input for each process independently (figure 1). In order to find the wavelength for this type of radiation-output, the blackbody simplification has been utilized, where  $\lambda$  can be found from solving the following equation for  $E_{\max}(T)$  and  $E_{\max}(T) / 2$ .

$$E_{b\lambda}(\lambda, T) = \frac{C_1}{\lambda^5 [\exp(C_2/\lambda T) - 1]} \text{ [W/m}^2 \text{ } \mu\text{m]} \quad (2)$$

Where,

$$\lambda_{\max \text{ power}} = \frac{2897.8}{T_{\text{process}}} \text{ [}\mu\text{m]} \quad (3)$$

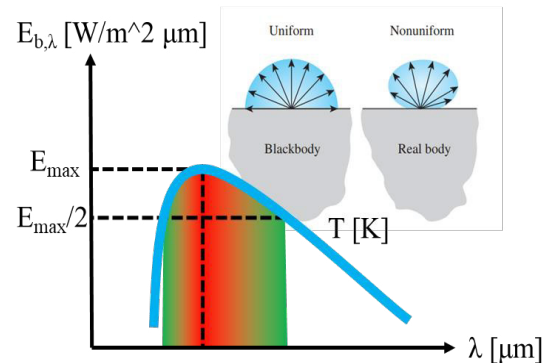


Figure 1. Black-body radiation intensity as a function of the wavelength over a specific temperature

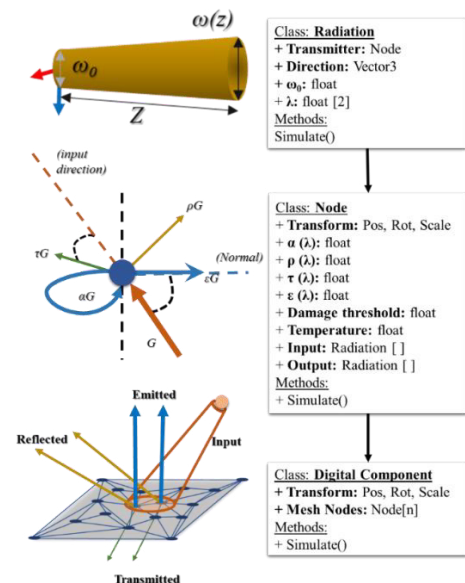


Figure 2. Base classes and visual entities for modelling the DT

The proposed modeling methodology has been programmed using Object Oriented Programming (OOP) i.e. .NET Framework, by means of creating the different objects providing those physical properties as variables, and with specific methods in order to simulate the physical interaction in-between.

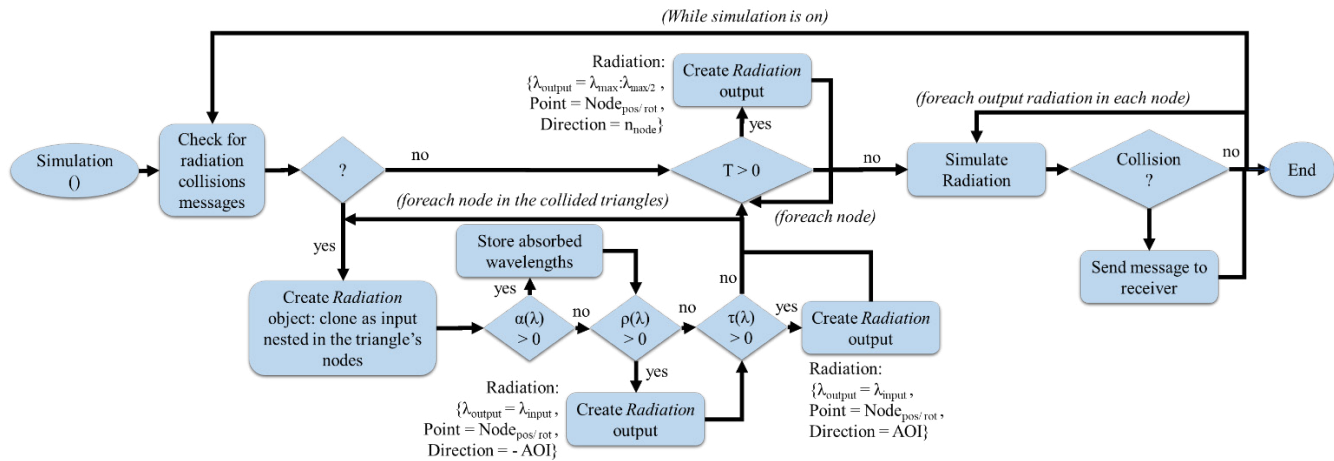


Figure 3. Workflow for simulation of the component's radiation inflow/outflow information over a single frame.

As it is illustrated in figure 2, there have been mainly introduced three class entities (C# objects) in the application that worked together in order to simulate how a possible monitoring system design would behave in a real environment. Figure 3 also shows what can be considered as the workflow diagram, followed by all the digital components at each frame in order to simulate the objects' interaction and update dynamically while changes are performed by the user. This workflow is simulated when the system is idle, meaning that no design changes are currently made. This has been a key feature in improving the performance of the design configuration phase, and let the user decide when any simulation will be carried. Once all the digital components are set, the application initializes the collision messages interaction, based on the different radiation objects. Following the above-mentioned methodology, radiation objects are created based on the nodes' properties and interact with the nodes of another component throughout those messages. The initialization of radiation objects by the laser source or the work-piece temperature, will trigger a series of events between the other components set in the scene, and will acknowledge the process engineers for the quality of proposed design in manner of meeting its requirements.

#### 4. Visualization & User Interfaces (UIs)

The application enabled four different components: *filters*, *thermal cameras*, *laser sources* and the *workpiece* (figure 4). Each of those components have been defined by the above DT methodology, although differentiated in some of the properties. The *laser* object is a single-node component, without any physical properties but lined to a predefined definition for the function  $\varepsilon(\lambda)$ . As such, laser objects can only provide output radiation and have no further interference on the simulation. *Filters* on the other hand are defined by multiple nodes and a definition for  $\tau(\lambda)$ ,  $\rho(\lambda)$  and the damage threshold. As can be seen the filter is considered to have no absorbing properties, but rather a specific threshold of failure. *Thermal cameras* are defined as a plane (multiple nodes) with a specific  $\alpha(\lambda)$  and stands as a passive object on the scene.

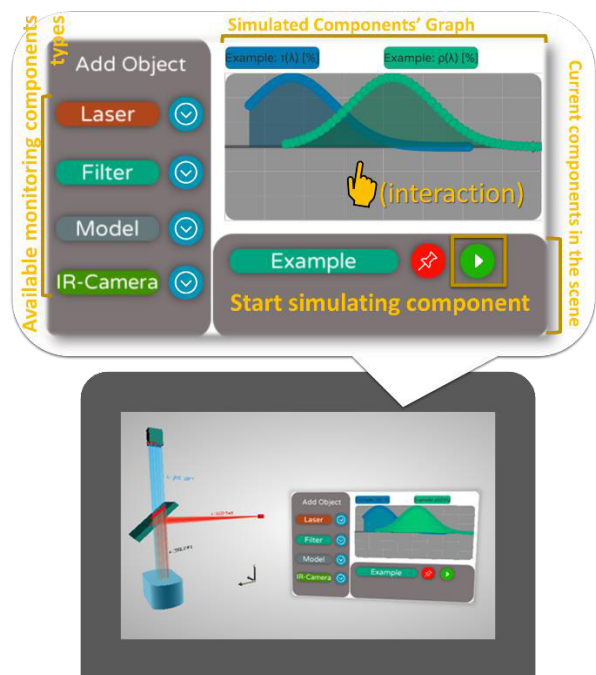


Figure 4. Screenshots during the development phase of the AR application's UI

Finally, the *workpiece* is defined by a specific 3D geometrical model in manner of the nodes' grid, and a setup for the  $\tau(\lambda)$ ,  $\rho(\lambda)$  and *Temperature*. The temperature is thus used for the calculation of the emission wavelengths for that process.

In order for this application to deliver a valuable tool for the process engineers, it needed to be operated at a robust and easily interactable environment with the actual machining system. To this end, the use of the latest innovations in eXtended Reality (XR) technology has been utilized to construct a stable environment for both AR/ MR devices (smart mobile devices/ headset devices). In AR – referring to smartphones and tablets – the development has been based on the use of Vuforia Engine and AR Foundation developed by Google, enabling an AR environment with spatial understanding, world anchoring and QR codes recognition, while at the same time the user could interact with the objects



throughout the device screen. For developing the equivalent version in MR i.e. Microsoft HoloLens devices, Vuforia has been also used for the calibration of the environment using specific QR-codes, in companion of the Mixed Reality Toolkit (MRTK). The two previous application versions have been built in Android version 7.0.0 (minimum requirement) and the UWP respectively.

Another main requirement of the tool has been to develop an easy to use, and comfortable UI, that will control the digital scene. The UI as showed in the above figure has been thus developed containing three main features. (1) A list of available components that can be used within the scene; (2) the scene itself, controlling the simulation status of the components currently instantiated within the AR environment; (3) a graphical display of the currently running components' main properties. (3) Is a key feature for the process engineer, since it illustrates the value of a current design in manner of the radiation interaction between the different objects. As such, multiple monitoring system design alternatives can be used in order to find the optimal way to track the key performance indicators of the process, in the minimum cost possible.

## 5. Validation & Results

The tool has been validated in a case scenario where a monitoring system needed to be designed and established for the on-axis monitoring of laser welding (figure 5). The process operator needed to identify that monitoring system configuration in manner of the exact components and their

position respectively, that will best fit the criteria. The criteria that needed to be fulfilled are the retrieval of the process related thermal radiation field coming from the work-piece object, without passing any of the laser beam radiation. The bellow properties reveal the process characteristics. A monochromatic laser source with wavelength band equal to  $[532, 540]$  nm and  $\omega_0 = 0.1$  mm; a work-piece containing 429 nodes, at an average machining temperature 1783.15K or  $[990, 2981]$  nm emissions wavelength respectively (calculated from eq. 2 for  $E_{\max}(1783.15K)$ ,  $E_{\max}(1783.15K)/2$ ). Accordingly, the filter that needed to be used has been an achromatic beam-splitter with a cutoff wavelength at 600nm, between the excitation/emission properties in order for the laser to be reflected while the radiation at a lower power (higher wavelength) could pass through the vertical axis where the absorber can be placed; the surface area of the filter that has been selected is  $25 \times 50$  mm<sup>2</sup>.

Given the above setup, the absorber that needed to be selected would need to have the requirements of being highly absorbing in between the wavelengths that the workpiece is radiating (due to temperature), and also be placed in the right position given the previously placed components. While using some of the different IR cameras components, included in the application, the bellow set up has been selected to address the monitoring solution. This design has been selected based on the absorption -  $\alpha(\lambda)$  - diagram of the IR\_Camera\_id\_00 in comparison with the inflow radiation, arriving throughout the beam-splitter. Those graphs show

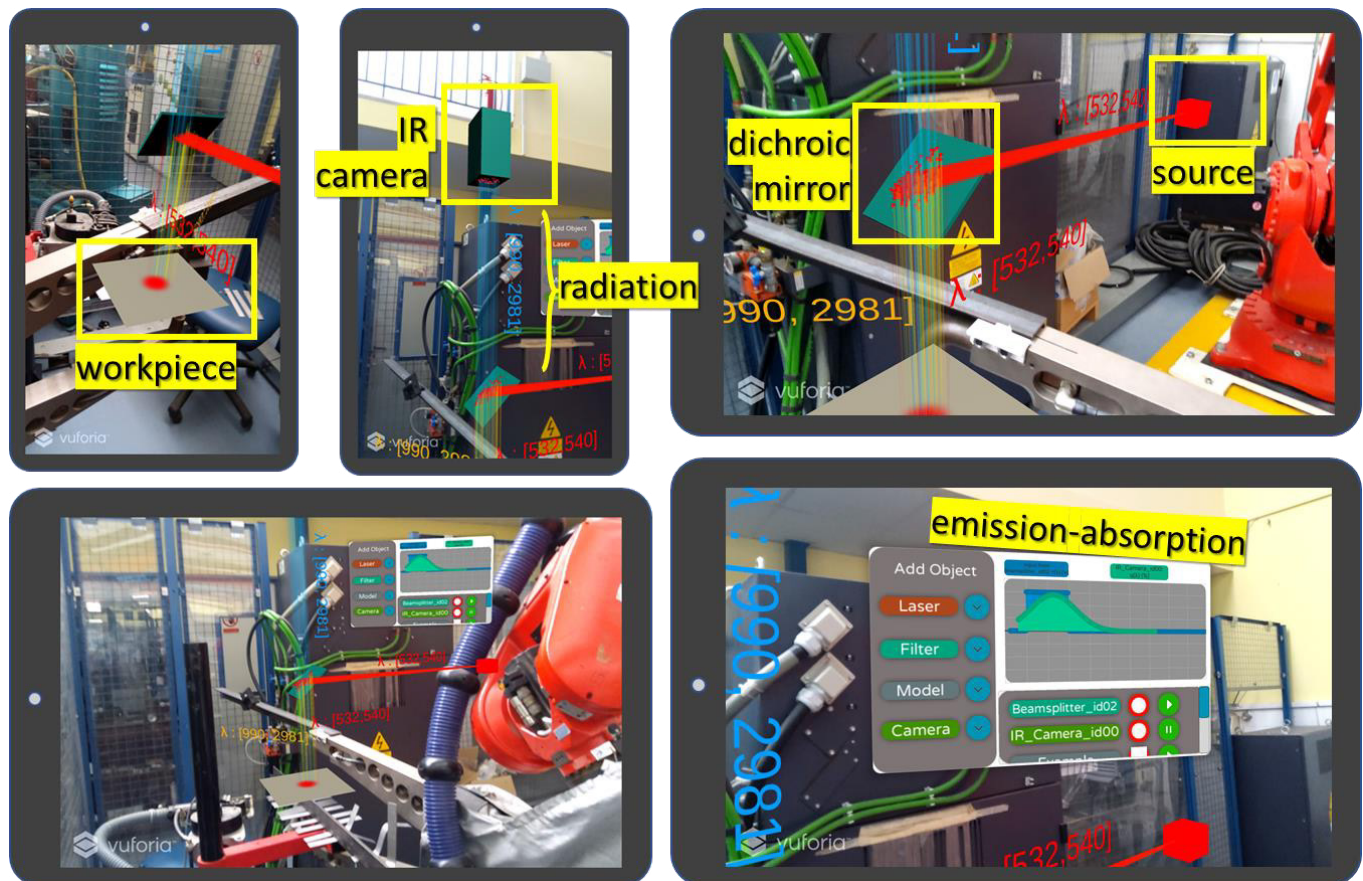


Figure 5. Validation screenshots while using the AR Digital Twin application

that the maximum absorption rate of the IR camera, is within the bounds of the radiation that needs to be captured, and thus the setup seem valuable. Lastly, an important aspect to the selection could be the cost of the components or even other resources constrains such as space limitations etc.

The AR tool allowed the user to run multiple monitoring configurations in a fast and comfortable manner; minimize the cost of the monitoring resources. In advance the dynamic data visualization into graphs for those simulated components, provided further support, since it can instantly reveal configuration errors or infeasible setup, and the user can come easily conclude to the optimal solution. Figure 6 indicates the profile of the performance while validating the AR application, using a SAMSUNG Galaxy Tab S5e android device. Within the graph it can be identified the decrease of fps rate throughout time, caused by the additional components that are added by the user.

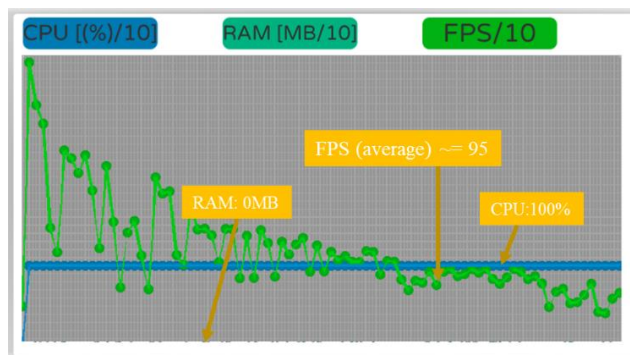


Figure 6. Screenshot with fps graph during the use of the application

## 6. Conclusion & Outlook

The proposed research study contributes in the phase of configuring a high-quality monitoring system for laser processes. To do so, the main components included in a thermal monitoring system are recreated in a DT application, where the user can easily interfere/ preview the system's design and setup in a digital way. The application features the environment using AR technology addressing advanced visualization requirements, compound with the real-world space. The modeling methodology of this paper associates all the important aspects of the monitoring components, in a simple and lean-computational way, enabling the application to run easily on any smart mobile and Head Mounted Devices (HMD) devices. The identified contribution over a more realistic model-based simulation in AR, gives engineers the ability to have quicker and more intuitive interactions with the monitoring system, acknowledging the surrounding environment and constrains, as well as improving mobility, in contrast to the conventional fully virtual simulation interfaces.

Yet, there is still a margin of improvement, considering the current status and limitations. The application's alternatives in designing a system is limited to the objects that are currently enabled by each version. To this end, with no backend platform to support a dynamic list of monitoring devices, the need of continuous developments is considered essential. Coupling this AR application with a platform of

monitoring tools and components, the user could go through a wide range of system setups or even get advises of suitable components for his/ her use case scenario. Further on, the modeling methodology could be upgraded into enabling the simulation of dynamic thermal energy field interactions between the objects. The application could then improve into a process control tool running in parallel with the actual process, while exploiting the features of XR technology to retrieve important machining information and interfere with the process in real-time.

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