Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 55 (2016) 254 – 259
www.elsevier.com/locate/procedia

5th CIRP Global Web Conference Research and Innovation for Future Production

Cloud-based Control of Thermal Based Manufacturing Processes

Alexios Papacharalampopoulos[a], John Stavridis[a], Panagiotis Stavropoulos[a, b], George Chryssolouris[a,*]

[a]*Laboratory for Manufacturing Systems and Automation, Department of Mechanical Engineering and Aeronautics, University of Patras, Patras 26500, Greece*
[b]*Department of Aeronautical Studies, Hellenic Air Force Academy, Dekelia Air-Force Base, TGA 1010 Athens, Greece*

* Corresponding author. Tel.: +30-2610997262; fax: +30-261 0997744. E-mail address: xrisol@mech.upatras.gr

Abstract

With non-conventional manufacturing processes, being increasingly integrated into manufacturing process chains, controllers and control strategies, remote nowadays, have to take into account a plethora of phenomena and criteria. The current study addresses the challenges, associated with the framework of the thermal oriented processes, having holistic (digital) modelling as a main objective. Herein two different case studies are performed; numerical examples regarding big data impact on manufacturing and simulation-based paradigms of control design taking into account communications. Implementation of the aforementioned takes into account the controller's complexity.

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production

Keywords: Thermal Process, Process Control, Performance, Networked Control System, Energy Efficiency, Cloud Manufacturing, Big Data

1. Introduction

With the automatic process control, dealing with the monitoring process behavior and the adjusting parameters [1], the signals become more and more vital, with the data communication requiring more resources [2]. The Cloud based Cyber Physical Systems [3] and Big Data [4] have therefore become a necessity.

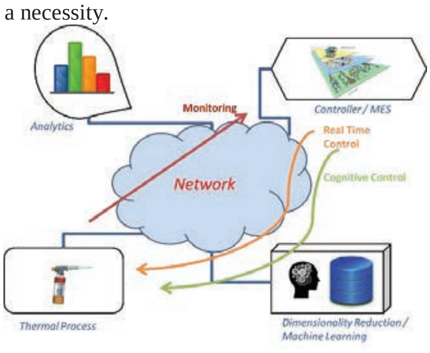

Fig. 1. Generic Schematic of Cloud Control

In addition, as Industry 4.0 [5] is increasingly come across in literature, Big Data in Process Control and Shop-floor Level in general, are expected to occur in the near future; this depends on five major factors: Regarding the Data size, the aggregation in remote control and Manufacturing Execution Systems [6] are already of a high level. Moreover, the Data related Velocity is affected by a sampling rate, which can be quite high, especially due to sensors, such as those of acoustic emission [7]. Regarding Data Variety, there is a plethora and diversity of reporters (machine tools, AGV's, robots [8], workers) and Key Performance Indicators [9]. Furthermore, the Veracity of Data is of high importance, since security [3], integrity, time-stamping and accuracy, due to control precision, all add up to this. Finally, there is the Value of the Data: Laser Welding Quality Assessment, on its own, involves a lot of data the usefulness of which is disputable.

On the other hand, the effect of communications on control is quite known [2]. As previously stated, the introduction to manufacturing and to processes control, is relatively new. However, there are older studies that imply such effects [10,11].

Peer-review under responsibility of the scientific committee of the 5th CIRP Global Web Conference Research and Innovation for Future Production
doi:10.1016/j.procir.2016.09.036

As such, there exist two major issues that can be addressed under this prism. The first one – under numerical case study, in Section 3, is the effect of control on data communications. As it is often addressed in literature [4], there are five factors (the "five V's" as stated above) that add up to the complexity of data acquisition, storage and processing / analytics [12-14]. Given the fact that cloud-based control (Fig. 1) is to be achieved, the effect of control through communications [2],[15-17], the effect of control signals is clear on Volume, Velocity, Variety, Veracity and Value.

The other issue that is studied (Section 4), is the exact opposite; as depicted in Figure 1, Cloud control forces the control signal to be transmitted through dedicated networks or even the internet. Various kinds of delays [2] are present thus, making the study on the effect of data communications in control systems, a necessary aspect for investigation.

2. Approach

Regarding the first case study (Section 3), a numerical example is given utilizing available data on cognitive control of Laser Welding in Automotive, to assess the probability of coming up with Big Data in Manufacturing (in process level).

Moreover, when approaching the control design (case study 2 / Section 4), as the communicational issues have to be taken into account, a thermal process is modeled as a system, described by an equation of differences. The process related metrics are selected and the effect of the communication delays on them is examined. In this regard, the paper is structured in the following sections, describing the approach followed for the design and evaluation of a static controller, towards the creation of a networked control strategy.

i. Effect on performance, related to quality [18]: It regards the system's efficiency in tracking a temperature profile as input.

ii. Effect on stability: Dealing with the capability of the system's output (temperature) practically, not to be exceeding high values

iii. Design and evaluation of a static robust controller.

iv. Effect on energy efficiency [19] is then investigated. This Key Performance Indicator (KPI) is relatively new in manufacturing and has been driven by societal needs. It reassures that the desired behavior is achieved by minimizing the resources (Energy Consumption in this case).

3. Case Study I: Effect of control signals on data communications

3.1. Description

Among the rest dominant monitoring technologies (vision & thermal cameras, optical sensors) implemented into thermal processing, acoustic emission sensing has been also investigated in literature and was put into practice in several cases [20,21]. The particular technique constitutes a very good paradigm of control, pushing manufacturing towards IoT and big data.

To begin with, acoustic emissions can be detected by a corresponding sensor in frequencies up to *1 MHz* [22] (corresponds to data velocity). For the conduction of a conservative calculation, a sampling frequency of *1.5 MHz* will be used. For the reassurance of the data veracity, a bit depth of *32 bits/sample* is considered. Then, for reasons of value reassurance, 3 sensors per machine tools are regarded. To demonstrate a quite range of data volume, 3 machine tools per shopfloor have been considered and two shopfloors in general. Consequently, a total bandwidth of *864 Mbps* for pure information is required. Judging by the capacity of the media [23,24], an optical network has to be used

3.2. Results

In the same context, using a thermal camera [25], the bandwidth required is:

$$bW = 80 \times 80\, pixels \times 10 bits / pixel \times 10 kHz \quad (1)$$
$$bW = 64 kbps$$

If one increases the number of sensors to achieve a multi-spectral image processing, the bandwidth will be equal to:

$$bW_N = 64N\ kbps \quad (2)$$

with N being the number of spectral channels.

Using as an example the welding of an automotive door, with *112* stitches [35] of *0,22 sec* [35,27] the storage capacity required is approximately equal to *1.8N MB*. Finally, an estimation of the data effect on the processing method is given. Since a matrix inversion is always relevant to these cases (i.e. PCA method [28]), the following diagram gives the inversion time through the Matlab's "inv" command [29]. A random matrix of dimensions $n^2 \times n^2$, with n being the pixels per direction, is considered and inverted. The inversion time is given in seconds. In Figure 2, the results are shown for this case. Moreover, in order for this subject to be addressed, the same results are shown, provided that a degree of parallelization is achieved by utilizing Schur's complement for matrix sizes over $16^2 \times 16^2$.

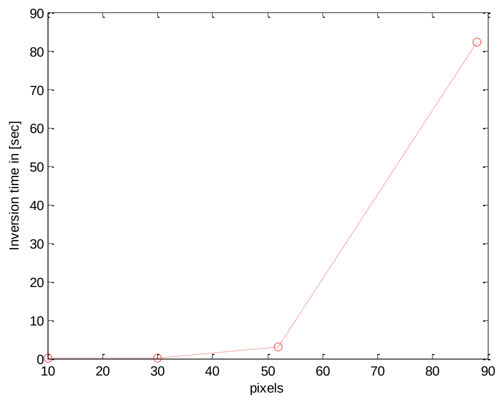

Fig. 2. Matrix Inversion Time as a function of Matrix size.

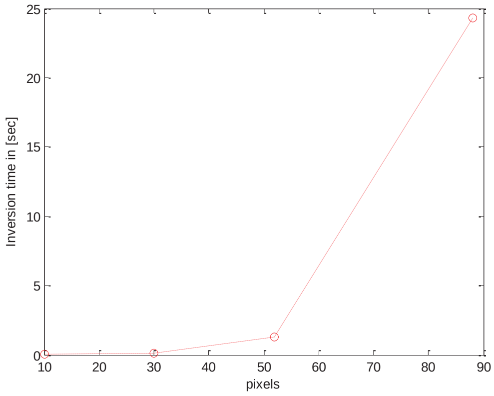

Fig. 3. Matrix Inversion Time as a function of Matrix size utilizing different degree of parallelization (Schur's complement)

4. Case Study II: Effect of data communications on control

4.1. Modelling a thermal process

The system (Process in Fig. 1) studied hereafter has been obtained from a *1D* heat transfer simulation (utilizing Mathematica's implicit Runge-Kutta [30] along axis *x* and time *t*). One end is considered to have been insulated, whilst on the other end, a temperature boundary condition has been applied. The material constants have been considered being as those in Table 1.

Table 1. Material Properties [31].

	Steel	
	Measure	Unit
Thermal Conductivity k	66	W/mK
Density ρ	7775	kg/m^3
Thermal Diffusivity α	14.6	mm^2/sec

The input of the system is identified as the temperature set as a boundary condition, while the output has been defined as the temperature found at the insulated end. A system identification technique established in the Matlab package [32] was performed under the arbitrary assumption of the thermal process, being described by a third order discrete time system. The system that came up was described in the z-domain by the following transfer function. The sampling frequency used was approximately equal to *1 kHz*.

$$F(z)=\frac{0.09627+0.09572z^{-1}+0.1203z^{-2}}{1-0.8699z^{-1}+0.2094z^{-2}-0.02557z^{-3}} \quad (3)$$

Then, introducing the following transform

$$\mathbf{z}[n]=\begin{bmatrix}\mathbf{x}[n]\\ \mathbf{x}[n-1]\\ \mathbf{x}[n-2]\\ \mathbf{x}[n-3]\end{bmatrix} \quad (4)$$

the following system descriptions are derived for various time delay values, forming an augmented state space for the closed system for delay *n=1*.

$$\mathbf{z}[n+1]=\begin{bmatrix}\mathbf{A} & \mathbf{BK} & \mathbf{0} & \mathbf{0}\\ \mathbf{I} & \mathbf{0} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{I} & \mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{0} & \mathbf{I} & \mathbf{0}\end{bmatrix}\mathbf{z}[n]+\begin{bmatrix}\mathbf{B}\\ \mathbf{0}\\ \mathbf{0}\\ \mathbf{0}\end{bmatrix}\mathbf{u}[n] \quad (5)$$

$$\mathbf{y}[n]=\begin{bmatrix}\mathbf{C} & \mathbf{DK} & \mathbf{0} & \mathbf{0}\end{bmatrix}\mathbf{z}[n]$$

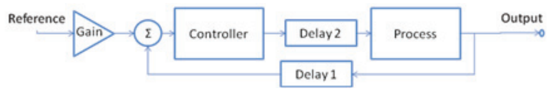

Fig. 4. Closed loop diagram of networked control system for thermal process with two kinds of delays

4.2. Effect on Stability

The performance of the controller in tracking, is ruined by the existence of delays and as a matter of fact, the more constant a delay is, the worse is the performance of tracking it. Metrics of the performance can be: the overshoot (reaching a percentage of *60%* as shown in Fig. 5) and the rise time [2] which is in the case of delay *n=3* is equal to *0.35 sec*, as shown below.

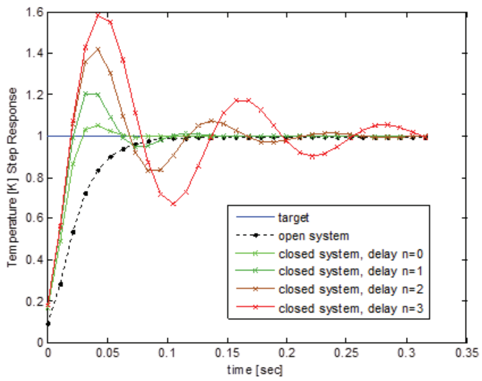

Fig. 5. Overshoot as quality metric

4.3. Effect on Stability

The system may have various kinds of delays, as shown in Fig. 4; the two delays exist as parts of the feed-forward and feedback branches. For completeness reasons, two diagrams are given in Fig. 6, for two controllers cases; for increasing values of delay 1 and delay 2 (as integer multiples of sampling period) the system is characterized either as stable *(o)* or as unstable *(x).*

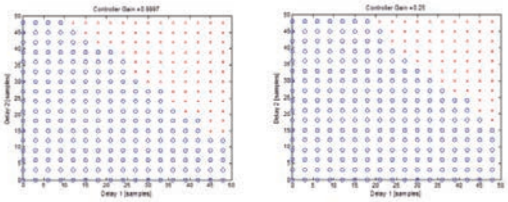

Fig. 6. Generic Schematic of Cloud Control

4.4. Results utilizing Static Robust Controller

The implementation of an output feedback controller that takes into account the system's delay is considered for the particular case study. To avoid utilizing a robust control method of greater complexity, such as the ones derived from the design with Linear Matrix Inequalities [33,34] - which will also involve stability, tolerance and disturbances definition - a simple test is being performed to see if an output feedback of pure gain can be utilized for enhancing the systems' tracking of varying delays.

The methodology is simple, since the controller (for reasons of simplicity) is considered to be a static gain: certain controller gains are computed for the enhancement of each system's constant delay performance. Then, these gains are used in order to compute a gain for the variable delay system. A mean value has been used as the simplest way of doing that. It can be seen in Figs. 7 and 8 that this has successfully enhanced the system's tracking

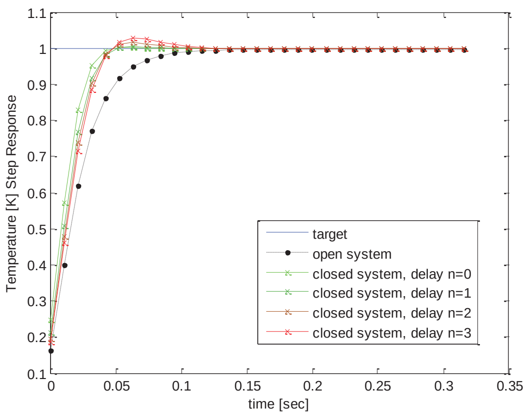

Fig. 7. Step response of individually closed thermal systems

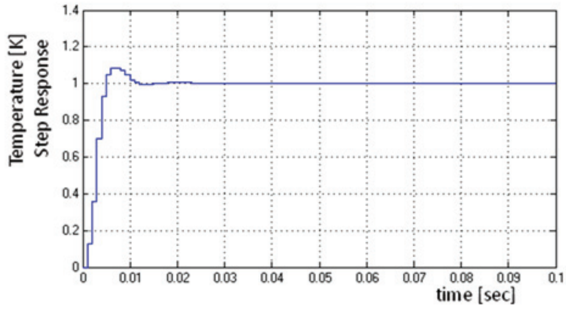

Fig. 8. Step response of robustly closed thermal system for varying delay

4.5. Results regarding Time-delay Robustness & Energy Efficiency

Robustness against time-delays in the control signals, utilizing static controllers, is a good achievement; however, it is of great importance to allow the presence of more criteria other than speed of response or precision in order for the engineers to develop control strategies, which will assure quality in thermal processes. Recently, the significance of energy efficiency was pointed out [35] for laser processing. So, in this section, energy minimization is considered being an extra condition in the controller design. A static linear quadratic regulator (*LQR*) of infinite horizon and output feedback [26] is implemented by minimizing the following cost. The system has changed; as input in the *1D* thermal problem is considered being the thermal flux, while the $J=\sum\left\{\xi\left(y[n]-u[n]\right)^2+\left(1-\xi\right)u[n]^2\right\}$, with input *u[n]* and output *y[n]*.

Thus, the two terms of the cost track performance and energy. They are weighted by the factor ξ. Successively, in the following figures, the parameter ξ obtains larger values, meaning that the energy gets to be more important than the tracking does and thus, performance and robustness worsen.

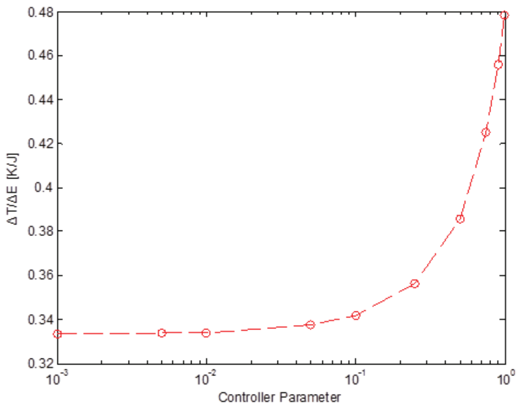

Fig. 9. Energy Efficiency in infinite horizon optimal control closed loop system with delay of one sample. Vertical Axis: Temperature increase regarding a constant increase in energy offered [Kelvin/Joule]. Horizontal Axis: Value of Controller Parameter ξ

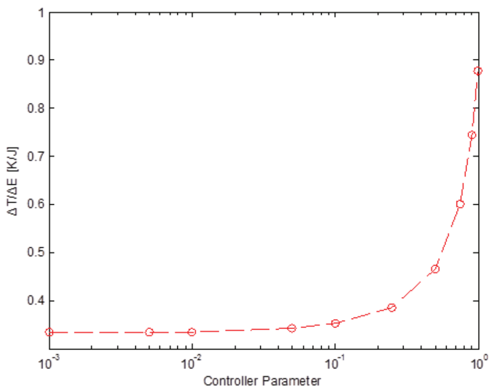

Fig. 10. Energy Efficiency in infinite horizon optimal control closed loop system with delay of two samples. Vertical Axis: Temperature increase regarding a constant increase in energy offered [Kelvin/Joule]. Horizontal Axis: Value of Controller Parameter ξ

5. Conclusions and Future Outlook

As shown in Section 2, the effect of the process control on data can be of great weight. Namely, it leads to Big Data Handling. Handling can either apply to storage methods, or to processing techniques. As a matter of fact, as figures indicate, the use of **intelligent algorithms that reduce the volume** (a.k.a. dimensionality) of the data will be inevitable in the near future for companies to avoid storage and processing costs.

On the other hand, on the control perspective, as proven, simple static controllers (preferably output over state feedback) are quite useful in manufacturing systems, due to their simple structure and minimum invasion of the system. This of course presumes the use of controllable and observable systems. Furthermore, simple static controllers are **fast and rather cheap to be implemented**. Thus, it is a step beyond the state-of-the-Art to achieve minimization of the delay effect on control signals, by utilizing simple gains as controllers in thermal processes. As a matter of fact, tracking performance has been tested for both the output feedback and the state feedback controllers, while the stabilizability of each controller was also considered. As also shown here and in previous studies [2], in the future, **networked control will have to be taken into account**, especially in the case of centralized control through non-dedicated networks.

In addition, when variable delay is considered, it is expected that the system will have a different behavior regarding the robustness against the time delay in the signals. Simple gain controllers were utilized in this case achieving good results (Figure 5 to 8). Also, besides the tracking performance, stabilizability is one more criterion for the evaluation of a controller. As far as the classical systems' stability is concerned, Figure 6, has helped in verifying the fact that the controller **may affect the stability limits**, defined by the signals' time delays.

Finally, **adding one more criterion (energy efficiency) for the evaluation of the control performance of thermal processes will affect the design procedure of the controller and modify the control strategies**, developed for that purpose. However, in this study, the multi-criteria optimization of the closed-loop system proved that energy minimization and robustness against time-delays can be **contradictive optimization objectives**, as shown in Figures 9 and 10, at least for the case of static (=simple) controllers. Utilizing an infinite horizon LQR controller, static gain was employed in this case, too.

Nevertheless, it has to be noted that the heat equation model alone is not adequate to describe laser-based processes such as laser welding. This is obviously due to the phase change and the (moving boundary) Stefan problem. The model that can be used is a switched system of three states, with a triggering event **changing the dynamics** being the system's very output, as in the case of utilizing operating point neighborhood [36]. In the following figure, the three states of the system can be seen, along with their physical interpretation. States 1 and 3 are heating states of pure solid and liquid, respectively.

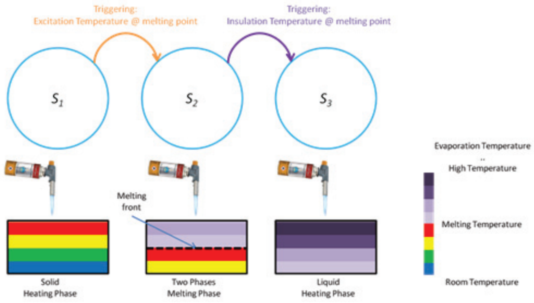

Fig. 11. Switching System model of Laser Welding

Attempts are foreseen, in terms of future work, utilizing more sophisticated approaches, such as **H-infinity** and Model Predictive Control, or a hybrid combination of the aforementioned in thermal processes.

Acknowledgements

This work is under the framework of EU Project MAShES. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 637081. The dissemination of results herein reflects only the authors' view and the Commission is not responsible for any use that may be made of the information it contains.

Factories of the Future
Public Private Partnership

References

[1] Chryssolouris, G. Manufacturing Systems, Theory and Practice. Second Edition. New York: Springer, 2006.

[2] Papacharampopoulos A., Stavropoulos P., Stavridis J., Chryssolouris G., "The effect of communications on networked monitoring and control of manufacturing processes", 48th CIRP Conference on Manufacturing Systems (CIRP CMS 2015), Procedia CIRP, 24-26 June, Naples, Italy, Volumue 41, pp. 723-728 (2016)

[3] Mourtzis D., Vlachou E., "Cloud-based Cyber-physical Systems and Quality of Services", TQM Emerald Journal , Volume 28, Issue 6(2016)

[4] Erl T., Big Data Fundamentals: Concepts, Drivers & Techniques, Prentice Hall; 1 edition

[5] Proto Labs White Paper "Data, Digital Threads and Industry 4.0", available online https://www.protolabs.com/resources/whitepapers/2016/industry-40/, accessed 31 August 2016

[6] Lapido, Cognitive high speed defect detection and classification in MWIR mages of laser welding, Industrial Laser Applications Symposium 2015, edited by Mike Green, Proc. of SPIE Vol. 9657

[7] Papacharalampopoulos A., Stavropoulos P., Doukas C., Foteinopoulos P., Chryssolouris G., "Acoustic emission signal through turning tools: A computational study", (CIRP CMMO) Procedia CIRP, 14th CIRP Conference on Modelling of Machining Operations, 13-14 June, Turin, Italy (2013)

[8] Michalos G., Kousi N., Makris S., Chryssolouris G., "Performance assessment of production systems with mobile robots", (CIRP CMS 2015), Procedia CIRP, 48th CIRP Conference on Manufacturing Systems, 24- 26 June, Naples, Italy Volume 36, pp.195-200 (2015)

[9] Hentz J.B., Nguyen V.K., Maeder W., Panarese D., Gunnink J.W., Gontarz A., Stavropoulos P., Hamiltong K., Hascoet J.Y., "An enabling digital foundation towards smart machining", (Procedia CIRP), 8th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Naples, Italy, Volume 12, pp.240-245 (2013)

[10] Saint GB, Valckenaers P, Van Brussel H, Van Belle J. Networked manufacturing control: An industrial case. CIRP Journal of Manufacturing Science and Technology; 2013. pp.324–326

[11] Xu S, Bao J. Plantwide process control with asynchronous sampling and communications. Journal of Process Control 21; 2011. pp. 927–948.

[12] Mori M., Fujishima M., Komatsu M., Zhao B., Liu Y. Development of Remote Monitoring and Maintenance System for Machine Tools, Annals of the CIRP, 57/1. 2008

[13] Brinkmann, Large-scale Electrophysiology: Acquisition, Compression, Encryption, and Storage of Big Data, J Neurosci Methods. 2009 May 30; 180(1): 185–192

[14] McAfee A., Big Data: The Management Revolution, Harvard Business Review, October 2012

[15] Zhang D., Wang W., Static output feedback control of networked control systems with packet dropout International Journal of Systems Science, 43 (4) (2012), pp. 665–672

[16] Torrisi N.M., Oliveira J.F.G., Remote control of CNC machines using the Cyber OPC communication system over public networks IJAMT, 39 (2008), pp. 570–577

[17] Mourtzis D., Vlachou E., Milas N., Dimitrakopoulos G., "Energy consumption estimation for machining processes based on real-time shop floor monitoring via wireless sensor networks", 49th CIRP Conference on Manufacturing Systems (CIRP CMS 2016), 25-27 May, Stuttgart, Germany, (2016)

[18] Stournaras A., Stavropoulos P., Salonitis K., Chryssolouris G., "An investigation of quality in CO2 laser cutting of aluminum", CIRP Journal of Manufacturing Science and Technology, Volume 2, No. 1, pp. 61-69 (2009)

[19] Fysikopoulos A., Papacharalampopoulos A., Pastras G., Stavropoulos P., Chryssolouris G., "Energy Efficiency of Manufacturing Processes: A Critical Review", (CIRP CMS 46) Procedia CIRP, 46th CIRP Conference on Manufacturing Systems, 29-31 May, Sesimbra, Portugal Volume 7, pp.628-633 (2013)

[20] Stournaras A.,Chryssolouris G., "On acoustic emissions in percussion laser drilling", International Journal of Advanced Manufacturing Technology, Volume 46, No. 5-8, pp. 611-620 (2010)

[21] Gu H., Duley W. W., 1996, A statistical approach to acoustic monitoring of laser welding J. Phys. D: Appl. Phys. 29 556–560

[22] Xiaodong Na, Stone (2010). Laser Welding: Techniques of Real Time Sensing and Control Development,Laser Welding, Xiaodong Na, Stone (Ed.), ISBN: 978-953-307-129-9, InTech, Available from: http://www.intechopen.com/books/laser-welding/laser-welding-techniques-of-real-time-sensing-and-control-development-

[23] Tanenbaum, A.S., 2003, Computer Networks, Fifth Edition, Prentice Hall.

[24] Lim C., Attygalle M., Nirmalathas A., Novak D., Waterhouse R., 2006,. Analysis of optical carrier-to-sideband ratio for improving transmission performance in fiber-radio links. Microwave Theory and Techniques, IEEE Transactions on, 54(5), 2181-2187

[25] Lapido et al, C Cognitive high speed defect detection and classification in MWIR images of laser welding Industrial Laser Applications Symposium 2015, edited by Mike Green, Proc. of SPIE Vol. 9657

[26] Matlab LQ Controller, http://www.mathworks.com/help/control/ref/lqry.html?searchHighlight=lqry

[27] Pandremenos J., Salonitis K., Chryssolouris G., "CO2 laser welding of AHSS", (ICALEO 09), 28th International Congress on Applications of Lasers and Electro-optics, Florida, USA, pp. 1507-1514 (2009)

[28] Wang et al, Independent Component Analysis-Based Dimensionality Reduction With Applications in Hyperspectral Image Analysis, IEEE Transactions on geoscience and remote sensing, vol. 44, No. 6, June 2006

[29] Matlab's Inversion command, http://www.mathworks.com/help/matlab/ref/inv.html?s_tid=srchtitle, accessed 30-03-2016

[30] Mathematica's Runge Kutta https://reference.wolfram.com/language/tutorial/NDSolveImplicitRungeKutta.html

[31] Pastras G., Fysikopoulos A., Giannoulis C., Chryssolouris G., "A numerical approach to modeling keyhole laser welding", International Journal of Advanced Manufacturing Technology, Available Online (2014)

[32] Matlab Least Square Identification, http://www.mathworks.com/help/ident/ref/arx.html

[33] Dritsas L, Tzes A. Robust stability analysis of networked systems with varying delays. International Journal of Control, Vol. 82, No. 12,; 2009. pp. 2347–2355

[34] Garcia E, Antsaklis PJ. Model-Based Event-Triggered Control for Systems with Quantization and Time-Varying Network Delays. IEEE Transactions on Automatic Control, Vol. 58, No. 2; 2013.

[35] Fysikopoulos A., Pastras G., Stavridis J., Chryssolouris G., "On the Performance Evaluation of Remote Laser Welding Process: An Automotive Case Study", 48th CIRP Conference on Manufacturing Systems (CIRP CMS 2015), Procedia CIRP, 24-26 June, Naples, Italy, Volumue 41, pp. 969-974 (2016)

[36] Vagia et al, Design of a robust PID-control switching scheme for an electrostatic micro-actuator, Control Engineering Practice, Volume 16, Issue 11, November 2008, Pages 1321–1328