The Intelligent Space Modeled as a Cyber-Physical System

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***Abstract*— According to a general rule definition, the intelligent space (iSpace) is defined as a location (or space) provided with electronic sensor networks that enable the considered environment with intelligent behaviors. As a result, the considered space will be able to perceive stimulus around them and to understand events that happen its near surrounding. Cyber-physical systems (CPSs) are building blocks in Industry 4.0 that links digital technology and the physical environment in an industrial context. They combine intelligent physical objects and systems on a high level of functions integration. This paper emphasizes the main idea that intelligent spaces may be also modeled as complex cyber-physical systems, as well. This approach has been developed by discussing the theoretical basis of both the iSpaces and CPSs, respectively unfolding a short comparison between their basic behaviors. As a concrete example, the CPS model of a given iSpace framework is presented and discussed widely in the paper. This model has been experimented by using a Field Programmable Gate Array (FPGA) processor-based ready-to-use development systems and software technologies that handles reconfigurable hardware technology. The implementation proves that the developed CPS model is well feasible and expresses in all the main behaviors and functions of iSpaces. It is also mentioned that the actual stage of the technological development terms and scientific areas related to iSpaces and CPSs overlaps. In fact, this is not surprising at all by considering nowadays evidence that iSpaces are widely present and shared components in modern manufactory processes that are an inherent part of Industry 4.0 vision and reality.**

Keywords—intelligent space; cyber-physical system; hardware reconfigurable technology; Industry 4.0; CPS model.

I. INTRODUCTION

From the related scientific literature is well known that the intelligent space (iSpace) technical term has been introduced first in 1995 in reference [1]. Basically, this concept refers to spaces or environments equipped with sensor networks, video cameras, or other electronic devices being able to capture information (to measure a set of physical magnitudes, to record audio information, or to capture visual information) about its near surrounding and to transmit it them to a computer system or robot. As function of these external stimuli received, the robot or a computing system will act to make human life more comfortable, by delivering basic services to us. In this way information and communication technologies will create interactive spaces with additional features that are provided by the considered space. In other words, the space becomes "intelligent" enabling to understand or perceive what is happening inside them. The high amount of information is captured or acquired by embedded microprocessors-based digital systems that process it using various algorithms. Then generate the adequate commands to actuators, mobile agents, or even humanoid robots. The result of all these actions is targeted to be a more comfortable human life in that spare or area. Such space may be a home, an office, a factory, or an industrial plant.

Without the claim to enter here in to more details or interpretations, it is mentioned only that same authors consider that there are iSpaces where all the electronic circuits and devices (sensor networks, wireless devices, cameras, smart phones, etc.) are interfaced and interconnected in the same physical space [2, 3]. Others consider that the same electronic circuits and devices may be placed in a location and the processing-supervising system in another physical space or location. Such different configurations in international references are named as virtual iSpaces [3, 4]. Of course, both two are considered proper approaches and the iSpace concept should not be limited to a given or specific physical space. In this way the term may be easily extended to a virtual one.

However, the Industry 4.0 concept widely discussed in recent years also uses the intelligent space terminology. Industry 4.0 represents a new vision that represents the next stage of organization and control of industrial processes. It is strongly associated with the so called "smart factory" concept [5, 6]. This last denomination identifies an environment that represents the structural basics of smart industry, or intelligent production and manufacturing processes. Cyber-physical systems (CPSs) are building blocks in Industry 4.0 that embeds intelligent physical components with a high level of functions integration where digital technology and physical environment it has been linked in an industrial context [5, 6]. CPSs often operate in intelligent space environments. Therefore, the iSpaces (where are placed sensor networks, video cameras, smart phones, wireless devices, or other electronic devices) in a plenty of manufacturing applications represents the natural environment of CPSs operation. Generally speaking, in the last around one decade the iSpace become a "traditional" component of modern industrial production environments. Hence, for specialists involved in this area nowadays is somewhere selfunderstanding that such high performance manufacturing processes are mostly unfolding in iSpace environments.

Starting from these last remarks emerges a challenging question: if is this so, iSpaces may be approached as CPSs? In other words, intelligent spaces can be modeled as complex CPSs? Next, the theory related to the iSpace concept not somehow overlaps with many theoretical aspects of complex cyber-physical systems? However, there are some interesting aspects which looks predestinated for a comprehensive analysis and theoretical discussion. For this reason, the main objective of this paper is to open a theoretical and practical analysis regarding the overlap degree of these two main concepts. This study also include a brief comparison of the iSpace and CPSs concepts, respectively a short example of how the iSpace may be modeled and approached as a complex CPSs system that operates under the Industry 4.0 vision.

II. THE ISPACE CONCEPT

The theoretical issues discussed in the introduction paragraph lead in a natural way to the general conclusion that the iSpace is in fact a space endowed with functions that allows the capture of complex events being useful for human beings. By utilizing the acquired information and sharing intelligently with computers and robots becomes possible to get useful services and support from them. In this way human life is improving to one more comfortable and convenient. In order to illustrate all these interactions and dependencies, let's consider a possible iSpace framework or topology, as given next in figure 1. Of course, many other similar iSpace configurations may be considered for study and analysis purposes, as well. This one focuses on a framework suitable to comprise as many events and services being possible to identify in a nowadays complex intelligent environments.

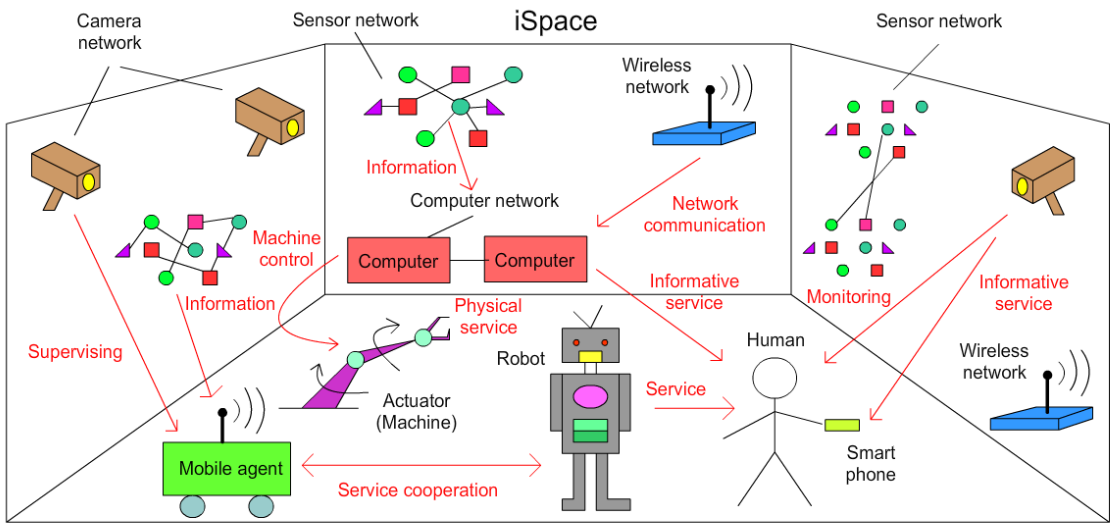

Fig. 1. Intelligent space

Obviously, in focus of any iSpace frameworks should be the human being, as receiver and end user to who has been built-up the entire system. An adequate designed and developed iSpace topology may deliver a wide range of services and support that makes human life more comfortable in that space. For example, in intelligent environments robots may understand various requests from people, are able to interpret gestures, mimics, voice signals, or to analyze image and video information. In this way iSpace allows robots to support humans more effectively. Concretely, robots may deliver healthcare services, information services, communication services, or a large scale of physical services [7]. Of course, in iSpaces not only robots are considered, there also exists various type mobile agents or machines (actuators) endowed with a certain level of intelligence. They can also receive (acquire) information from sensor networks, or perceive stimuli from their near surrounding environment. As result, they become able to initiate service cooperation with robots or machines from that space, as well as to ensure high level services for humans. On the other side, the placed sensor networks are able to generate a plenty of useful environmental information for computers (or computer networks) and after the adequate processing operations these computers may generate informative services for peoples. Nowadays such services usually are transmitted wireless to smart devices, such as smart phones or iPads. In a natural way, in iSpaces both audio and video signals are generated, transmitted and processed. Usually, the video cameras generate visual information about that intelligent environment, respectively performs supervising and monitoring operations. However, as the block diagram from figure 1 attempt to suggest, the intelligent space frameworks embeds a high level of complexity and cross-over interactions, difficult to handle it in many concrete applications. At the same time, it is important to mention here that nowadays iSpaces advances as some kind of "spaces of life" where physical space has been linked with digital technology [7].

Finally, it is not without importance to make a few remarks about the technological support of modern intelligent spaces. What is out of any question is that network communication technology represents the main framework or background of any iSpace environments. On this support are linked and fused then a large scale of other last generation technologies. Of course, network communication among components of any iSpace is facilitated primarily by modern wire- and wireless Internet technology. For this reason the vast majority of nowadays used cameras, sensors, phones, actuators, or other electronic devices placed in intelligent spaces a full capable for high speed internet communication. They can deliver their captured data on the internet framework, may be uniquely identified via individual IP address, as well as they are able to receive instructions from the internet environment. One other important technological issue linked to the iSpace concept refers to network computing. This term covers the network computing technologies between the well known desktop- or laptop computers, wearable computing, or ubiquitous computing techniques. Wearable computers are miniaturized and wearable mobile computing units that are network access points in intelligent space [7]. They have the function to improve human life and comfort in that space and to relieve computation tasks from human side. Ubiquitous computing refers to all the computers that are positioned so as to be invisible and during their operation to not disturb or hamper human activity. Sensor technology also represents an important issue that supports the iSpace framework. It is almost self-explanatory that sensor technology used in intelligent environments (such as infrared, microphones, visual, olfactory, or other sensor types) must be large-scale miniaturized, and hypersensitive [7]. Actuators and micro electro mechanical systems technology is another key factor related to the iSpace concept. They fulfill the important role of improving the hardware support of robots, mobile agents, or machines that are present in the considered space. The main concepts of this technology are miniaturization of mechanical sizes, modularization and compaction. Without enough room to enter here into details, it is mentioned only, that there are also a lot of other important technologies which strongly supports of modern intelligent spaces, such as : remote control, recognition technology, interface technologies, telerobotics, a large scale of artificial intelligence technologies (image recognition, voice recognition, human gestures understanding, etc.), or network robotics [7].

III. THE CYBER-PHYSICAL CONCEPT

By entering into the technological era named “Industry 4.0” the CPSs research and development emerges as one of the most important and challenging research topic for scientists. In fact, CPSs represents the next generation engineering systems that integrate on the highest level the digital technology-based knowledge into physical objects [5, 8]. There is no mistake to declare that this unprecedented integration level is full predestinated to articulate a high impact on the entire human society evolution in the next decades. The final goal of this evolution is targeted in the “intelligent manufacturing” or “smart factory” concept.

Among the main characteristics of a CPS mandatorily should be mentioned that they represents the next evolution stage in manufacturing, embeds intelligent control systems that communicate in complex network systems, and can be uniquely identified via individual IP address. At the same time CPSs also integrates a wide range of intelligent sensors, camera networks, wireless networks, artificial intelligence technologies, robots, mobile agents or actuators, computer networks, information technologies, and so one [5]. If all these are tightly integrated into a coherent frame it is obtained a block diagram similar with the one shown next in figure 2.

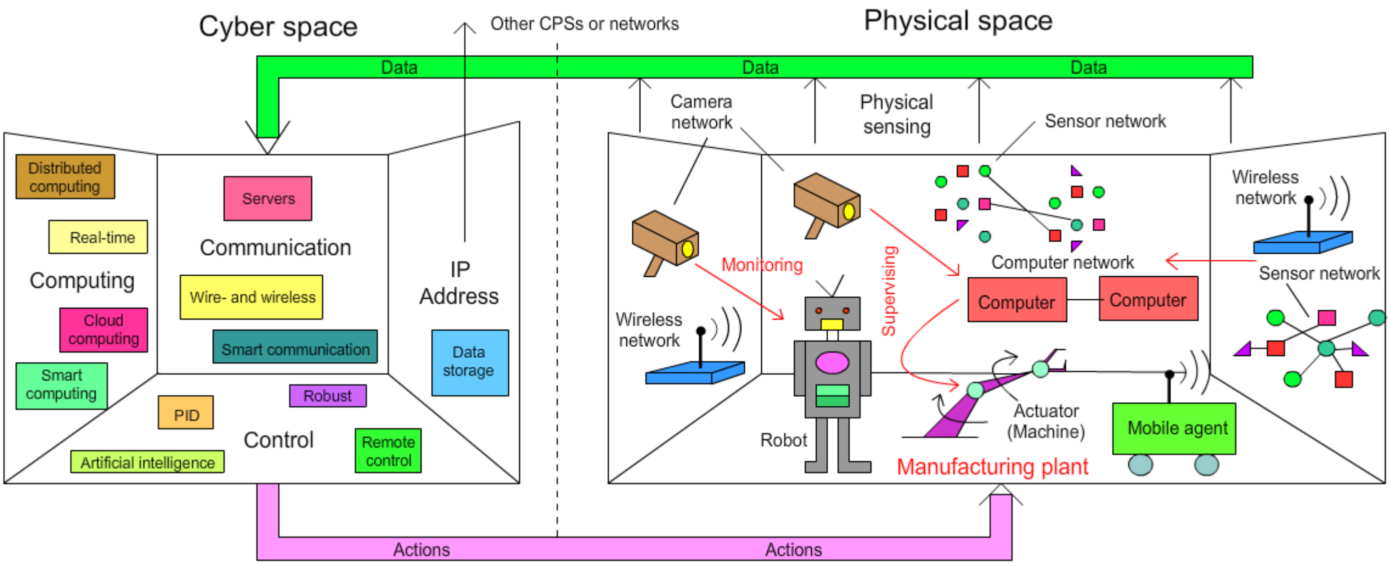

Fig. 2. Cyber-physical system

This picture evidences that each CPS architecture it is divided in two main spaces. One is the “physical space” or “physical world”. This comprises all the physical elements or components which are located inside of the space considered for study. In this particular case such physical elements are the robots, mobile agents, electromechanical actuators (or machines), various sensor networks, cameras, computer networks, or other electronic or mechanical devices. For more convenience let's consider that all these elements represent a last generation manufacturing plant. This physical space being densely populated with a wide range of sensors, transducers, or audio-video signal recorders captures a huge amount of useful information about the events that are taking place inside the monitored area. All these information will be sent via wire- or wireless communication networks to a next space. This is the so called "cyber space" or "cyber world". The cyber space represents a layer where three main tasks are executed: communication, processing and control. The communication part embeds activities such as communication with servers, smart communication with electronic devices, or wire- and wireless communication between various networks. On the computing framework are implemented foe example algorithms for real-time computing, cloud computing, or distributed computing purposes. Last, on the control side are implemented various process control algorithms, such as PID control, remote control, robust control, or a large set of artificial intelligence algorithms. As final result of all the communication, processing and control activities imposed (or reference) signals will be generated back to the physical world. These means imposed activities to this space. Of course, each CPS possesses its own IP address for unique identification, respectively for communication with other neighboring CPS units.

However, from the above remarks it is not difficult to conclude that a CPS approach represents a difficult multidisciplinary undertaking. The complexity of such a system is huge, there being mixed a lot of different type analog and digital signals, cohabitates analog- and digital hardware, respectively are used very different software technologies. Beside all these, is well known that a CPS is a confluence of a wide range of last generation technologies. At the same time, the most important conclusion is that the primary role of a CPS is linking physical world with the digital technology, achieving the highest functional integration level of physical with digital.

IV. EXAMPLE OF ISPACE MODELED AS CPS

Let is support the theoretical remarks unfolded in the previous paragraphs with a concrete modeling and implementation example. Of course, in order to avoid excessively sophisticated iSpace or CPS models looks more suitable for study and analysis purposes one significantly simplified, but with quite similar functions and basic functionalities. For this reason it is considered the iSpace block diagram from figure 3. There is shown a particular iSpace model with a few of component elements. Obviously, the central element of this environment is the human being and the main target is to make human life more comfortable and convenient in that area. It is supposed that in different locations of the considered space are placed various sensors to measure physical magnitudes. For example, one sensor is fixed for ambient temperature measurement, respectively another is placed for ambient light intensity measurement. It is expected that by controlling these information becomes possible to take some particular actions and as result human life becomes more comfortable. Here particular action means for example to close the door, to open a window, or to open/close a heather module in order to maintain an optimal temperature level in that room. Such operations may be completed by using adequate electromechanical actuators. In this case there are considered two DC motors-based actuators, each one driven by a power electronic converter.

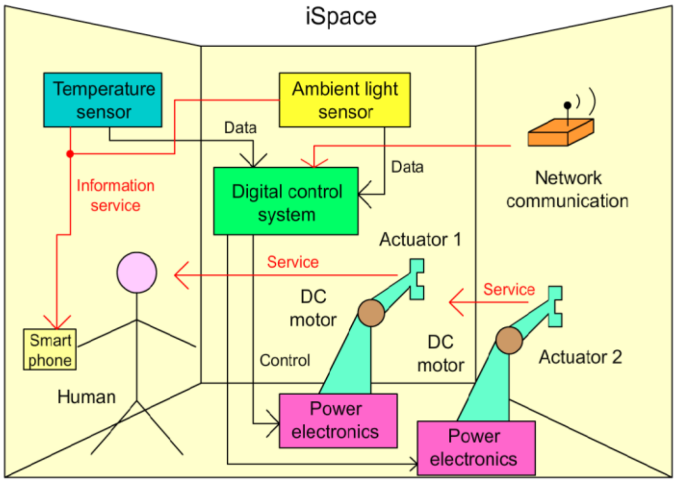

Fig. 3. Particular iSpace topology

By utilizing the acquired information and sharing intelligently with a digital control system or other modern electronic devices (for example a smart phone) the human can get useful services. Such support may be some information services, communication services, or other interactions and dependencies.

However, it is not difficult to build-up an experimental model of the considered iSpace architecture. For this purpose the adequate physical counterparts of the elements marked on figure 3 should be selected. As example, a good choice for the ambient temperature measurement looks the Digilent Pmod TMP3 sensor. This is a ready-to-use manufacturer board that has been built-up around the TCN75A integrated circuit [9]. The module provides up to 12-bit resolution information about its surrounding temperature that is transmitted via high performance I^2C serial protocol to a host unit. For the ambient light intensity measurement a well fitted solution is the Digilent Pmod ALS sensor. This small size PCB converts light intensity into digital information with 8-bit resolution by using the ADC081S021 analog to digital converter IC. The captured information is transmitted toward a via high speed serial-parallel interface protocol to a digital host module [9]. For electromechanical actuators may be chosen the Digilent DC motor/Gearbox units. They exhibit rugged heavy duty construction that includes incremental encoder for sensing rotation and speed [9]. The gear ratio is 1:19 and the motors supply voltage is up to 12V DC. These two DC servomotors are driven by Pmod HB5 inverter units that are 2A H-bridge circuits including sensors feedback pins to capture position and velocity information [9].

Perhaps the most difficult issue is to select the adequate digital control system that is able to integrate in efficient manner above ranked interface modules. Digital system manufacturers provide customers with a wide range of ready-to-use hardware architectures specially designed to fulfill the most demanding user requirements. Among these a high performance ready-to-use manufacturer board is the Zybo Zynq-7000 ARM/FPGA development system [10]. Zybo is a last generation FPGA (Field Programmable Gate Array) processor-based embedded system specially conceived for sophisticated control algorithms implementation. Its central processing unit is a dual-core ARM Cortex-A9 processor with a Xilinx 7-series FPGA circuit that is interfaced with a rich set of peripherals, such as Pmod-type modules, on-board memories, or audio/video inputs/outputs. Among the main features of Zybo also may be mentioned the followings: 249 kB Block RAM, 80 DSP (Digital Signal Processor) slices, on-chip dual channel 12-bit 1 MSPS analog-to-digital converter (XADC), on-board JTAG programming, UART to USB converter, 512 Mb x 32 DDR3 memory block, 650 MHz dual-core Cortex-A9 processor, 1G Etherent and USB2.0 communication ports, VGA output port, 128 Mb Serial Flash interface, audio codec with headphone out, microphone and line in jacks, and general purpose input/output (GPIO) interfaces embedding 6 pushbuttons, 4 slide switches, 5 LED diodes, and 6 Pmod-type ports with 6 pin communication bus [10]. All the above immense facilities provide an ultra-low-cost alternative for designers who require massive parallel processing power and wide hardware flexibility [11].

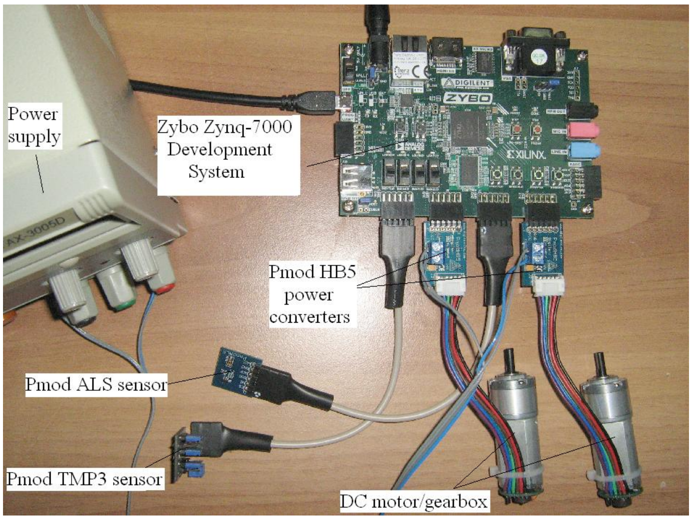

Fig. 4. The experimental setup of the iSpace topology

In figure 4 is presented a simplified experimental laboratory setup of the above discussed iSpace configuration. There are evidenced the Zybo Zynq-7000 development system, as the central processing unit, the interfaced Pmod ALS ambient light and Pmod TMP3 temperature sensors, respectively the two DC motor/gearbox actuators driven by their corresponding Pmod HB5-type power converter units. These are supplied via a 12V DC power module. The Zybo board also allows wireless internet communication, RS232 protocol, or other high speed serial communication protocols. The developed hardware configuration is full suitable for implementation of a wide range of support, service and communication tasks of the considered iSpace. Of course, in this implementation framework has been consciously omitted same mechanical element parts suitable to contribute to improvement of some physical services. Even so, the implemented hardware framework ensures sufficient physical support to implement the discussed iSpace topology. Additionally, this high performance embedded system offers versatility for a large set of intelligent space related algorithms and control strategies implementation.

Nevertheless, let's approach now the iSpace model from figure 3 as a cyber-physical system. For this reason it is proposed a block diagram as shown next in figure 5.

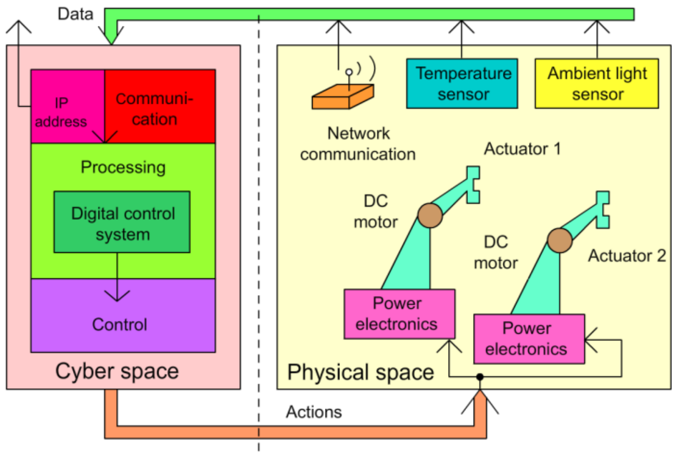

Fig. 5. The iSpace modeled as a CPS

In this figure all the physical elements of the iSpace (excepting the digital control system) has been placed and rearranged into a single layer named "physical world" or "physical space". Next, let is suppose that these physical elements performs the very same actions and operations as have previously stated in figure 3. All the implemented communication, processing and control tasks are considered collected in another layer, named "cyber world" or "cyber space". In this space only logical actions take place. Even being a physical component, the digital control system has been placed here, in order to express that all the cyber activities flows on this framework or support. The two clearly delimitated spaces communicate to each other via buses. The entire information amount captured from the physical space is delivered as data flow on the one-way bus. Respectively, the cyber space performs its control strategies over the physical elements via another one-way bus as a large set of actions. It is not difficult to observe from the above remarks that the same iSpace environment now has been approached and modeled as a complex CPS, discussed before in paragraph 3.

V. Discussion and Conclusions

As is possible to deduce from the previous presentation, this paper emphasizes the main idea that iSpaces also may be modeled as complex CPSs. Of course, this approach is suitable to generate a lot of welcome observations and discussions, as well as many questions and concerns. However, the basic idea of the paper is to open a theoretical analysis regarding the overlap degree of these two main concepts widely used in international references. In this endeavor is better first to underscore what are the clear issues in which a powerful confluence of the two terms can be evidenced. Therefore, a few of arguments that indicate the iSpaces and CPSs high overlapping degree may be ranked as follow:

- they both may embed or can be built-up with the very same physical elements or components;
- a primary role of both iSpaces and CPSs is to link physical space with digital technology (CPSs in an industrial context, iSpaces usually in a human life context);
- iSpaces and CPSs may use the same digital hardware technologies;
- iSpaces and CPSs may use the same software and programming technologies;
- they both have been built-up upon powerful network structures and architectures;
- often they use the same network communication technologies and protocols;
- the same control strategies may be implemented both in iSpace and CPS topologies;
- they often performs the same computing strategies (distributed computing, cloud computing, real-time computing, etc.);
- they often implements very same artificial intelligence strategies;
- both iSpaces and CPSs uses wire- and wireless communication;
- both iSpaces and CPSs may use the same electromechanical actuators, robots, or mobile agents;
- they uses very same sensor technologies;
- they both shares and an identity expressed in a space dimension (3D identity).

As is possible to summarize from the above, there are a plenty of issues or behaviors in which iSpaces and CPSs exhibits very similar identity. Therefore, it is not surprising at all that an iSpace may be modeled as a CPS. In spite of all these, there may be ranked two very important differences between iSpaces and CPSs:

- if the central element of an iSpace is usually the human being, the central element of a CPS is the physical object (or manufacturing plant);
- the main scope of an iSpace is to improve human life conditions (to make more convenient and comfortable), respectively the main goal of a CPS is to improve manufacturing processes (to implement smart production).

Of course, there it is no mistake also to remark that in a wide range of industrial applications the iSpaces specially have been built-up with the main goal to improve manufacturing processes. On the other side, CPSs during the smart production process also widely contribute to the humans working conditions improvement. So from this point of view other interesting interferences occur that are predestinated for discussion and comprehensive analysis. Hence, as expresses the title, this paper focuses on the main idea expressed as: iSpaces modeled and approached as CPSs. Obviously, arises the next question: vice versa is true? In other words, it is possible also to model and approach CPSs as iSpaces? It is no doubt these questions may generate a lot of discussions and various approaches or view points from different authors. Foremost of all, any study, opinion, or theoretical and experimental analysis that are focused to highlight iSpaces and CPSs confluence area and their overlap degree, is welcome. However, as a general conclusion the iSpace and CPSs concepts are widely used in recent international references and there it looks additional need for more investigations and refined approaches regarding these theoretical aspects and research issues.

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