Visual Computing as Key Enabling Technology for Industrie 4.0 & Industrial Internet

Jorge Posada, Carlos Toro, Iñigo Barandiaran, David Oyarzun *Vicomtech-IK4 Foundation (Spain)*
Didier Stricker *DFKI – German Research Center for Artificial Intelligence (Germany)*
Raffaele de Amicis *Fondazione Graphitech (Italy)*
Eduardo B. Pinto *Centro de Computação Grafica (Portugal)*
Peter Eisert *Fraunhofer HHI (Germany)*
Jürgen Döllner *Hasso Plattner Institut (Germany)*
Ivan Vallarino *Mivtech (Panama)*

Members of GraphicsMedia.net

***Abstract*—We present in this paper a comprehensive view of the important role of Visual Computing as Key Enabling Technology in the materialization of the different global visions of new generation of ICT solutions in Manufacturing and Industry in general. A worldwide trend in advanced manufacturing countries is defining Industrie 4.0, Industrial Internet and Factories of the Future as a new wave that can revolutionize the production and its associated services, based on the emergence of the Internet of Things and Services in the factory, allowing the configuration of Cyber-Physical Systems in combination with other key technologies. Visual Computing plays an important role as "glue factor" in complete solutions.**

***Index Terms*— Advanced Manufacturing, Digital Manufacturing, Industrial Internet, Industrie 4.0, Computer Graphics, Computer Vision, Visual Computing**

I. Introduction

There is a clear, worldwide trend in some of the most advanced worldwide economies in reinvigorating (and revolutionize) the industrial and manufacturing core competencies with the use of the latest advances in ICT. A tacit recognition in the fact that ICT could open completely new possibilities to improve productivity and efficiency in manufacturing is leading much of the actual efforts. The aforesaid trend states that the relative weight of ICT in the new competitive approaches to manufacturing will be growing in the years to come. Local and regional governments are aware of the importance of ICT in industry and for such reason, novel initiatives and programmes are being developed and launched. Initiatives such as the Industrial Internet and the Advanced Manufacturing Partnership in USA, the Industry 4.0 (*Industrie 4.0* in German), la Nouvelle France Industrielle, etc. are just a few of different examples of this vision. Even smaller regions with a long tradition in manufacturing (and not only countries) are following the trend from their own local perspective (e.g. the Basque Country intelligent specialization policy RIS3 in Advanced Manufacturing).

Fully complementary with the fields of Internet of Things and Industrial Internet but more focused in aspects close to Automation, Connectivity and Ubiquitous Information, Cyber-security, Intelligent Robotics, Product Lifecycle Management, Semantic Technologies and Industrial Big Data, the technologies comprised in Visual Computing provide a feasible support for the new aforementioned initiatives and are explicitly considered for example in the German vision of Industrie 4.0 [6], which will be used as the context initiative of this paper.

Some of the key aspects addressed by Industrie 4.0 are: (i) the IT-enabled mass customization of manufactured products, in which production must adapt to very short batches or even individual needs, (ii) the automatic and flexible adaptation of the production chain to changing requirements (iii) the tracking and self-awareness of parts and products and their communication with the machines and with other products, (iv) the improved human machine interaction paradigms, including the coexistence with robots or radically new ways to interact and operate in the factory, (v) the optimization of production due to IoT-enabled communication in the Smart Factory, and (vi) the emergence of radically new types of services and business models contributing to new ways of interaction in the value chain. As explained in [6], with the introduction of the Internet of Things and Services, the Cyber-Physical Systems –CPS- are central to this vision, and include smart machines, storage systems and production facilities that are able to exchange information with autonomy and intelligence, are able to decide and trigger actions, and can control each other independently.

To achieve this vision, as stated in [11], it is necessary to capture, analyze and interact with both the *real* -physical- and the *virtual* –digital/cyber- production world, with high level of precision in all dimensions (spacial, temporal, etc.). From this perspective, the application of Computer Graphics and Computer Vision (Visual Computing) technologies play an important role in achieving Industrie 4.0 solutions, as for instance in HMI aspects, in visual monitoring of the real and the physical worlds, to name just two aspects. This article will analyze in detail how Visual Computing technologies are key enablers for Industrie 4.0 and Industrial Internet.

Visual Computing is understood as the entire field of acquiring, analysing and synthesising visual data by means of computers which provide relevant-to-the-field tools [29]. Among the most recognizable technologies advantaged by Visual Computing, Computer Graphics and Computer Vision (including Human-Machine Interaction), are proving to be instrumental.

In this article we introduce a conceptualization of the main technologies of Visual Computing for Industrie 4.0. We show some concrete examples of applied research projects (in different international scenarios) and their alignment with aforesaid view. Furthermore, we identify key technologies and challenges to be addressed by the scientific community approaching the realization of Industrie 4.0. We intent to

provide an integrated view and an international perspective of the current trends and challenges of Visual Computing for Industrie 4.0. Our discourse is based on the common view and aggregated experiences of relevant applied research centres in Europe and America).
We argue that Visual Computing could play and important role in the development of Industrial Internet and Industrie 4.0 paradigms.

This paper is structured as follows: in section II we present an illustration of concepts focusing in the topics of Industrial Internet and Industrie 4.0 and showing the need of Visual Computing technologies. In section III we illustrate the relevance of Visual Computing as Key Enabling Technology with an arguably central role in both visions, detailing the most relevant technologies for the related industrial priorities. Section IV proposes specific application and research challenges in the field, and lastly, in section V we show some examples of projects where Visual Computing plays a relevant role for Industrie 4.0.

II. Industrie 4.0 and Industrial Internet as Global Trends with Visual Computing Needs

Advanced Manufacturing is defined as the kind of manufacturing that entails rapid transfer of new knowledge into industrial processes and products [15]. It is widely accepted that ICT technologies are Key Enabling Technologies to accelerate and improve productivity in manufacturing. The deployment of ICT in the late 60s into production was actually an Industrial Revolution. The competitive factories of today cannot be conceived without today´s Industrial Automation pyramid (including PLC, MES, ERP and other key technologies) in production, or without the Product Lifecycle Management supported by advanced CAD/CAM/CAE tools, just to mention a few evident cases.
Recent developments in ICT are arguably opening revolutionary possibilities for manufacturing and production, being the most important one the implementation of the latest internet-related technologies in the industry. Due to several technical, market and cultural reasons, industry is paradoxically one of the last niches to be conquered by the pervasive and ubiquitous developments associated with the Internet of Things and Services.

In the USA, the so called "*Industrial Internet - the Third Wave*" –term coined by General Electric in their visionary paper [1] already widely accepted in many American academic organizations such as NSF I/URCC Center for Intelligence Maintenance Systems (IMS) and other relevant industrial actors, has a strong focus on a higher degree of *intelligence* with the power of advanced computing, analytics, low-cost sensing and new levels of connectivity permitted by the Internet [23]. Three elements characterize this vision:
(i) intelligent machines,
(ii) advanced analytics, and
(iii) people at work.
In Figure 1 the data loop of Industrial Internet points out very relevant aspects for which Visual Computing could be a Key Enabling Technology, such as *remote and centralized data visualization*, or *big data analytics.*

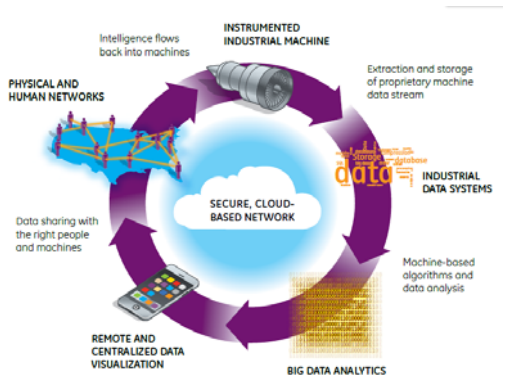

Figure 1. Industrial Internet data loop (General Electric) [1]

On the other side, the strategic initiative *Industrie 4.0* (whose leitmotiv is as ambitious as "*Securing the future of German Manufacturing Industry*") [6] has created not only a German-wide but an international landmark in terms of setting the vision, technological opportunities and scientific challenges, related with the entrance of the new generation of ICT technologies, including the Internet of Things and Services and the *Cyber-Physical Systems* (or CPS) [10,16], in industrial production systems. The basic idea is that we are facing a fourth industrial revolution (see Figure 2), with disruptive applications of new generations of ICT in manufacturing.. Interestingly enough, the CPS concept was actually coined by US in 2006-2008 by Lee et al. [7]. This concept has been readily adopted in Europe by Germany in the Industrie 4.0 initiative and later by the European Union in their H2020 research framework program [5]. CPS refers to the convergence of the physical world and the digital world (cyberspace). When applied to production, CPS is specialized in CPPS or *Cyber-Physical Production Systems*. Even considering that there is some criticism regarding certain vagueness in the term and sometimes excessive marketing [4], it is now widely accepted that the vision and the related technologies of Industrie 4.0 have set already a real impact in current and future industrial manufacturing systems.Reputed independent studies [22] show that the potential of Industry 4.0 is already on its way, and that its international scope is clear, especially for Europe. This study shows specific examples of European companies (such a Trumpf –smart social machines-, Siemens –customized knee implants-, Bosch and many others in Germany, but also Rolls-Royce -3D printing of jet engine components- in UK, and Dassault –cloud based collaborative 3D CAD- in France, for instance) are pioneering this trend
In both USA and European visions a strong industrial commitment with long term associations is backed up by research institutions: The *Industrial Internet Consortium* was constituted in 2014 and the *Industrie 4.0 Plattform* in 2013.

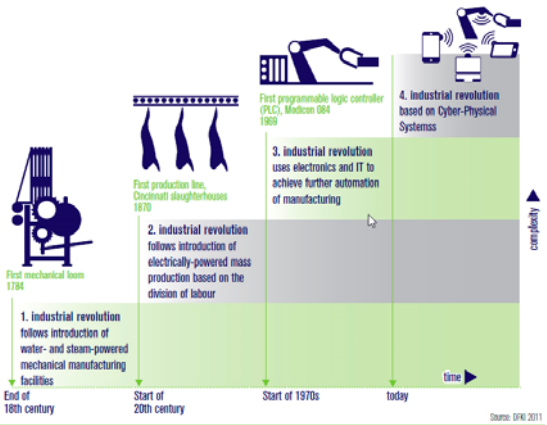

Figure 2. Industrie 4.0–The 4th Industrial Revolution with CPS [6]

In Figure 3, a conceptualization of Industrie 4.0 and implied interaction technologies by a leading machine tool producer (Trumpf) [9] is shown. The coexistence and mutual interaction of the physical world and the virtual (cyber) world, with the use of emerging ICT, opens possibilities such as:
(*i*) the concept of social machines following paradigms of Internet connectivity and Social Networks,
(*ii*) the seamless interconnection of global facilities,
(*iii*) the advantaging of augmented operators with extended perception and action possibilities and
(*iv*) last but not least, the use of Smart Products able to know and update their status providing services in a virtual production context.

As it will be shown in the next section, the detailed technological concepts behind Industrie 4.0 are somewhat lacking of cohesion. Diverse technologies such as Big Data, Advanced HMI, 3D Models and Simulations, Cloud Computing, Cyber-Physical Systems, Internet of Things and Services, Machine to Machine (M2M), and Smartization [8] can be applied in Industrie 4.0 solutions. Isolated, they seem to have no evident relation but when used together in an industrial application context their added value brings new possibilities.

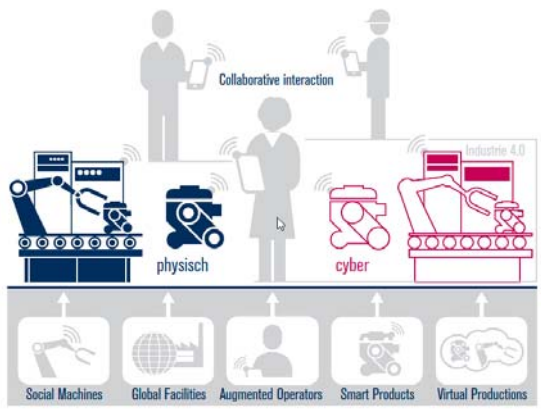

Figure 3. Interaction possibilities in a Smart Factory scenario [9]

We argue that *Visual Computing technologies* are an important Key Enabling Technology that could act as a *"glue factor"* providing a cohesion element in many applications related with Industrie 4.0 and Industrial Internet. Although in several scenarios of Industry 4.0 there is no specific role for Visual Computing (as for instance in pure IoT connectivity applications between machines and parts), in many relevant cases its role as facilitator and integrator of other technologies enhances sensibly the final application. As a relevant example, Visual Analytics solutions can link industrial Big Data processing & mining, with Semantic Technologies and Product Lifecycle Management technologies (each technology separately would have a more limited impact).

III. Visual Computing as Key Enabling Technology for the Next Industrial Revolution

One of the most successful application areas for Computer Graphics has been industry and manufacturing. To point out a very relevant example, the whole field of 3D CAD/CAM/CAE is a very direct consequence of the key enabling capability of Computer Graphics in the right industrial moment. 3D CAD research that started in the late 60´s has been decisive for the competitiveness of many industrial sectors, conspicuously the automotive, aeronautic, industrial plants and machine-tool sectors. In the case of Computer Vision, the industrial sector has also a great importance, especially when applied to quality control and inspection (Machine Vision) of manufactured products, and more recently to robotic control, to name two relevant fields. Almost every manufacturing industry has such systems integrated. These evident examples complemented by many others, showing how Visual Computing technologies have a very strong position in modern digital manufacturing. We consider that Visual Computing will be also a Key Enabling Technology in the new generation of Industrial Internet and Industrie 4.0, along with other technologies such as Industrial Automation.

Looking at the future, in the strong global wave represented by Industrie 4.0, Industrial Internet, and other similar initiatives, a somewhat disperse collection of technologies is mentioned recursively as necessary for achieving these visions. Surely the *Internet of Things and Services* is the core technology, since this is being revolutionized by the emergence of *intelligence* (intelligent devices, intelligent networks, and intelligent decisioning) [2], and complemented by fully cloud-based systems, cost-effective Internet solutions for industrial set-ups, secure and robust networks, mobile Internet possibilities, etc. But it is also true that a few key additional technologies are indeed necessary for complete solutions, such as Cyber Security or Semantic Technologies [17]. A comprehensive review of relevant technologies for Industry 4.0 from the point of view of an authorized relevant standardization body can be found in the chapter 4 of [27]. We simplify this comprehensive view in Figure 4, pointing out the relevance of Visual Computing technologies (explicitly quoted as computer graphics, image processing. 3D, image representation, visualization, user interfaces, etc.) in this context.

We suggest that Visual Computing could play a key role in *enhancing* and *enabling* the realization of Industrial Systems that follow the new paradigms of the next industrial

revolution. In many cases it is precisely the use of Visual Computing technologies what allows a complete and integrated solution (see Fig. 4), since acts as a "*glue factor*". This is not necessarily always the case (there are for instance solutions purely based on Industrial Automation and IoT that don´t require Visual Computing). However, when we see the overall picture of the possibilities of this wave-revolution, Visual Computing plays indeed an important role and will be present in many solutions.

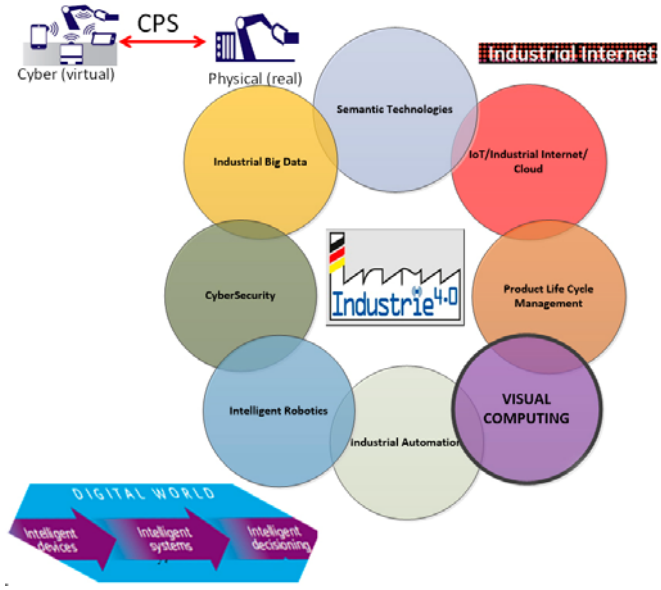

Figure 4. Visual Computing as part of the technologies in Industrie 4.0

In order to achieve *Cyber-Physical Systems* for Industry, the *virtual simulation* of products and processes, before and during operation, are a key aspect for achieving critical goals for product configuration and production flexibility. The modeling and simulation of processes covering the full product lifecycle (from design to disposal) is a very relevant aspect, especially with the emergence of the *Cyber-Physical Equivalence (CPE)* concept, coined by Lukas and Stork [11]. The aforementioned concept refers to the fact that virtual and physical dimensions coexist synchronized in time. The equivalence given in terms of digital twins provides very interesting features as virtual simulation can be overlapped with the physical object feeding real data being processed in realtime and overlapping the simulation model in an unobtrusive way. CPE is relevant in our approach because the set of tools that will allow the inter equivalence between the real object and its twin need advanced Computer Graphics techniques for its implementation in a real world scenario. Not only is the product level addressed but also the processes level, the machines and the factories. Virtual simulations should be ready to cope with self-organizing production and control strategies [21]. This is a clear linking example of *Product Lifecycle Management*, *Industrial Automation* and *Semantic Technologies* [20], in which Visual Computing plays a central role.

A new generation of Human Machine Interaction applied to industry is needed for optimizing the configuration of manufacturing jobs, including not only operation of machines and production lines, but also aspects related to extended training and qualification. These are intelligent and multimodal assistance systems that put the person in the centre of production. For instance, there are HMI related research projects financed by the German Government in the program "*Virtual Techniques for the Factory of the Future – A Contribution to Industry 4.0*", [3]. Many of those projects address enhanced HMI development with a special focus in involving the interaction using personal mobile devices with scattered and heterogeneous CPS. The traditional and de-facto standards for operation of machines can move towards radically new forms of interaction, including gestures, mimics and haptics, using new forms of "interaction primitives" in analogy to the currently normalized functions and symbols for machine operation. HMI by itself is a factual part of today's manufacturing systems and it is present in the manufacturing lines more and more. New technologies related to HMI like multi touch and contextual menus categorized by user roles are new approaches in both the technical and conceptual perspectives and they are now part of some of the catalogues of machine-tool providers. It is a fact that HMI new developments need to be aligned with CPS gathering of data and being essentially oriented towards a user perspective. Such systems will involucrate the user in the factory as a consumer and producer of knowledge that can be advantaged by the manufacturing processes.

A last example is related with the Industrial Big Data and the need of new enabling capabilities for *Intelligent Decisioning* emphasized in the Industrial Internet initiative. The potential of Visual Analytics (an important scientific field in Visual Computing) is serving as "glue factor" and enabling technology for linking otherwise separated technologies such as Industrial Big Data, IoT-Cloud, Intelligent Devices and Semantic Technologies. Industry is one of the most demanding and challenging scenarios for Visual Analytics: as pointed out in [18] in many cases billions and even trillions of individual products of certain industries are produced per year. Also, the level of information provided by modern machines and production lines can be of very high orders of magnitude (a single complex machine can have a couple of thousand sensors, that in some cases should be read in milliseconds pulses, providing many billions readings per year). This requires not only new ways of handling the sheer amount of information, but also new forms of organizing the information in a sensible way to be understood by humans and allow them to take decisions. Visual Analytics can help to provide new insights and hidden patterns, not evident by purely automatic data mining.

There are many other examples that reinforce our claim, such as the *IntoSite* project of Ford and Siemens using Geographic Information Systems and VR Environments to navigate global manufacturing sites and share best practice information; or the *SmartFactory Lab* hosted by DFKI in Kaiserslautern (Germany) demonstrating the use of Visual Computing through the use of mobile devices and advanced visualization techniques such as Augmented Reality for accessing and

analyzing the information generated in an integrated Intelligent Factory;; or the Spanish applied research project *Thinking Factory* led by the crankshaft manufacturing company Etxe-Tar, where Visual Computing techniques are applied for visualizing and analyzing Big Data, gathered by CPSs installed in several manufacturing cells for the generation of services such as preventive or predictive maintenance.

In Figure 5 we have performed an analysis of the most relevant Visual Computing technologies to determine the significance for future applications in Industrie 4.0 and Industrial Internet as it has been proposed for example by the ARVIDA, SOPHIE, ProSense, SmarPro and similarprojects in Germany [24]. This is a useful guide to identify critical crossings between priorities of the next industrial revolution based on ICT and the fundamental Visual Computing technologies that can act as enablers. The criteria in the left side of the figure will be explained in more detail in the next chapter, where concrete examples will be introduced developing the concepts of this matrix. This matrix is by no means exhaustive, in the sense that other crossings are also possible depending on the application scenario.

The figure shows interesting confirmation of the relevance of Visual Computing in this context, and at the same time is a way to align research priorities in the specific technologies with regard to the different needs of the new generation of industrial systems based on Industrie 4.0.

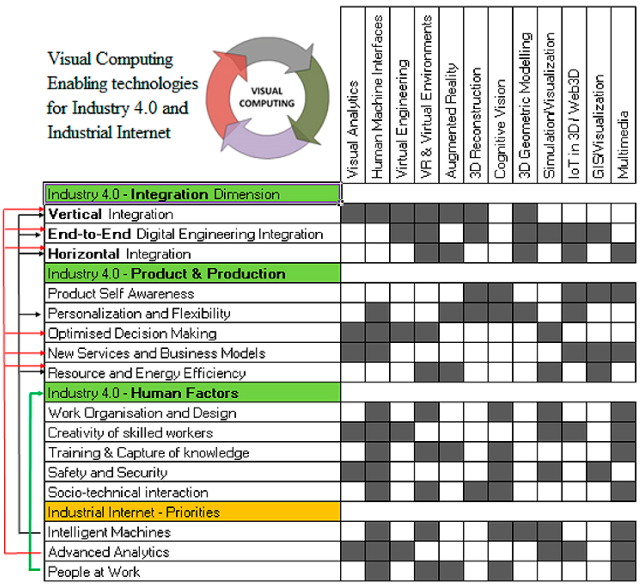

Figure 5. Visual Computing technologies relevant for Industrie 4.0

IV. Visual Computing Research Challenges and Applications for Industrie 4.0 and Industrial Internet

This section will focus on specific research challenges and potential applications of Visual Computing for the next industrial revolution proposed by Industrie 4.0 and Industrial Internet. We order these proposals according to high-level criteria that are at the core of these initiatives [1, 6], and that are depicted at the left side of Figure 5. We will summarize the relevance of these criteria and propose application scenarios for the crossing with Visual Computing technologies. The purpose is to suggest interesting research lines in each of the priorities and show at the same time from a global perspective the integrative and relevant role of Visual Computing.

In this context, we would like to recall the work by von Lukas and Stork [11] (in German), that proposes that Visual Computing can help in a bidirectional way to achieve Cyber-Physical Equivalence in Industrie 4.0: the direction of "*cyberizing the physical*" (inluding different sensors/actuators with physically-based simulation) and the opposite direction, "*physicalizing the cyber*" (realistic, real-time visualization and interaction with digital models and also the 3D printing area). They also point out a short summary of themes of Visual Computing relevant for Industrie 4.0, related with geometric data models adapted to CPS, real-time simulation approaches, or image processing needs to reconstruct and "*cyberize*" the physical world. With a similar approach, our work gives an enhanced and more comprehensive and global overview, with concrete examples, and adds a direct and explicit link with the strategic priorities of both the Industrie 4.0 and the Industrial Internet initiatives.

Our proposed matrix is designed based on three main criteria:
1) the integration dimensions,
2) the product and production priorities, and
3) the human factors dimension.

The methodology that we use to present these challenges and applications is to sketch them in the 3 tables of this section,. The Computer Graphics and Visual Computing researcher should be able to define and identify, from the context and the proposed subject, specific research contributions in each line. The tables focus more on providing a path (a roadmap of main global challenges) than in detailing each challenge. To illustrate this approach we present one scenerario for each table category.

The first criterion in our proposed matrix is related with the "*integration dimensions*. According to ACATECH [6], there are three dimensions in the integration of manufacturing systems:

- *the Vertical* integration and networked manufacturing systems
- *the End-to-end* digital integration of engineering across the entire value chain
- *the Horizontal* integration through value networks

Vertical integration allows CPS be used to create *flexible* and *reconfigurable* manufacturing systems. The setting for the vertical integration is the Factory. It refers to the integration of various Information Technology systems at different hierarchical levels during a manufacturing process and that is where CPS plays an important role as sensor/actuator duality

behavior elements. Visualization of the complex interaction between these levels may help the user to improve the factory planning.

ICT systems in *end-to-end digital integration* refers to a holistic digital engineering view, and proposes to close the gap between product design and manufacturing and the customer (Product Lifecycle Management), from the product design and development, through production planning, production engineering, production and associated services. This is one of the central aspects where Visual Computing has an influence, since CAx systems are highly visual.

Finally, *horizontal integration* refers to the use of these technologies for exchanging and managing information across different agents around a manufacturing process such as resources management system, logistics, marketing, or inter-company value chains. As an example, Augmented Reality based maintenance, with the newest advances in devices and processing, can be an excellent case for Visual Computing contribution to horizontal integration

Table 1 shows how Visual Computing enabling technologies are related with aforementioned integration dimensions. Vertical Integration requires a level of communication and interaction between different production layers, towards a Smart Factory vision. Visual Computing technologies such as as real-time 3D representation of data-flow during product manufacturing are important enablers in this dimension

Table 1. Industrie 4.0-Future Factories – Visual Computing Challenges in the 3 ***Integration*** *Dimensions*

Industrie 4.0–**Integration** Dimension	Visual Computing Enabling Technologies and Challenges
Vertical Integration, networked manufactured systems: Autonomous CPPS that exchange information, trigger actions and control each other	**-Virtual Environments**: Visually empowered 3D Simulation scenarios for new ways of planning production, especially suitable for dynamic & fast changes. Scenarios for testing different configurations. -Real time representation of production: **Visualization of flows of information/material/knowledge** in the factory, not only physical representation. **-3D Scanning / 3D Reconstruction** of factories: real need and big challenge to adapt old factories to new paradigms. **-End User Interfaces** to edit configurations in demanding work conditions (in production lines).
E**nd-to-end** digital Engineering Integration: Holistic Lifecycle Management	-Natural flow of the **persistent** and **interactive digital model** in Product Lifecycle Management in **Full 3D Web**: Real industrial large **3D CAD/CAM models** with full access to semantic/product dynamic data in Web3D. **-3D real-time simulations** for a cyber-physical equivalence of production. -New paradigms of **3D Geometric representation of new processes** (e.g. laser based manufacturing, fast-speed material removal, micro and nanomanufacturing, etc.) and new **materials** (biomaterials, metallic powders for 3D metal printing, etc.). **-Computer Vision "Closing the loop" of 3D production** planning, giving real-time coupling of production process and 3D models. Geometry adaptation to physical conditions.
H**orizontal** integration through value networks: Value chain integration	**-Augmented Reality for service-based actions** with providers and clients. **Maintenance and installation** are the main drivers. Main Challenges are in the **ergonomic aspects** of the solutions going from the lab to the real factory and in the **integration** with the information systems. **Intelligent Media streaming/search** is also a key technology to improve service (as in teleoperation). **-3D Model automatic simplification** preserving critical features for service tasks and at the same time allowing **interaction/visualization in mobile** low-power devices in the client.

The end-to-end integration dimension can benefit from Visual Computing techniques such as 3D visualization techniques for realistic product representation and simulation.Also Computer Vision related techniques for product quality management, both offline and online, are relevant. Online real-time Computer Vision techniques allow closing the loop from product design and product manufacturing, i.e., providing immediate feedback from the real part to be compared with the digital 3D model. In an Industrie 4.0 scenario, this can be a *dynamic* feedback as the part is being manufactured, not a comparison between the final part and the static 3D model

Finally, horizontal integration is also enhanced by Visual Computing through the using of, for example, Augmented Reality techniques for added-value services, such as functional or installation augmented manuals (AR manuals).

Also, techniques related with 3D compression, model simplification or model adaptation by using semantic information can be fundamental when big amounts of 3D data need to be interchanged or transferred to different entities through value networks. This problem existed also before, but with Industrie 4.0 it becomes more relevant.

To illustrate some specific challenges that stem from Table 1, let´s look into "new paradigms of 3D Geometric representation of new processes" in more detail. For the Computer Graphics researcher, there is a challenge in devising new ways to represent 3D Geometry for CAD/CAM, since radically new fabrication processes emerge and require new 3D representations and algorithms (for instance slicing). Take as example 3D Printing: computational aspects of this type of fabrication are posing research challenges such as appropriate orthogonal slicing [25][26]. Other challenges here include volumetric representations, to cope with multiple materials and a sheer number of voxels.

The second criterion in the matrix, described in Table 2, is related with *product* and *production* priorities in Industrie 4.0. We have taken as basis the priorities explained in [6] (pages 15-18 and 20-25) and have conceptualized, reorganized and summarized them in such a way that the applicability of Visual Computing technologies is more evident for a meta-category of *product* and *production*, leaving all priorities related with *human factors* in a separated category. This classification also helps to bridge more clearly with the

Industrial Internet priorities.

According to this classification, the product *self-awareness* is a requirement for the so called "Smart Products". In this context, the use of technologies such as 3D Cyber-Physical Equivalence, to make the physical and virtual representations of parts, machines and lines fully synchronized, are essential. *Optimized decision-making* is one of the most critical requirements where Visual Analytics applied to Industrial Big Data can give new insights to decision-makers. The feedback given by production data to 3D digital engineering in real-time can be a key factor to model the deviation between the theoretical model and actual product. Specially adapted *User Interfaces* are also necessary, adapted to user profile and context. Web3D can provide new possibilities for the *Emergence of new services and business models*, which is a very important motivation in Industrie 4.0, technologies such as the "in" or "digital alter-ego" of the product [19]. *Resource and Energy Efficiency* is another field of high interest, where virtual environments, GIS, simulation & visualization, open new ways to improve these aspects in Industrie 4.0. As an example, the interactive study of different logistic paths to transport parts from one factory to another can lead to energy efficiency measures

Let´s analyze in more detail one of the challenges of Table 2: Visual Analytics for Production Big Data. As presented in [18], a typical real-life scenario in the manufacturing industry of personal care products can produce 152.000 data samples a second (in millisecond cycles), 13 billion of samples a day, and 4 trillion of samples per year. Visually inspecting clusters of sample data in time may give a hint for a specific production bias due to, for instance, machine deterioration. Visual Analytics opens in this context new ways to handle this complexity and get insights from this overwhelming amount of data, but only due to newest advances in Big Data and visualization (such as presented in several articles of IEEE Big Data 2014) such challenges can start to be addressed today.

*Table 2. Industrie 4.0-Future Factories – Visual Computing Challenges in **Product & Production***

Industrie 4.0– Product & Production	Visual Computing Enabling Technologies and Challenges
Product self-awareness (history, status, location, delivery strategy, service)	-Integration of **GIS** (outdoor) with in-factory (indoor) **localization-visualization systems**, for individualized product tracking and as underlying connection layer between factories and products when delivered. **-Cyber-Physical 3D equivalence** at all times linking product digital model and situational status.
Personalization / flexibility – flexible adaptation to Individual customer requirements	- **3D interactive tools to empower of the end user** in the final configuration of his/her own product. - Automatic generation of **options catalogue** according to production parameters and user preferences. - **3D Shape automatic adaptation** that fits production and manufacturing restrictions. - Linking of **3D changes** with **resource impacts** (in time and cost).
Optimized decision-making with access to real-time production and design data	**-Visual Analytics** of **Production Big Data**: Trillions (or more) samples per year (e.g. GE Industrial Big Data [18]). -Real-time **mixing** of production **Big Data with 3D digital engineering** design data **-User Interface dynamic adaptation** of information to user-profile, devices and context. Visual Analytics system for the engineer and the worker.
Emergence of new services and business models	-Digital **coexistence or "alter-ego" of the physical product**, enabled by **Web3D, localization** and **mobile interaction** technologies, allowing new services (e.g. social networks of users of the same product line).
Resource and energy efficiency & Sustainable production	**-Dynamic resource visualization** at the factory level, including sustainability footprint (e.g. CO2 consumption), energy distribution in the plant, material waste, etc. Can be mixed with **VR** and in some cases **Augmented Reality.**

The third criterion, described in Table 3, is related with the *human factors* dimension. Industrie 4.0 and Industrial Internet visions, and also the visions of EFFRA/EU (EFFRA roadmap for the Factories of the Future) [5], recognize the strategic importance of skilled workers and engineers for a competitive Smart Factory vision. For *work organization and design* where novel multimodal HMI and new interfaces can change the current operation of machines and factories by workers. *Fostering the creativity* of skilled workers by means of virtual simulation of production, and *training and knowledge capture* [17] can also be achieved with new multimedia and Augmented Reality techniques. For *safety and security*, cognitive vision and virtual simulation of emergencies are enabling technologies. Finally the *socio-technical interaction* with robots and intelligent machines is a promising area enhanced by Visual Computing technologies such as 3D reconstruction, virtual environments and visual programming of robots.

Let´s analyze as an example for Table 3 the challenge of "New Human Machine Interface modalities" in an Industry 4.0 perspective. A very good and detailed study on this subject, where the challenges are explained in detail, can be found in [28]. To mention a few of th 26 identified tools and challenges in this work: separation of display and interaction logic, integration of multimedia, real-time data from different perspectives, support for different HMI variants, self learning context recognition, dynamic user profile, interfaces to MES for a preview of simulation results, HMI design and communication interfaces for mobile devices, support for multi-touch and gestures, social (chat/wiki/blog), and open to new input possibilities.

As a summary of this section, the researcher interested in computer graphics and Visual Computing can identifyrelevant research lines and challenges for Industry 4.0 and Industrial Internet. We provide hints to main topics of interest and open challenges, researchers can follow to detect more specific and detailed challenges in each of them.

*Table 3. Industrie 4.0-Future Factories – Visual Computing Challenges in **Human Factors***

Industrie 4.0– Relation with Human Factors	Visual Computing Enabling Technologies and Challenges
Work organization and design, productivity enhancement though improved human intervention	-New **Human Machine Interface** modalities allowing new modes of interaction adapted to workers job restrictions: **voice-based interaction, gesture recognition,** etc. - Need of **Post-WIMP interfaces** adapted to the future trend of mobile devices in the factory. -Advanced **Manufacturing and Production Planning** visualization: linking SCADA systems with Virtual Reality paradigms for interaction in the planning and understanding of the production plan. -Interfaces with **Manufacturing Execution Systems** (MES) allowing different configuration capabilities.
Foster creativity in skilled workers instead of routine	-End user tools for **visualization of flexible production plans** including the location of different machines and persons (with complementary skills) in alternative production scenarios. Tools for discussions between **engineers** and **workers.**
Training and continuing professional development. capture and systematic reuse of the knowledge of the worker	-**Multimedia capture** and **intelligent retrieval** of the knowledge of the worker, as a Key Enabling Technology to capture and transfer knowledge between the workers. -**3D Authoring tools and end-user UI** for **operational training** of complex machines, and in some cases in Virtual and Augmented Reality set-ups.
Safety and Security	-**Cognitive Computer Vision** systems able to detect and contextualize the events occurring in the factory with the goal of improving safety and security. Focus on hazardous area exposition, collision detection with massive objects. -**Visual Simulation for Emergency Response** in the factories.
Socio-technical interaction, co-working with configurable robots	-Visual programming of robot interactions: imitation of **human motion** based on **Computer Vision** for anthropomorphic robots. Ease of use and control of the robot by the worker, not necessarily the engineer. -**Virtual Environments** simulations for human-robot coexistence in production, different configuration and parameters.

V. EXAMPLES OF RESEARCH PROJECTS WITH IN THE CONTEXT OF INDUSTRIE 4.0

In this chapter we present 3 selected examples of research projects directly related with Visual Computing applications for Industrie 4.0, covering a broad spectrum of the criteria presented in last chapters.

MACHS: Virtual platform for professional training of complex machine operation scenarios based on Serious Games

The main goal of the R&D project MACHS is the development of a game-like 3D environment to accelerate and improve the training process (previous to actual operation of the machine) of specialized machine-tool maintenance staff. It is promoted by the industrial group Danobat –(part of Mondragon Corporation, one of Europe's largest industrial groups). Target user of the system are professional workers who have to apply their knowledge to new and different specialized machines, that in some cases are not even produced yet. Therefore, it is important to generate high quality interactive 3D environments, with a pedagogical focus, to enhance the immersivity and user experience, but it is even more important to provide appropriate authoring tools and graphical interfaces for non-ICT specialists to construct the learning experience, and to follow the maintenance tasks performance during the execution in the system [12]. Serious games environments can support different configuration scenarios that may come as a result from machine adaptation to flexible production, in contrast with static manuals (in the form of written manuals or videos showing specific sequences) where everything is predefined in advance. In the future, this kind of environments should be, if possible, automatically generated even in changing conditions, although in current versions of the project this is still not possible, and require a preliminary definition that can evolve according to programmed rules in the game.

The preliminary definition of the interaction of the worker and the machine in MACHS is a basis for the planning of new generation of *Cyber-Physical Systems* in which in many cases the proper interaction between the workers and machines and/or robots have to be carefully monitored, more especially if we consider and flexible configuration scenarios. By providing different training experiences (such as the point-of-view vs. external observer perspectives), and allowing multiple trial-error actions with appropriate feedback, MACHS allow a natural way to expose the worker to the unknown environment of these new machines scenarios.

This links with the *Human Factors* requirements in Industrie 4.0 [6], described in Table 3, related to training and continuing professional development for supporting future demands of having even more production flexibility.

The interaction with the module is intuitive and visual, giving the user the possibility to include 3D virtual models of specific machines and to define actions directly by interacting with the 3D model of the machine. The module also provides custom functions to enhance the commitment of the target user of the course, such as the inclusion of the 3D virtual tutor, and gaming and motivational features. XML-compliant forms are automatically generated by the authoring module, which is based on an intuitive state diagram graph editor linking machine parts and worker actions (Figure 6), and they include the virtual machine specifications (describing the main functional parts of the machine, and the degrees of freedom and constraints for their relative movement) and all the information that is required to build the actions that compose a training course. The concrete specification of these XML compliant forms can be found in [12]. A sequence of actions is then defined where the user can simulate the operation of the machine in different conditions.

The animation engine is able to automatically generate a 3D interactive environment from the information stored. It interactively reproduces the graph that has been created with the authoring module, reacting to the user actions in the way

the author of the course has specified, and following the rules that allow possible different configuration of the actions
The project has been evaluated by machine-tool companies from Danobat Group and is under prototype test with their new machines for two main purposes: training and marketing.

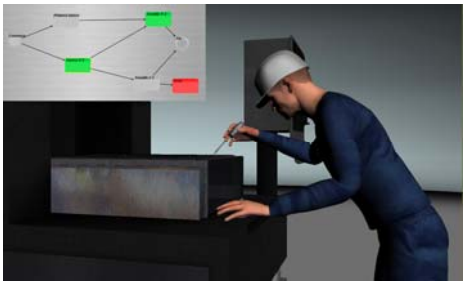

Figure 6. Immersive 3D & Authoring Tools for training of workers, relevant for Industrie 4.0

COGNITO: Capturing of manipulative workflows with Augmented Reality

The main objective of COGNITO is to develop technologies, which allow the capturing of manipulative workflows in industrial production scenarios in such a manner that it can be then used as training material for *adaptive Augmented Reality* training set-ups.

COGNITO is an EU-funded collaborative research project related with Industrie 4.0 –the SmartFactory KL is the laeding partner for the Industrie 4.0 demonstrator [19].

The relationship with the priorities presented in *human factors* is related with the capture and systematic reuse of the knowledge of the worker, as shown in Table 3. It is also related with the *vertical*, *horizontal* and *end-to-end* dimensions of integration in Table 1, regarding the use of Augmented Reality techniques for implementing advanced HMI, applied to training and maintenance. Although capturing systems already exist on the market, they focus primarily on capturing raw motion data, matched to a coarse model of the human body. Moreover, the recorded data is organised as a single kinematic sequence, with little or no reference to the underlying task activity or workflow patterns exhibited by the human subject. The result is data that is difficult to use requiring extensive editing and user manipulation, especially when cognitive understanding of human action is a key concern, such as in virtual manuals or training simulators in industrial scenarios.

COGNITO technology addresses these issues by advancing both the scope and the capability of human activity capturing and rendering. Specifically, it developes novel techniques that allow cognitive workflow patterns to be analysed, learnt, recorded and subsequently rendered in a user-adaptive manner [13, 14]. Our concern is to map and closely couple both the afferent and efferent channels of the human subject, enabling activity data to be linked directly to workflow patterns and task completion. Focus has been put particularly on tasks involving the *hand manipulation of objects and tools* due to their importance in many industrial applications. The key elements of the developed technology is a novel on-body sensor network consisting of miniature inertial and vision sensors, estimation of an osteo-articular model of the human body, recovering the workflow digitally, and developing novel rendering mechanisms for effective and user-adaptive visualization. The work has been evaluated within the context of designing effective user assistance systems based around Augmented Reality techniques for specialised industrial manufacture and has been carried out in close collaboration with industrial and end user partners with promising results.

Figure 7: Created visual workflow using video observation (upper images); Augmented Reality support, using previous digitalized visual workflow

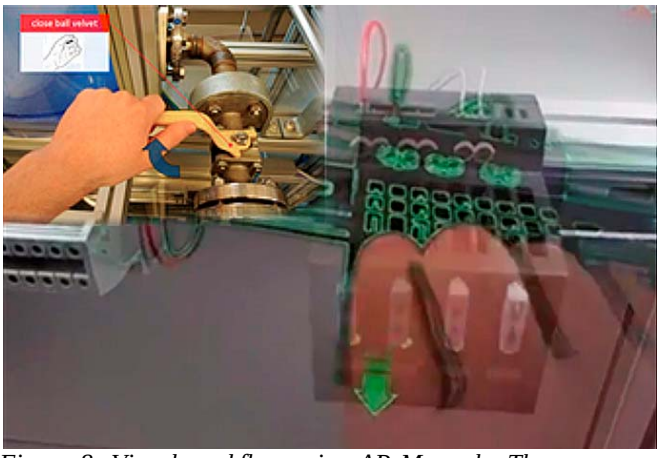

Figure 8: Visual workflow using AR Manuals. The user sees his/her own hand overlapped with the hand of an expert who recoded the sequence previously. Green color means that movements are correct in order and tolerance.

SLOPE: Integrated Processing and Control Systems for Sustainable Exploitation of Forests

This is rather unconventionalexample of how Industrie 4.0 and Industrial Internet can affect not only the factories themselves, but can affect also important production scenarios closely related with logistics and industrial exploitation of raw materials (in this case, wood from forests) – considering the *horizontal integration* dimension introduced in Table 1,.
Mountains in Europe occupy ~35% of the land area and are

mostly covered by forests. Forestry operations in mountain areas are seldom performed by the harvester/forwarder system, being the sector still characterized by manual felling and extraction of timber by cable cranes. Due to the limits posed by steep terrain conditions, poor road network of mountain areas, limited storage and operational room, harvesting and extracting systems are more expensive and less flexible compared to the cut-to-length systems based on wheeled machines, commonly found in flatland forests of EU Nordic Countries. Powerful and more intelligent machines must be developed for forest works in steep terrain. This is the gap that the European project SLOPE is trying to fill, by developing an integrated system (CPS), supported by information technologies such as GIS-based 3D visualization, tracking technologies, covering the cycle from forest information system to logistic transportation, and allowing optimization of the forest production in mountain areas. Information about material origin, quality and availability will be integrated in a unique system, accessible online using Web3D and GIS technologies, and available in real time to a series of operators.

The historical series and up-to-date remote sensing data, and other relevant information related to the area (i.e. local land-use plans, cadastral maps, and other thematic maps) will be loaded into the system. Remote sensing analysis of multi-spectral images will be performed in order to extract macro information of the forest (biomass volume, spectral vegetation indices –SVIs-, growth rate). Furthermore a combination of UAV or Vehicle Mounted LIDAR (Light Detection and Ranging) and Terrestrial Laser Scanner –TLS- surveys will be planned and carried out some weeks before the scheduled harvesting operations (point 1 in Fig.9). The processing of the acquired data generates the Digital Forest Model (DFM), where each tree is a single object in a 3D Geodatabase providing greater product knowledge (point 2 in Fig.9).

The DFM will support the forest planners for multiple criteria decision analysis (MCDA), to plan and simulate the harvesting operation, taking into account all possible constraints (e.g. infrastructural, geomorphological, etc.) and optimization procedures (e.g. joint forest management and coordination of harvesting of adjacent parcels owned by different landowners) (point 3 in Fig.9). The DFM will also support specific logistic decisions, such as the selection of the optimal cable crane positioning and set-up. As an added application, the DFM could be used as a tool for pre-selling procedures, where one or more customers commit to buy the whole lot upon estimation of the volume and the timber assortments potentially available.

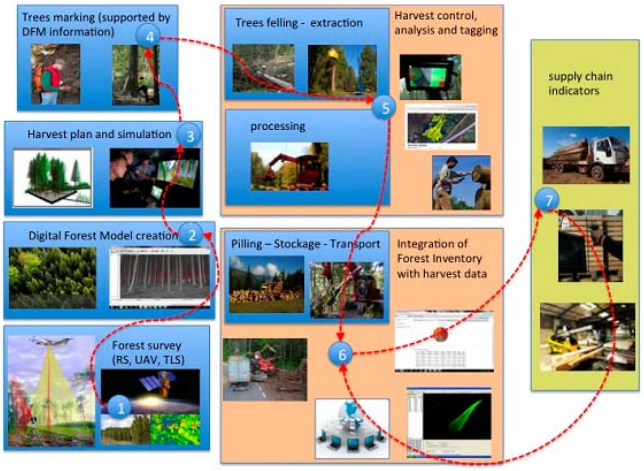

Figure 9: SLOPE project – full cycle

In this example, we may say that the "smart factory" location is actually the forest: the actual industrial activity happens in the forest and not in man-made physical premises. Also the "products" are not manufactured goods, but trees cut. However, many of the possibilities and concerns of Industrie 4.0 are also present in this case, as explained before: logistic chains, virtual models, flexible/adaptive production, etc.

VI. CONCLUSIONS

We have presented in this work a comprehensive view of how Visual Computing can contribute as a Key Enabling Technology to Industrie 4.0 and Industrial Internet. This new wave (or revolution) is now opening new fields for productivity, the emergence of new business possibilities and opportunities for securing the future of Manufacturing in advanced economies with a high industrial value added. There are four compelling reasons to consider Computer Graphics, Computer Vision and in general Visual Computing technologies essential to these visions:
(i) the deep roots of 3D CAD/CAM modeling as Key Enabling Technology for digital manufacturing
(ii) the "*glue factor*" capability that makes possible to integrate other key technologies together (iii) the "*virtual*" component in the Cyber-Physical Systems of Industrie 4.0 and the visualization component in Industrial Internet address core Computer Graphics and Visual Computing concepts, and
(iv) the human factor and HMI are recognized in all these vision as one of the main enablers (people at work in Industrial Internet, people at the forefront in EFFRA/EU roadmaps, and all human factors-related priorities in Industrie 4.0) Despite this central role, the current strategic vision documents and research literature provide a somewhat scattered view of Visual Computing technologies in this context. This article positions Visual Computing in its intrinsic crucial role for Industrie 4.0 and provides a general and broad overview pointing out specific directions and scenarios for future research. The scientific community in Visual Computing will have new exciting fields of research linked to the challenges of the next industrial revolution.

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References

[1] Annunziata, M., Evans, P.C. *"Industrial Internet: Pushing the Boundaries of Minds and Machine."* General Electric, 2012.

[2] Annunziata, M. Evans. P.C. *"The Industrial Internet@Work"*, General Electric, 2012.

[3] Bundesministerium für Bildung und Forschung, www.bmbf.de/foerderungen/21327.php. available online, last visited 12/12/2014

[4] Drath, R.; Horch, A., *"Industrie 4.0: Hit or Hype?" [Industry Forum]*. Industrial Electronics Magazine, IEEE, vol.8, no.2, pp.56-58, June 2014.

[5] European Commission *"Advanced computing"* Available in http://tinyurl.com/okpfpp4, last visited 15/12/2014

[6] Final report of the Industrie 4.0 Working Group. *"ACATECH: Recommendations for implementing the strategic initiative INDUSTRIE 4.0."*, July 2014.

[7] Lee, Edward A. "*Cyber physical systems: Design challenges*." Object Oriented Real-Time Distributed Computing (ISORC), 2008 11th IEEE International Symposium on. IEEE, 2008.

[8] Heng, S."*Industry 4.0 Upgrading of Germany's industrial capabilities on the horizon*", Deutsche Bank Research 2014.

[9] Kagermann, H., Wahlster, W., Helbig, J. *"Umsetzungsempfehlungen für das Zukunftsprojekt Industrie 4.0."* (vorabversion) 2012. http://tinyurl.com/pq5ltm6

[10] Kim, K.D, Kumar, P.R. *"Cyber-Physical Systems: A Perspective at the Centennial."* Proc. of the IEEE, vol. 100, pp. 1287- 1308, May 2012.

[11] Lukas, U., Stork, A. *"Visual Computing für die nächste industrielle Revolution Economic Engineering: Intelligente Methoden."*, Prozesse und Technologien,4, pp. 36-38, 2013.

[12] Mujika, A., Oyarzun, D., Iparragirre, I., Dominguez J., Arambarri, J.*" MACHS: An authoring tool to create serious games for machine-tool operator training."* IEEE ICETA, pp. 147-152, 2011.

[13] Petersen, N., Stricker, D. *"Learning task Structure from Video Examples for Workflow Tracking and Authoring "* In IEEE ISMAR, pp. 237-246, 2012.

[14] Petersen, N., Pagani, A., Stricker, D. *"Real-time modeling and tracking manual workflows from first-person vision."* In IEEE ISMAR, pp. 117-124, 2013.

[15] Ross, G. "*Advanced Manufacturing and its implications for Business"*, 2013. Available online: http://tiny.cc/5f5njx

[16] Sha, L., Gopalakrishnan S., *"Cyber-physical systems: A new frontier."* in Machine Learning in Cyber Trust. New York: Springer, pp. 3-13, 2009.

[17] Szczerbicki E., Graña M., Posada, J., Toro, C. *"Current Research Advances and Implementations in Smart Knowledge-Based Systems.", Cybernetics and Systems 44 (2-3), pp. 95-97, 2013.*

[18] *"The Rise of Industrial Big Data. Leveraging large time-series data sets to drive innovation, competitiveness and growth—capitalizing on the big data opportunity."*, General Electric, 2012

[19] Zühlke, D. *"Industrie 4.0 from Vision to Reality."* Report Technologie-Initiative SmartFactory KL e.V., *Kaiserslautern* 2013.

[20] Toro,C. Vaquero. J., Graña, M., Sanín, C., Szczerbicki, Posada, J.: "*Building Domain Ontologies from Engineering Standards."* Cybernetics and Systems 43(2): 114-126 (2012)

[21] Priego, R. Orive, D. Marcos, M. "*Maintaining the availability of the Control System in Industrial Automation*." Agenten im Umfeld von Industrie 4.0. pp- 15-19. Sierke Verlag 2014.

[22] Blanchet, M. Rinn, T., von Thaden, G. de Thieulloy, G. "*Industry 4.0: The New Industrial Revolution. How Europe will succeed.*" Roland Berger Strategy Consultants GmbH. March 2014. http://tinyurl.com/otq4azn

[23] Jay Lee, Edzel Lapira, Behrad Bagheri, and Hung-an Kao "*Recent Advances and Trends in Predictive Manufacturing Systems in Big Data Environment*." Manufacturing Letters 1(1):38-41 (October 2013)

[24] Keppmann, F.L., Käfer, T., Stadtmüller, S., Schubotz, R., Harth, A: "*High Performance Linked Data Processing for Virtual Reality Environments*." International Semantic Web Conference (ISWC 2014), Riva del Garda, Italy

[25] Bernd Bickel, Marc Alexa: Computational Aspects of Fabrication: Modeling, Design, and 3D Printing. IEEE Computer Graphics and Applications 33(6): 24-25 (2013)

[26] Olivier Rouiller, Bernd Bickel, Jan Kautz, Wojciech Matusik, Marc Alexa: 3D-Printing Spatially Varying BRDFs. IEEE Computer Graphics and Applications 33(6): 48-57 (2013)

[27] DKE Standardization Roadmap. The German Standardization Roadmap Industrie 4.0. VDE Association for Electrical, Electronic & Information Technologies. April 2014. http://tinyurl.com/lz8vwtr, last visited 01/12/2015

[28] Matthias Peissner, Cornelia Hipp. The potential of Human-Machine Interaction for the Efficient and Networked Production of Tomorrow. Report from the Fraunhofer IAO. Fraunhofer Verlag. ISBN: 978-3-8396-0563-9. http://tinyurl.com/ljlbxak

[29] Saarland University. http://www.master-visual-computing.de/

Dr. Jorge Posada is Associate Director of Vicomtech-IK4 Foundation (Spain), and President of GraphicsMedia.net. He is guest member from IK4 Research Alliance in the subgroup "Industry 4.0" of Acatech (German National Academy of Science and Engineering). He has published over 60 articles in Computer Graphics, virtual engineering and multimedia.

Dr. Carlos Toro is Senior Researcher at Vicomtech-IK4. He is expert in semantic technologies for virtual engineering and has chaired international conferences in the field.

Dr. Iñigo Barandiaran is Head of Department of Industry and Advanced Manufacturing in Vicomtech-IK4. His main research topics in Visual Computing are Computer Vision and machine learning for feature extraction and recognition.

Dr. David Oyarzun is Head of Department of 3D Animation and Interactive Virtual Environments in Vicomtech-IK4. His main research interests are Virtual and Augmented Reality.

Dr. Didier Stricker is Scientific Director of "Augmented Vision" at the German Research Center for Artificial Intelligence (DFKI) and CEO of the international organization of Computer Graphics institutes "GraphicsMedia.net".

Dr. Eng. Raffaele De Amicis is Managing Director of Graphitech. His interests are in CAD, virtual reality, virtual engineering, and geoVisual Analytics.

Eduardo Pinto is Senior Advisor of Universidad do Minho, and was during 8 years Executive Director of Centro de Computação Grafica in Portugal.

Dr. Peter Eisert is head of Computer Vision & Graphics at Fraunhofer HHI and is Chair on Visual Computing at Humboldt University. His research topics are 3D scene and surface reconstruction, object tracking and visualization.

Dr. Jürgen Döllner is full professor of computer science at the Hasso-Plattner-Institute. His research fields are Computer Graphics systems and geovisualization.

Ivan Vallarino Jr. is CEO from Mivtech, Panama.