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Virtual Reality for Manufacturing Engineering in the Factories of the Future

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Abstract. This paper discusses the possibilities of applying Virtual Reality (VR) technologies to Manufacturing Engineering, and in particular assesses its role in the Factory of the Future (FoF). We review, classify and compare the recommendations given by four major European reports on the challenges that have to be met for a successful deployment of the FoF, and we identify the potential contributions of VR to this vision in terms of new technologies, worker-factory relationship, modular infrastructure and production efficiency. We argue that VR can be a key technology to support the FoF at all levels of the Systems Engineering approach, either directly by applying it in standard engineering processes, or indirectly by leveraging other useful technologies.

Introduction

From manufacturing to services companies in military, aerospace, medical or automotive industries, the engineering of physical systems hasgrown more complex than ever. Modern systems often have large architectures and require interdisciplinary competences. They must not only be functional, but also reliable, maintainable and safe. These challenges require new methodologies and have profound consequences on systems modeling, analysis, validation, safety, decision making, and skills learning [1] [2].

Systems Engineering, which appears as a necessary approach in this case, is a "Goal-Independent methodological approach", whose first concern is not a specific design objective, but the optimization of all involved engineering processes. As defined by the International Council on Systems Engineering (INCOSE): *"Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs*". [3]

Much research effort has focused on proposing appropriate tools for Systems Engineering, yet not all technologies that might support this approach had full attention of the industrial and academic communities so far, either because they are recentlike Big Data or the Internet of Things, or because, up until recently, they were immature and unaffordable, like Virtual Reality (VR). In this paper, we are especially interested in the question of how VR technologies can be successfully applied to Systems Engineering in the context of the Manufacturing Industry (Manufacturing Engineering).

The paper is organized as follows. Section tworeviews the concept of the Factory of the Future (FoF) anddiscusses its challenges and recommendations given by four different reports on the subject. Section threepresents a number of VR initiatives in the context of a traditional factory, and subsequently compiles the most promising ways for an efficient use in the FoF. Finally, section four concludes by discussing the potential role of VR in the FoF.

The Factories of the Future

In the last years, the terms “Factory of the Future” or, equivalently, “Industry 4.0” have drawn much attention from governments and companies. They describe the vision of a transformation of industry based on new technologies and innovative concepts, and resulting in more efficient production methods. This section reviews the conclusions and recommendations given in four major European reports on the subject.

2.1. European Commission (2010)

The European Commission issued a strategic roadmap which identified a list of R&D challenges to be considered for transforming today’s factories into future manufacturing systems with higher competitiveness [4]:

a. Cost efficiency, with extensive adoption of standards
b. Energy and material efficient processes for optimized consumption of resources
c. Short time-to-market (from the concept to the final product)
d. Increased focus on high added value components/goods;
e. Adaptability/re-configurability of infrastructure through a modular approach in production systems;
f. Higher and more stable product quality through increased process robustness and accuracy;
g. Enhanced safety and ergonomics conditions;
h. Increased re-usability of production systems towards global interoperable factories;
i. New manufacturing technologies adapted to new product features.

2.2. United Kingdom (2013)

The Government Office for Science defined a template for the FoF based on six components [5]:

a. *Goals and metrics*: the FoF has sets of goals and metrics focused on meeting the needs of customers and a wider green agenda.
b. *Culture*: the FoF works closely within the supply chain and has partnership agreements with local universities and schools, between which there is a sustained flow of people, projects and ideas.
c. *Technology*: social media and big data are used routinely to support the first component. They are integrated through design, manufacture, service and supply, promoting and enabling interaction between the various partners.
d. *People*: in empowered and responsible teams, people are knowledge-workers and problem-solvers. People may start apprenticeships when they are in their 40s and 50s with plenty to offer and plenty to learn. Men and women are equallyrepresented at all levels.
e. *Processes and Practices*: they are agile, cutting through internal and external silos. The systems are simple to communicate and understand.
f. *Infrastructure*: all this is supported by the physical environment, which is open and welcoming. It has a ‘wow’ factor that attracts people to join.

2.3. Germany (2013)

The Federal Ministry of Education and Research gave eight recommendations for putting into practice Industry 4.0 [6]:

a. *Normalization*: partners needs to agree on global subjects, like end-to-end product engineering, as well as on details like data acquisition from sensors.
b. *Virtualization*: the simulation of production systems and products facilitates the understanding and management of complex processes.
c. *High-speed broadband*: Industry 4.0 requires an infrastructure capable of exchanging very large volumes of data and guaranteeing their integrity.

d. *Security and safety*: digital data must be protected from abuse and unauthorized access.
e. *Work management*: innovation efforts also need to take into account an intelligent work management and the employees' competences. It is likely that their role will change due to open platforms, virtual work and the evolution of human-computer/system interaction.
f. *Training methods*: Industry 4.0 will impact the content of initial and further training because the traditional manufacturing processes characterized by a clear division of work will be integrated into new organizational structures where decision making and coordination are decentralized.
g. *Regulations*: new manufacturing processes will face inadequate existing regulatory frameworks, at least partially.
h. *Resource optimization*: ensuring the supply of raw materials and energy requires the reduction of the overall consumption. Human and financial resources must be taken into account, too.

2.4. France (2014)

The group of French electrical manufacturers (Gimélec) segmented the productive apparatus into six domains and identified a number of key technologies for each domain as [7]:

a. *Digital technology:* prototyping and additive manufacturing (3D printing), virtual factory.
b. *Monitoring and control:* remote monitoring, condition sensors and shared CAPM (Computer Aided Production Management).
c. *Manufacturing operations:*cobots (collaborative robots) and intelligent robots, direct manufacturing.
d. *Services:* and particularly predictive maintenance services.
e. *Transverse technologies:* Industrial Internet of Things, Cloud Computing, Big Data Analytics, Energy Harvesting.
f. *Work management:* with respect to the new manufacturing requirements.

2.5. Discussion

Table. 1 offers a synthetic view of the challenges and recommendations in each surveyed report, which we classified into four categories. Some recommendations have been classified into more than one category. It can be seen that each report addresses all four categories, however with different prominence depending on the respective vision of the FoF.

The European recommendations particularly aim at enhancing production efficiency, in terms of cost and time efficiency, product quality, etc. The British recommendations focus on the place of the human being in the FoF, by considering culture, gender equality, worker skills, customer involvement in the product design, etc. The French recommendations emphasize the vision of introducing as many new technologies as possible in the FoF such as connected factories through the Internet of Things, human-robot collaboration or remote monitoring. Finally, the German recommendations seem to be distributed in a rather balanced way among the four categories.

In the scope of this paper, we particularly focus on the introduction of VR as a technology to assist the Systems Engineering approach in the FoF. We take into consideration the place of the user and suggest some ways to use this technology, in order to meet the requirements at all levels in the FoF.

Table 1: Classification table of the recommendations and challenges for the Factory of the Future

	New Technologies	Worker-Factoryrelationship	Infrastructure and resource management	Production effiency (cost, time, ecology, etc.)
European Commission (FoF PPP)	i. New manufacturing technologies	g. Safety and ergonomics	e. Adaptability of infrastructure b. Optimize resources h. Re-usability of production systems	a. Cost efficiency c. Short time-to-market d. High added value components f. Stable product quality

United Kingdom (FoF)	c. Technology	b. Culture d. People e. Processes and practices	f. Infrastructure	a. Goals and metrics
Germany (Industry 4.0)	b. Virtualization c. High-speed broadband	e. Work management f. Training methods	h. Resource optimization	a. Normalisation d. Security and safety g. Regulations
France (Industry 4.0)	a. Digital technology c. Manufacturing operations e. Transverse technologies	b. Monitoring and control f. Work management	b. Monitoring and control c. Manufacturing operations	d. Maintenance services

Virtual Reality in the Manufacturing Industry

VR is a technology allowing users to immerse in an artificial reality and to have interactive experiences via sensorimotor channels [8, 9]. Although the concept exists since several decades, it has been democratized only recently, and currently undergoes rapid growth especially owing to the emergence of affordable HMDs devices. In 1993, Burdea and Coiffet [10] put forward that the quality of a VR user experience can be evaluated through the following three components:

- *Immersion:* the feeling of being in a virtual scene through fully or partially real-world occulting devices.
- *Interaction:* the set of sensorimotor actions/reactions interfaces and interaction techniques for the users to communicate with each other and with the system.
- *Imagination*: the interpretation of the parameters that result from a VR experience.

More recently, J. Tisseau proposed a similar yet alternative set of criteria [11]: *Immersion*, *Interaction* and *Autonomy*. Autonomy is defined as the ability to adapt the behavior to unknown changes in the environment.

3.1. Related Work

A number of research initiatives have already explored the benefits of VR technology for engineering purposes. VR has been successfullyapplied in the followingcontexts:

- **Systems Simulation**: Dorozhkin et al. [12] proposed an immersive VR environment for simulation analysis, allowing for interactive modification of the simulation input parameters. The user is placed in the midst of the environment being simulated.
- **Engineering Education**: Abulrub et al. [13] investigated the benefits of VR in skills transmission and learning, by the realistic reproduction of learning situations in 3D virtual environments. It was found that VR learning environments increase creativity, innovation, communication, problem solving, team work and business skills.
- **Immersive CAD:** Bourdot et al. [14] developed a framework combining VR and CAD, allowing intuitive and direct edition of CAD objects in immersive virtual environments. Moreover, the authors designed a set of haptic interaction methods to overcome the accuracy problems of free-hand gestures in 3D environments.
- **Virtual Prototyping and Assembly:** Seth and al. [15] proposed a software solution using physically-based modeling and haptic force feedback for the virtual prototyping and the assembly of complex CAD geometry in immersive VR environments (Fig.1 and Fig. 2). The work shows promising results by providing realistic user control over the assembly part movements during the engineering process.

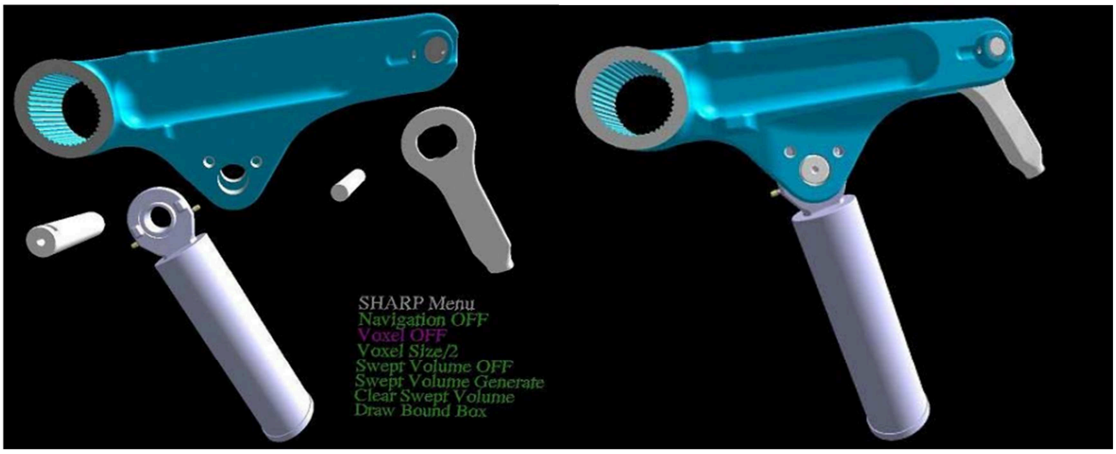

Figure 1: Parts to be assembled [15] Figure 2: Assembled parts [15]

- **Collaborative Engineering**: Daily and al. [16] presented a solution for distributed and collaborative design review through the use of heterogeneous multi-site 2D and immersive 3D environments. It has been shown that the introduction of avatars, different levels of interaction, spatial audio and speech recognition, allow communicating design concepts and ideas with a natural, intuitive interface over great distances.

3.2. VR in the Factories of the Future

The surveyed VR initiatives of the last section address particular engineering tasks in a traditional factory. However, due to the complexity of the systems that will be designed and produced in the FoF, it appears necessary to integrate VR technology at the level of the entire Systems Engineering approach.

Based on the proposed categories of recommendations in section 2.5, this section compiles the potential usages of VR within a number of key Systems Engineering processes. We target five processes defined in the EIA-632 standard [17] where the use of VR is particularly promising. The EIA-632 standard proposes a blueprint of all necessary processes and requirements for engineering a complex system. The selectedprocesses are:

- Requirements Definition Process: transform stakeholder requirements into a set of system technical requirements.
- Solution DefinitionProcess: generate an acceptable design solution (specifications, drawings, models, etc.).
- Implementation Process: transform the characterized design solution into an integrated end product that conforms to its specified requirements.
- Requirements Validation Process: assure that the subject set of requirements describes the input requirements and objectives such that the resulting system products can satisfy the requirements and objectives.
- System Verification Process: ascertain some points such as: the system design solution is consistent with the source requirements; the end products meet at each level theirs specified requirements, etc.

VR as a key technology for the FoF	Worker-factory relationship	Infrastructure and resource management	Production efficiency (cost, time, ecology, etc.)
VR for the requirements definition process	VR allows adapting the system view according to the user profile/intentions	Virtual navigation in the virtual production line or product to extract requirements and useful information	Connecting knowledge bases to the virtual objects in the virtual environments enables reliable decision making at early stage
	Multidisciplinary collaboration through virtual environments provide the users with a better feeling of presence	When defining the requirements in a virtual environment the user can predict the needed resources in the implementation process	Virtual representations of the tangible product early at the concept stage allows for a better understanding of the problem by all kind of stakeholders
	VR allows for a better estimation and perception of depth and virtual objects information.		
VR for the solution definition process	Collaborative and distributed immersive virtual design allows for a rapid definition of the system, and a better feeling of presence	A virtual adaptation of the production line allows saving time and resources.	The ability to define the system with respect to standards and constraints in the virtual environments
	Boosting creativity and innovation skills with virtual reality capabilities for multiple experimentation situations	Providing the users with data in virtual environments and intelligent information processing	Interactive and immersive simulations increase systems quality and enhance safety checks at early stage
	The customer may participate in the solution definition/customization through VR environments	Learning of Engineering/Reverse-engineering using virtual environments (e.g. assembly/disassembly)	High quality and realism offered by VR helps defining and discussing realistic prototypes/mockups
VR for implementation process	User-machines (industrial robots) interaction and collaboration through VR control environments	Visual assistance for users to manage production resources	Virtually validate the production-line before the physical realization
	VR is an efficient tool for knowledge transmission and knowledge validation through realistic simulations	Remote control of factories through VR environments is an efficient way to obtain real-time results	Ergonomic consideration when adapting the factory to new products manufacturing
VR for the requirements validation and system verification processes	VR can help adapting the system view according to the user profile/intention to facilitate result verifications	Virtual navigation in the virtual factory or virtual products to validate the requirements	VR allows verifying the reliability of the product-line and the product assemblies
	In virtual environments, the user can choose how to interact with the system to check, which is not the case in real environments..	VR allows for failure analysis techniques with the virtual objects to validate the systems behavior before producing it	High quality interactive prototyping facilitates faults detection at early stage
	Product review by the engineer or the end-user through VR environments	Virtual-physical world data exchange to automatically compare the physical adaptation of the factory compared to the virtual adaptation	Interactive and immersive realistic simulation is a good tool for visually checking design quality requirements, and experiencing different behaviors of system before manufacturing
	Users-workstations ergonomic requirements verification using VR		

Conclusion

After having surveyed and classified the challenges and recommendations proposed by four European reports on the FoF, we conclude that all of them share the same vision, even though each one may emphasize a different aspect. In this paper, we were particularly interested in the recommendations related to the introduction of a new technology which is VR.

We argue that the best approach of using VR in the FoF, allowing to meet as many recommendations as possible, consists in integrating this technology at the level of the standard Systems Engineering processes. The variety of suggestions that can be made for five EIA-632 processes attest the potential of VR to be one of the key technologies for supporting the FoF. VR can also help leveraging other useful concepts and technologies in the FoF, e.g. by using it as a learning environment or as an efficient visualization tool (Big Data, Internet of Things, Monitoring and Control).

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