Smart Architecture-Bots and Industry 4.0 Principles for Architecture

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Industrial robots from the automotive industry are being repurposed for use in architecture fabrication research in academic institutions around the globe. They are adapted for a variety of fabrication techniques due to the versatility of their 6-axis arm configuration. Though their physical versatility is an advantage in research, their computational and sensory capabilities are rudimentary and have not evolved significantly in the past forty years of their existence. In the meantime the manufacturing industry has moved on by introducing new forms of manufacturing namely Industry 4.0. In this position paper we look at the characteristics necessary to bring architecture robotics into line with Industry 4.0 standards. By presenting the fabrication process as a relationship model of 'tool-process-outcome' we will examine the way in which these entities and their interrelations might be augmented vis-a-vis Cyber-Physical Systems (CPS), Social Robotics and Human-Computer Interaction (HCI) approaches such as the Tangible User Interface (TUI).

Keywords: *Robotics, Social robotics, Innovation in robotics, Industry 4.0, Human-robot interaction*

INTRODUCTION

Robotic fabrication is a rapidly expanding field of inquiry in architecture research. Many institutions are currently investigating applications of industrial robot arms for manufacturing unique and complex structural forms, with various notable scholarly contributions by Gramazio & Kohler (2014a, b); work from Taubman College / University of Michigan (2014), as well as the Association for Robots in Architecture (2014), to name but a few. The robots used in research undertakings of these groups are generally 6-axis robot arms that were initially designed for simple repetitive tasks in the automotive industry. These industrial robots are rudimentary machines that are operated by researchers with specialised computer programming skills. Their accuracy, speed and versatility make them an advantageous tool for architecture fabrication research, yet in the field of robotics these machines are far from the state of the art [ER1]. Having applied industrial robots successfully in the manufacturing industry for over forty years, manufacturing is beginning to turn its attention towards newer fields, to step away from manufacturing principles defined in the third industrial revolution, also known as the digital revolution, where the use of electronics and IT helped to further automate the production process (Boerse ARD, 2013). This next step is defined as Industry 4.0 (VDI Nachrichten, 2015) first introduced in 2011 at the Hanover Fair outlining six design principles to support enterprises and companies in implementing Industry 4.0 principles (Hermann, Pentek, Otto, 2015). For the purposes of this paper the following two of these six design principles are considered relevant here:

- Interoperability: the ability of cyber-physical systems, humans and smart factories to connect and communicate with each other via the Internet of Things and the Internet of Services.
- Decentralisation: the ability of cyber-physical systems within Smart Factories to make decisions on their own.

Given this, the focus for this paper is to extend knowledge in the CAAD research community in robotics and architecture with particular consideration of Cyber-Physical Systems (CPS). Cyber-Physical Systems are defined by Lee (2008) as a network of interacting elements with physical input and output instead of as standalone devices, thus bringing together robotics (in its form used currently in robotics in architecture and elsewhere) together with sensor networks, combined with intelligence mechanisms. The ability of robots to interact with their environments through sensor networks and intelligence mechanisms has also been discussed in Social Robotics (Beetz, 2014). Social Robotics is a branch of robotics research that focuses on autonomous robot interactivity in social spaces. The objective of this research is to emulate the way humans make decisions based on sensory data and prior knowledge in order to perform physical tasks that may in turn result in further interactions. These robots employ various types of artificial intelligence to achieve the desired behaviours. Collaborative-robots or Cobots are social robots whose prime function is to collaborate with humans and other cobots on specific tasks that have been taught to them (Surdilovic, 2010). Many industrial robot manufacturers are now introducing their first cobots for tasks such as sorting and packing, which is intended to be implemented on the factory floor alongside human counterparts. Given the field's infancy, the vast range of applications for social robotics remains yet to be explored (established in the 1990's).

RESEARCH QUESTION

As argued by Rosenberg et. al. (2015) robotics in architecture requires a paradigm shift towards applying new concepts in manufacturing, such as Industry 4.0 and social robotics, and testing and analysing them in the context of architecture. Significantly, this position paper puts forth the hypothesis that collaborations in architectural practice between human architects and intelligent social robots could produce superior results vis-à-vis spatial optimization, complexity, efficiency, and possibly design decision-making. Therefore we posit that in the same way that robotic tools have already increased the efficiency and accuracy of architectural fabrication processes, social robotics could increase the productivity of the entire architectural process from design through to production. As researchers with the architectural field explore the ways in which computationally programmed mechanical tools can improve the manufacturing processes of non-standard architectural parts, it seems natural to then ask -

Using Industry 4.0 standards as a benchmark for next generation manufacturing, what elements of the architecture workflow could be augmented by intelligent social robotic intervention within the framework of cyber-physical systems?

METHODOLOGY

Using systematic research in the form of a literature review as a method, the paper introduces the following to the research community: (1) Background on Industry 4.0 in order to give the reader an overview of findings in the field; (2) based on these findings, an argument for a causality of Tools - Process - Outcomes as a framework to operate in the following; (3) comparison of tools via a taxonomy of robotics with robots currently used in architecture and social robotics; (4) analysis of the process of interacting with a social robot; before (5) concluding what other outcomes could be achieved by Smart Architecture-Bots & Industry 4.0. Hence we refer to research in Industry 4.0 (Boerse ARD, 2013; VDI Nachrichten, 2015; Hermann, Pentek, Otto, 2015; BMBF, 2011; Kagermann, 2015; Sabbagh, et al, 2012; and Hermann, et. al., 2015) as a method to apply research in robots in architecture; with Cyber-Physical Systems here in particular social and collaborative robotics research by XXX to inform new findings on the process how objects can potentially be designed and fabricated in the Architecture Engineering Construction (AEC) industry.

BACKGROUND INDUSTRY 4.0

Within the Architecture Engineering Construction (AEC) industry, robotics technology is a rapidly growing technology that is identified as a mechanism for revolutionary change. As outlined in the introduction and through Rosenberg et. al. (2015), this paper argues that the type of robots used in the AEC industry are already an out-dated manufacturing technology in other industries and that nations such as Germany are working towards adopting new, so-called Industry 4.0 manufacturing processes (BMBF, 2014).The origins of Industry 4.0 concepts are found in the evolution of the Information and Communication Technology sector (ICT), which had transformed organizations and economies in the digital world (Turban, et al, 1997). Digitization, known as the continuing convergence of the real and the virtual domains is identified as the main driver of innovation and change in economic sectors around the world (reference here). The exponentially growing amount of data and the convergence of different affordable technologies that come along with the establishment of ICT networks have transformed all areas of the economy (Kagermann, 2015). ICT technologies, such as mobile broadband, cloud computing, Big Data, and the Internet of Things are ushering in a new information age. Traditional industries now have at their disposal an unprecedented degree of integration between information, communication, and manufacturing systems (Zhang, 2015). With ICT access approaching ubiquity, policymakers' next challenge is to ensure that individuals, businesses, and governments are making the best possible use of networks and applications. Countries that have achieved advanced levels of digitization- the mass adoption of connected digital technologies and applications by consumers, enterprises, and governments- have realized significant benefits in their economies, their societies, and the functioning of their public sectors (Sabbagh, et al, 2012).

Based on these foundations Industry 4.0, developed by Germany as a white paper to pioneer the role of industrial IT in its major sectors (Kagermann, et al, 2013), is now a term widely used to refer to a fourth industrial revolution and is fast becoming a major game changer across Europe, the United States and other world-leading Western nations. In short Industry 4.0 refers to the interrelation of technologies that are to facilitate the emergence of the "Smart Factory". These technologies include the Internet of Things, Smart Objects, Cyber-Physical Systems, Cloud computing, and Internet of Services. It is seen as the meeting point of the electronic mechanization of the manufacturing industry and the networked computerization of all industries. Hence this paper argues that the purpose of Industry 4.0 is to eliminate current human barriers and bottlenecks by automating processes that are more efficiently performed by computers and smart machines. As outlined earlier Hermann, et. al. (2015) argued for six design principles to implement Industry 4.0 scenarios.

- Interoperability: the ability of cyber-physical systems (i.e. work-piece carriers, assembly stations and products), humans and Smart Factories to connect and communicate with each other via the Internet of Things and the Internet of Services

- Virtualization: a virtual copy of the Smart Factory which is created by linking sensor data (from monitoring physical processes) with virtual plant models and simulation models
- Decentralization: the ability of cyber-physical systems within Smart Factories to make decisions on their own
- Real-Time Capability: the capability to collect and analyse data and provide the derived insights immediately
- Service Orientation: offering of services (of cyber-physical systems, humans or Smart Factories) via the Internet of Services
- Modularity: flexible adaptation of Smart Factories to changing requirements by replacing or expanding individual modules

While this paper has listed two principles as particularly pertinent for this discussion, each of these principles are also relevant in the manufacturing industry, the CAAD community, and where robots are applied in architecture, the objectives share similarity, chiefly the use of a tool (the robot) for a process (customising a design) to achieve an outcome (a product or building). Hence the following section intends to outline the causality of Tools - Process - Outcomes as a framework to compare existing and new workflows in order to demonstrate the advantages of the research for the CAAD community.

TOOLS - PROCESSES - OUTCOMES

For our purposes, we identify key aspects of Industry 4.0 that provide the foundation for understanding critical enablers in the AEC industry. These key aspects will serve as a guide for creating a strategic approach to developing smart infrastructure. Firstly, this begins with the 'smart' tool. This refers to smart machines and devices that can affect the digitization of conventional analogue processes. Secondly the focus is on process. Smart intuitive processes and logical infrastructure such as Cyber-Physical Systems (CPS) can facilitate communication exchange between humans, tools, materials, and outcomes. Thirdly, a key aspect concerns the outcomes. Here the paper speculates on how outcomes (designed objects) could be realised differently through Cyber-Physical Systems (CPS) by applying Industry 4.0 principles, where, through 'interoperability' (the ability of cyber-physical systems, humans and smart factories to connect and communicate with each other via the Internet of Things and the Internet of Services) and 'Decentralizations' (the ability of cyber-physical systems within Smart Factories to make decisions on their own) a new relationship between tool and used material can advance computer-integrated manufacturing and digital fabrication in the AEC industry.

From Tools to Smart Tools

As Industry 4.0 focuses on the establishment of intelligent products and production processes, it anticipates that in future manufacturing, factories have to cope with the need of rapid product development, flexible production as well as complex environments (Vyatkin, 2007). Within the factory of the future, the so-called smart factory, CPS aims to enable the communication between humans, machines and products alike (Einsiedler, 2013), (Achatz, et al, 2009). As they are able to acquire and process data, they can self-control certain tasks and interact with humans via interfaces (Brettel, 2014). In order to outline this shift the paper will briefly reflect on how robots are currently used in architecture before introducing a Cyber-Physical Systems (CPS) approach to robotic fabrication where specialised machines communicate through physical and wireless networks, are regulated by intelligent processing of input data and are arm controlled via intuitive user interfacing.

Robots used in Architecture Research

Gramazio and Kohler's research (ETH Zurich, 2006) in robotic architecture assembly processes reestablished the robotic research field within architecture. Their brick-laying robot proved that robot intervention in one specific architectural process could elevate the architectural outcome to a degree not possible with any other type of in-situ process. Following on from this research, many other research groups from academic institutions around the world have established their own robot fabrication research projects. These projects include foam/hot-wire cutting, stone/diamond wire cutting (McGee et al., 2012), milling, complex element assemblies, additive fabrication, hybrid additive/subtractive fabrication, to name a few. These research projects have a common tool - the 6-axis industrial robot arm - a tool that was developed for use in the automotive manufacturing industry. In an automobile factory these robots sit in a production-line configuration and work on each car as it comes to them. The robots will usually weld a few joints and then repeat the same specific process for their entire life cycle. A reason many architects have explored this technology is that the 6-axis robot is much more versatile than the current tools being used in the production of architecture. This way of thinking comes into line with the Industry 4.0 model where tools and objects will evolve into multifunctional machines like our smart phones. However where these robotic architectural approaches lack is the complete adoption of the Industry 4.0 strategy, and resultantly 'intelligence'.

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Cyber-Physical Systems

One element necessary for the emergence of the Smart Factory is Cyber-Physical Systems. Baheti and Gill (2011) describe how "...cyber-physical systems (CPS) refers to a new generation of systems with integrated computational and physical capabilities that can interact with humans through many new modalities" (page number). The aim of CPS is to augment the interaction capabilities of the physical world through computation, communication and control, thus resulting in more efficient automation of physical processes. It is through the development of Information and Communication Technologies (ICT) that the networking of computationally controlled machines and smart objects has chiefly been made possible. This suggests more efficient and flexible strategies for manufacturing than current methods offer. Yet cyber-physical systems do not necessarily focus on Human-Computer Interaction (HCI). A framework for human influence and control of the manufacturing CPS is also integral to future architecture processes. It is therefore a requirement of the smart architecture factory to incorporate user interfaces that allow specialist human knowledge to be harnessed. The interaction and collaboration of humans and robots is studied in the field of Social Robotics.

Social Robotics is a subfield of robotics, which deals with robots that are intended to function in social spaces. They must perform tasks in constantly changing environments containing interactive and noninteractive entities. Social robots must therefore also be interactive entities that respond to and filter events in real-time as they navigate the tasks they are given. Social robots are embedded with a vast array of sensors that are used to gather environmental and task specific data for processing. The processing of live data enables them to continuously review their progress and reevaluate their strategies to achieve the desired objectives. In future Industry 4.0 architectural processes, robots will need to interact with both human architects and the smart materials which they will be producing/manipulating to produce architecture.

Collaborative robots, or Cobots are a type of social robot that are designed to work in collaboration with, and physically alongside human counterparts (reference). The first generation of cobots to reach the marketplace are now being implemented in factories where the labourforce is relatively unskilled. Factories where human workers jobs consist of picking, sorting, arranging, packing, and assembling are now investing in cobots to replace human workers on the factory floor. These cobots are able to work amongst human workers and not just in a designated safety area as is the case with earlier generation industrial robots. This is because they are able to sense the human workers and robot workers around them and have built-in safety mechanisms that stop the robot from colliding with other entities in their vicinity. Some examples of cobots that are currently being implemented in industry are: Baxter (Rethink Robotics), YuMi (ABB), LWR (Kuka).

Process

The second key aspect is process. Although ICT gained advantages in the AEC industry resulting in collaborative efficiencies, current practices still necessitate and generate segregated individual processes that deal with design, optimization, construction, maintenance, logistics and management. As the quality of outcomes in the AEC industry is dependent on these rigidly linear processes, the capacity for creating smart infrastructure is limited. Another aspect to be considered is the type of processes involved in AEC. These processes, unlike other industries, relate to elements with high levels of physical components with strict parameters of flexibility, portability and manageability, combined as well with virtual systems and digital processes. In Industry 4.0, Cyber-Physical Production Systems (CPPS) address vital issues that deal with mechanization of these physical components and that are relevant to the AEC industry. Cyber-physical production systems (CPPS) made up of smart machines, logistics systems and production facilities allow peerless ICT-based integration for vertically integrated and networked manufacturing (Kagermann, et al, 2013). Additionally in an Industry 4.0 process not only the tools have a greater intelligence the same applies to the materials used to fabricate objects and artifacts. Smart materials in the context of Industry 4.0 refer to any material that has been augmented either via a bar code, QR Code, a RFID tag or similar. Hence the material can contain information of either how many pieces are still in the store and create feedback to the storage facility to re-order them via the suppliers but more importantly the material can store information for the robot what to do with the materials. This aspect will become subject of further research by the authors.

Workflow in AEC

In the last decade the advances in factory automation became aware of the fact that any significant improvement may be achieved only by considering the tight integration of computational, physical and social elements (NIST, 2013). The same can be said about the AEC industry. An approach for a closer integration of individual processes to combine into a fluid activity would advance towards smart infrastructure. New emerging concepts must also be examined and considered in the process, such as Cyber-Physical-Social Systems (Zhuge, 2010), Human System Integration (NASA, 2013), Smart Environments (Poslad, 2009). Their principles refer to an Anthropocentric Cyber-Physical System (ACPS) that integrate the physical component, the computational/-cyber component and the human component (Zamfirescu, 2014).

A CPS poses some exclusive features that differentiate it from the conventional systems (i.e. embedded systems, sensor networks, etc.) (Rajkumar, 2007),(Lee, 2008), (Zamfirescu, et al, 2013): integrality (the CPS's functionalities are relying on the unified composability of its elements with self-organization capabilities, such as learning, adaptation, auto-assembly, etc.); sociability (the ability to interact with other CPSs via different communication technologies, not only device-centered but human-centered as well in an open mixed network environment); irreversibility (self-referential timescale, sensed as dynamics, not discrete, nor spatial); adaptive (with self-organization and evolving capabilities); autonomous (control loop must close over the life-cycle of a PS, including the assimilation of human factor who is constantly closing the loop of any engineered artefact, despite its automation degree); and highly automated (as a key driving-force of eroding the boundaries between its composite elements and favouring their structural interactions) (Zamfirescu, 2014). This]

Outcomes - Human Computer Interaction with Tangible User Interfaces

At present we are seeing social robots making their way into industry to work alongside people for tasks such as small parts assembly, packing, picking and sorting in a production-line setup. These robots are 'taught' their tasks rather than being programmed in the traditional sense. They are taught by example and require a human counterpart to demonstrate the tasks to be undertaken by the robot. This is achieved by moving the robot's limbs and end effectors in such a way as to teach the robot various processes that they will be performing autonomously.

ABB calls this method of teaching their YuMi robot 'lead-through programming'. However the tasks being performed by YuMi (and other cobots of her ilk) are quite simple and repetitive. These tasks may vary slightly in each instance and so the robot must have a level of intelligence that can handle these variations (eg. varying orientation of parts that are to be assembled). These variations are solved with the use of sensors and pattern recognition software, but YuMi's environment is still quite controlled and her tasks have little to no room for interpretation.

Lead-through programming is an intuitive method of cobot programming that transforms the robot's entire physicality into a Tangible User Interface (TUI). More generally, this method of programming is called Tangible Programming. The term tangible programming was coined by Suzuki and Kato in 1993 to describe their AlgoBlocks system which helps children to learn programming. "Several TUIs allow children to teach an electronic toy to move by repeating a set of guiding motions or gestures."(Tangible User Interfaces: Past Present and Future Directions: Orit Shaer and Eva Hornecker, 2009). Another successful example of a TUI is the system of Navigational Blocks designed by Camarata et al (2002), where a multimedia kiosk in Seattle's Pioneer Square enables visitors to explore the area by moving and rotating wooden blocks on a query table in front of a display monitor.

These examples demonstrate how TUIs can be used to communicate both physical and conceptual tasks. The practice of architecture involves both of these (physical and conceptual) activities. It is therefore pertinent to ask: What kinds of tangible user interfaces would be most suitable in an AEC context/-workflow? In essence this paper outlines a conceptual/methodological framework for future research into the intersecting fields of robotic architecture fabrication and HCI vis a vis tangible user interfaces and tangible programming theory.

SIGNIFICANCE AND CONCLUSION

To bring robotic fabrication into line with Industry 4.0 (2014) principles we must understand how robots might fit into a future architecture workflow. The relationships defined by Tool-Process-Outcome allow us to examine the changing nature of architecture and how the tool might become a cyber-physical system with intelligent, collaborative HCI capabilities specific to architecture. This is significant as social robotics can be positioned within the emerging field of 'Construction Scale Additive Fabrication' within the construction industry (Gardiner, 2009). Gardiner argues that design for Construction Scale Additive Fabrication has major advantages in the manufacturing process. Gardiner's research in construction and parallel industries indicate the need for and the advantages of adopting production processes and concepts from the manufacturing industry other than fabrication alone. On this basis the paper argues for an investigation of Industry 4.0 principles discussed in the manufacturing industry and its translation into the architecture and construction industries. Further research into intuitive programming through tangible user interfaces for the communication of physical and conceptual processes between human and robot collaborators is therefore an important step for integrating architecture robotics into the Industry 4.0 ecology of smart technologies. The investigation of this position paper, its proposed hypothesis, methodology, implications, significance and evaluation are presented, as well as proposing next steps towards applied research projects.

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