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MANUFACTURING SYSTEMS OF THE FUTURE: A MULTI-DISCIPLINARY APPROACH

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Successful manufacturing systems for the future have to be based on know-how originating from more than the traditional manufacturing domains. Approaches such as Reconfigurable Manufacturing Systems, the Agile Assembly Architecture and Holonic Manufacturing Systems go into the right direction; combined with approaches known from Mobile Robotics, Collective Artificial Intelligence and Complexity Science, there is considerable potential for creative solutions to the problems of low volume – high change productions. Systems must be enabled to self-organize, take profit of emergence and become more autonomous.
More due to human factors than due to technical reasons, system autonomy and emergence belong to industry's worst nightmares. It is therefore crucial to address this fear while at the same time working on reliable methods and tools.

Keywords: Evolvable Assembly Systems, Reconfigurable Production Systems, Automation, Autonomous Systems, Emergence

1. INTRODUCTION

The field of manufacturing paradigms targeting at low volume – high change production systems is relatively scattered. There are **Reconfigurable Manufacturing Systems** (ElMaraghy 2006), **Holonic Manufacturing Systems** (Ulieru 2004; Valckenaers and Van Brussel 2005; Colombo, Schoop et al. 2006), **Biological Manufacturing Systems** (Ueda 2006), the **Agile Assembly Architecture** (Rizzi, Gowdy et al. 1997; Kume and Rizzi 2001) and **Evolvable Assembly Systems** (Onori 2002; Frei, Ribeiro et al. 2007). Diverse topics serve to justify their specific focus or orientation of these approaches – be it Biology, Self-Organization, Holarchies or Mobile Robots or **Emergent intelligence in MAS for industry** (Rzevski and Skobelev 2007).

Most of them use nowadays Multi-Agent Systems as their control solution (Monostori, Vancza et al. 2006). It has been broadly recognised that for production systems which require optimality and which rarely undergo changes while producing high volumes of identical products, the hierarchical control approach works in satisfying manner, but the challenges of agile manufacturing for small volumes, many variants, frequent changes and dynamic conditions make it less favorable.

Many research domains are relevant for bringing the manufacturing systems of the future to success. There is abundant know-how available in the scientific world; the challenge is to gather it and combine it into a consistent framework. A corresponding article is to be submitted soon in a journal.

After identifying some enabling research domains earlier (Barata, Onori et al. 2007), this article will show the multitude of relevant research areas which can serve as important inspirations for future-oriented solutions to manufacturing systems and will stress what must be done for making the manufacturing systems of the future successful.

System autonomy and emergence are important topics which appear in many of the recent manufacturing paradigms, also due to the inspirations laid out in the first part of this article; however, industry is very reluctant to accept anything which has to do with autonomy or emergence. The second part of this article addresses this is issue.

2. A MULTI-DISCIPLINARY APPROACH

Building manufacturing systems is a domain which, already in the traditional approach, brings together several branches: **Mechanical Engineering**, **Electrotechnical Engineering** and **Production Engineering** as well as **Systems Engineering**. These are certainly core competences, but they are not enough.

Computer Science is another classical discipline which is fundamental for developing innovative control systems. **Cybernetics**[16], itself an interdisciplinary approach which studies all kinds of systems and their unifying control principles, is obviously the right domain to learn more.

That body and brain cannot be considered separately is one of the teachings of **Embodied Cognitive Science** (Pfeifer and Scheier 1999). Hardware and Software need to evolve together, in any context – including manufacturing systems.

Studying issues related to **Complexity Science** in general[17] and Self-Organization and Emergence in particular has lead to the conclusion that these domains can be highly helpful to tackle the problems of production systems (Frei, Barata et al. 2007). The Multi-Agent Community can provide us with mechanisms for Self-Organization which work in reliable fashion (Di Marzo Serugendo, Fitzgerald et al. 2007). This knowledge alone, however, does not lead to success yet. It has to be combined with specific expertise in the application area – namely assembly and production engineering.

Mobile Robotics and **Collective Intelligence / Swarms** often already go together (Mondada, Gambardella et al. 2005). Experiments with robot swarms are highly useful to find out more about engineering methods and the ways predictable results can be achieved.

Natural / biological systems have considerable potential for being useful for manufacturing systems. This potential goes far beyond simply "copying" mechanisms as it is done in ant-inspired algorithms or AGV swarms. Natural systems have a plenitude of highly attractive characteristics which should be achieved in artificial systems – even if sometimes by other means than it happens in natural systems. A deeper analysis will be published soon in a journal.

Figure 7 illustrates the situation of the researcher intending to build the manufacturing systems of the future, standing in the middle of a high number of relevant scientific areas. A multi-disciplinary approach and the ability to communicate with specialists from many different domains are required. How can this overwhelming richness of concepts be managed? Are there useful principles?

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16 „Principia Cybernetica Web" : http://pespmc1.vub.ac.be/

17 The Complexity & Artificial Life Research Concept for Self-Organizing Systems, http://www.calresco.org

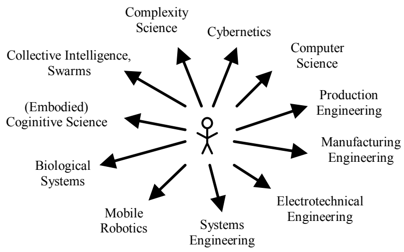

Figure 7. Research areas of influence in an interdisciplinary approach to the manufacturing systems of the future

First of all, it is necessary to very well understand the requirements imposed to the systems of the future in terms of adaptability, reconfigurability and evolvability. Second, it has to be stated that systems designed to correspond to these specifications are not solutions to any kind of manufacturing situation. There are limitations. E.g., systems for mass-production need to be optimal but do not require fast reconfigurability nor the avoidance of re-programming efforts. Third, the key concepts for success have to be identified. Most of them cannot be found in traditional engineering disciplines. Fourth, the concepts and methods taken from non-engineering domains have to be adapted in order to comply with engineering principles.

As a consequence, this highly promising domain needs to be thoroughly studied. The inherent multi-disciplinarity requires researchers able of understanding a broad range of concepts, methods and principles.

3. INDUSTRIAL ACCEPTANCE OF AUTONOMY AND EMERGENCE

As resulted from the discussion above, autonomy and emergence are two important ingredients for the industrial systems of the future. They allow systems to reach much higher levels of service to the user. But unfortunately, autonomy and emergence belong to the industry's worst nightmares. In this chapter, we look into the reasons for this aversion and propose ways out.

3.1. Why autonomy and emergence create fear

At the origin of the fear from emergence and autonomy in industry is probably a deep belief that humans are better at controlling systems than machines or computers ever could be. In some cases, this may be true – but there are many counter-examples. For instance, computers can calculate much faster as humans. They can execute big numbers of processes in parallel – while talented humans are limited to a handful (e.g. talking on the phone while passing the vacuum cleaner and at the same time keeping an eye on the playing children and the dog). Robots can repeat the same task with the same precision for a very long time, but humans get tired much faster and lose precision as well as attentiveness. The reasons for most of the airplane accidents reported recently were human mistakes, not technical defects! So why do people still believe in the absolute human superiority? Why not rely more on machines, also in production systems?

A reason why people try to suppress emergence is that most known examples of emergence are linked to a negative feeling, to the loss of control. When software crashes, the user is rather helpless; restarting is often the only solution.

Popular science fiction movies created a very bad image of “robots ruling the world”. A recent example is the musical “Evil Machines” by Luis Tinoco and Monty Python's Terry Jones, where a humanoid robot takes over the role of the human inventor and incites any kind of machine, from electro-domestic gadgets to motorcycles, to revolt against their slavery and take over the power. It is only a logical consequence of such fantasies that everything advancing a little into the direction of autonomous machines causes fears.

These fears unfortunately interfere with the advance of new technology in industry.

3.2. Differences in the understanding of the terms autonomy and emergence

When people hear the word “emergence”, they most often think about unexpected problems and trouble. The fact that something happens which was not predicted is naturally disturbing. In engineering, this is even stronger than in our every-day life. Engineering is strongly linked to the feeling that everything was carefully analyzed and designed in order to behave exactly in the expected way. If systems break this law, the user has a reflex to dislike it. It requires a certain mental distance to see that sometimes the unexpected occurrence can also have positive effects.

But is emergence obligatorily linked to surprise or unexpected situations? The intuitive answer mostly heard in industry is “yes”. Researchers who have studied the topic are likely to negate. Emergence refers to the fact that system properties or behaviors sometimes appear at the global level without having been designed explicitly at this global level – which is clearly different from being unpredictable. If the local parts are conceived accordingly, they interact in the desired way and it is possible to determine how the global system will behave. Corresponding frameworks to elaborate methodologies exist, e.g. (Auyang 1998).

The term “System autonomy” induces people to think of the above-cited robots that get out of control and take over the power. This has obviously nothing to do with what researchers intend to create. Fist of all, autonomy is never absolute. It is much more appropriate to talk about a certain (modifiable) degree of autonomy. Also a highly autonomous system never gets completely out of control; a vehicle on Mars (one of the popular examples used for illustration of concepts in (Pfeifer and Scheier 1999)) which loses its contact to Earth may be an exception – but even then, the vehicle will not suddenly start doing crazy things. In the worst case it will stand still and do nothing any more, latest when the batteries are empty. Taking care of worst case scenarios are a fundamental aspect of an engineer’s work. A simple example is that the designer of an axis has to think of what happens in case of a power cut. Will the axis fall down and by accelerating put into danger equipment and user? Or will the power cut not have any further consequences because the axis has passive breaking devices?

The same design principle applies to autonomy. The engineer will always provide ways of taking over control at any time – simply by including the obligated emergency power interrupter, this system can be stopped in any situation. Besides this, the degree of autonomy has to be adjustable. Every-day standard tasks should be executed without requiring the user’s help, but if desired, every action can be confirmed manually. For special cases or safety-critical steps, a suggestion should be given for the user to confirm or modify at wish.

We should keep in mind that we are the creators of these systems, and this means that we choose where to put the limits.

Additionally, if wished, a second system can be implemented separately in order to monitor the first and alert the user in case of problems. With responsible engineers at work, there is no reason for industry to be worried about autonomous systems which might get out of control! This is and stays science fiction.

3.3. Why autonomy and emergence are useful for industry

Besides the aspects addressed in previous chapters, systems with a certain autonomy and emergence also offer other advantages.

Numerous manufacturing companies report that they experience increasing difficulties in recruiting skilled staff to operate production machines. It seems that this kind of profession is not popular any more. In some cases, off-shoring to other countries / continents may be a solution (with the disadvantage to lose business), but especially in the domains which require high-precision, automation is the only alternative. The more autonomous the systems work, the better.

Autonomy is also fundamental for coping with "ghost shifts": in countries with high salaries, it is too expensive to employ staff for supervision the machines during the night. This means that the machines run as long as everything goes well, and in case of minor problems, they simply stop production[18]. Valuable production time is lost every night. Some system autonomy to handle complications could avoid this.

If systems can care for themselves to an important degree and can propose solutions to the type of problem which frequently occur, there is less need for highly specialized staff. Choosing among a few proposals for how to proceed is much easier than having to imagine what to do from zero. In this sense, limited autonomy is a way of assisting the user as much (or as little) as he or she desires.

The more complex the system, the more assistance the user may require. High complexity in the body needs corresponding complexity in the brain[19]; this means that the human user can easily become overburdened with managing systems with many modules, many products and many interactions.

A system which is made to run autonomously also has to be able to cope with changes, be it the addition / removal of modules or the confrontation with new requirements without programming. In other words, autonomy leads to evolvability.

Industry as well as research often asks for reactive systems. This is certainly reasonable, but proactive systems can even offer more – they can put themselves at the service of the user and take the initiative to solve problems.

3.4. Preparing people for emergence and autonomy

The resistance in industry against new approaches is more due to human factors than due to technical problems. This means that to make industry accept, we must work on people. Frightening buzzwords must lose their mystery. They need to be explained, they must get reachable, and people must be able to "touch" them. A way to achieve this is to let customers play with autonomous / emergent systems at manufacturing fairs and when visiting labs at university.

They must be shown how the user always keeps the highest command, even if allowing the system to be proactive and autonomous. Similar to the situation of the robot on Mars, which is explores autonomously while still receiving certain commands from earth – with the difference that the user can stand next to the machine in the shop-floor. Constantly giving orders is neither necessary nor useful.

Understanding the concepts of partial autonomy, controlled emergence and supervised proactivity is fundamental. Nevertheless, we will not try to hide that there are also serious technical challenges to solve on the way towards more autonomous systems with emergence: there is still a lack of tools and methods.

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[18] Recently heard in a radio report on channel DRS1 about the Swiss Textile Industry

[19] From „Principia Cybernetica Web" : http://pespmc1.vub.ac.be/

To conclude: It is difficult to understand emergence, difficult to implement autonomy, and difficult to convince people, but still worth the effort!

4. CONCLUSIONS

This article has placed current research for manufacturing systems of the future in the context of a plentitude of other relevant scientific areas. They can help manufacturing systems to get useful characteristics found in natural systems as well as artificial systems made for other purposes.

Two fundamental properties are autonomy and emergence. Their advantages for manufacturing have been illustrated, and an attempt to explain and mitigate the reluctance of industry to adopt them has been made.

Obviously, a lot of work is still needed. Without a paradigm-shift from traditional engineering to more flexible ideas, the manufacturing systems of the future will probably never be able to cope with the challenges they are already facing today.

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