Symbiotic Assembly Systems – A New Paradigm

Pedro Ferreira*, Stefanos Doltsinis, Niels Lohse

*University of Nottingham, Manufacturing Research Division, University Park, Nottingham, NG7 2RD, UK

Abstract

Assembly systems have been pressed in recent years to provide highly adaptable and quickly deployable solutions in order to deal with unpredictable changes following market trends. This has led to the development of multiple paradigms, namely Flexible Assembly System, Holonic Assembly Systems, Evolvable Assembly Systems, Modular Assembly systems, etc. Mostly these focus on increasing availability of automation, however this focus has overshadowed the human element in assembly systems. The lack of a clear human element in these approaches resulted in non-necessary automation and increase complexity. This paper proposes a new paradigm of Symbiotic Assembly Systems (SAS) in order to integrate the human aspects into these developments. The motivation is human actors should be treated as an intrinsic component of assembly systems. This would result in a system that can take advantage of its component’s individual strengths (human or machines), and create a symbiotic environment. Beyond machine automation, human interventions in the system need not only to be modelled as processes but also integrated into the whole system operation. The idea builds on biological systems and their ability to establish symbiotic environments resulting in optimal collaborations. This paper proposes the conceptual vision of Symbiotic Assembly Systems and identifies the necessary developments required to achieve such paradigm. Furthermore it reports on how the developments from other paradigms can be integrated into SAS. An illustrative example is presented to demonstrate the potential of this approach.

Keywords: Symbiosis, Agile Assembly Systems, Sustainable Systems, Symbiotic Assembly Systems

1. Introduction

The field of manufacturing has been constantly changing in the last decades along with technological advances. New products define stricter production requirements, motivating the development of several assembly paradigms to enable the required level of automation and agility. Most approaches today focus on building intelligence into fully automatic systems and reducing human involvement in decisions, as the solution for higher productivity. Results have shown that human intelligence and accuracy are not easy to replace, especially in human driven processes which require high precision and flexibility. People can operate in uncertain environments and can learn how to react to changes, hence bringing flexibility on the shop-floor. In addition, in disassembly processes operations are highly customized and less automated, making humans and their collaboration to machines essential [1, 2]. This is a critical point due to the current drive towards sustainable production.

Current assembly system paradigms target the improvement of assembly systems by either introducing more flexibility, or by using modularity to provide more adaptable solutions. These paradigms focus mainly on the automatic and semi-automatic solutions not realizing the potential of having a heavy human involvement in the new solutions. Despite being a step forward, these treat automation and manual labour as separate issues. This means that systems change from manual to automatic by decoupling parts of the process. Ultimately these solutions target the use of technology for better automation and more agile systems. However, they fail to realize is the potential of achieving true agility through closer human/machine collaboration. Particularly, since the
proposed paradigms have significant technological limitations to deliver solutions that can cater for every eventuality. This is a critical problem in production environments which are more and more characterized by perpetual change.

The inclusion of people in production has several advantages. Human intelligence, intuition, perception, etc. are characteristics that need to be utilized to their maximum to create more efficient production processes. Additionally, the technological progress of artificial intelligence and robotic systems should not be underestimated. Robotic systems have matured to a level of robustness and controllability that under certain safety requirements can support interact with people in the same environment. Nevertheless, physical interaction on a shop-floor is still restricted. This is due to the lack of trust that the respective technologies will prevent the risk of serious injuries. The gain of having technology that allows teaching and guiding a robot, as well as the emerging advantages from human-robot collaboration, demonstrates the potential of machines entities that are complementary to operators.

Understanding the current challenges in the assembly domain is critical to raise the awareness that a new paradigm is needed which includes the people in production systems, rather than ostracizing them. Assembly systems nowadays are manual, semi-automatic or fully automatic solutions. Manual solutions are used for low volumes and highly complex products. This is due to the human flexibility to quickly adjust to changes, to interpret problems and find quick solutions. Fully automatic solutions target mainly high volumes and low product complexity. The idea with these systems is to be able to automate the assembly processes, which is quite difficult for complex products. These solutions are normally quite stable and are not open to changes. In semi-automatic solutions one decouples some tasks for the human operators and automates others.

An analysis of the current assembly systems provides a clear relation between the product complexity and level of automation. In fact in complex product such aerospace, automation is quite reduced, since automation systems cannot easily deal the existing level of variation. However, these sectors are currently under pressure to increase production rates, which would be desirable to achieve through automation. This raises a question, how can we push towards bigger production in complex products. Some authors advocate that technological advances will provide the solutions through more complex automation. But are we ready for this, or should we actually integrate these advances in an existing human environment, enhancing it to deliver better solutions.

Human labour has a clear flexible advantage in relation to automation. However it lacks the ability to deliver high volumes at comparable efficiency. So why not provide a system where both elements are present and interacting towards taking advantage of each other’s strengths. The idea is simple why not create an environment in which people and machines collaborate drawing inspiration from the heterogeneous ecosystem in nature. This premise establishes a relation that goes away from usual master slave relations by creating self-aware machine elements which have a set of objectives that can only be achieve in direct collaboration with people. Similarly, people should rely on their automated counter parts to realise tasks that they would otherwise not be able to perform.

The Symbiotic Assembly System (SAS) paradigm aims to integrate all current technological advances in order to deploy a symbiotic environment between humans and machines in an industrial environment. This will allow both human and machines to take advantage of their characteristics without the current restrictions. On the shop floor, the aim is to use machine strengths, such as physical power and repeatability, collaboratively with the ability of human workers to make decisions under uncertainty and learn from experience. Machines will need to support this through more intelligent dialogue which will provide a level of autonomy that allows this interaction. It is important to note that the required close interaction can only be achieved if one can guarantee a safe interaction environment. This will provide the ability to achieve higher volumes for complex products, pushing the boundaries of systems to the next level as shown in Fig. 1.

Currently available technology is at a stage where this vision can be realised if the focus is shifted to develop SAS instead of fully automatic agile solutions.

2. Literature review

Product manufacturing is constantly evolving according to the requirements of modern society and technological advancements. The evolution in the last century has progressed rapidly bringing automation and high volume production lines up to the peak of their evolution. However, their application is mainly focused on high volume production and provides less economically viable solutions for higher variant production, driven by the need to respond to customer demands and allow high levels of product differentiation. This has resulted in many flexible solutions that can rapidly change to produce goods which encapsulate new technologies, are unpredictable and grow in complexity. Several paradigms have been proposed in the last few decades; flexible, holonic, modular, evolvable etc. assembly systems are just a few of the terms that have dominated the research and industry [3].

All paradigms have the aim to incorporate new automation technologies and support more agile solutions. The focus on developing the aforementioned paradigms is placed on providing quick automated solutions without though considering the human element as an intrinsic part of the system. Human operators are cited as the appropriate way to increase system flexibility in low level productions [1].
Consequently, human-machines collaboration as an enhanced entity has become an important research topic and an aspect of future systems [3-5]. Both sides hold capabilities that are currently suppressed and can be brought out through a new type of relation. New paradigms need to enable the operation of humans and machines in a collaborative way and promote it as a central element where it will evolve into a symbiosis.

2.1. Symbiosis

The term symbiosis finds its origin in the ancient Greece where the first symbiotic relations in biological systems are reported. Herodotus first describes the Egyptian Plover which sits in the mouth of a crocodile and picks its teeth for food leftovers, while the crocodile does not eat it. This example of nature shows a relation based on mutual benefit of the two organisms. Biology reports on a number of examples where two different organisms live in a symbiotic relation under the advantage of mutual benefit. Margulis relates symbiosis to evolution and symbiogenesis as the process of evolutionary novelty that arises from symbioses [6]. Outside the strict biological domain, the Oxford English dictionary defines it as “the interaction between two different organisms living in close physical association, typically to the advantage of both” [7]. A relation where all parties benefit from the interaction is also pursuit in contemporary vies of human-machines interaction [5]. In a Symbiotic Assembly System, symbiosis is viewed as intrinsic close collaboration between human and machine towards achieving their objectives. Through collaboration both can coexist and most importantly achieve the best results.

2.2. Human-machine symbiosis

The term symbiosis outside the biological context has been reported recently in order to describe the mutually beneficiary interaction between humans and machines. Licklider in a visionary study in 1960 is the first to foresee a symbiotic relation between humans and computers that will lead to “…think in interaction with a computer in the same way you think with a colleague whose competence supplements your own…” [8]. Licklider names four areas of technology as the prerequisites to enable human-computer symbiosis (memory components, memory organization, programming languages and input output equipment). Research on symbiotic systems did not progress as initially predicted. Only few references can be found since Licklider’s paper. Lesh et al. in 2004 attempt to update the requirements for symbiotic systems and roadmap the latest technological developments [9]. The requirements for symbiosis are named as “division of labor”, “user representation” and “nonverbal communication”. They claim that technological developments are not far from achieving these requirements. In a similar type of study Roy presents the work of the MIT media lab towards symbiotic systems and questions the lack of technological developments as a inhibiting factor toward the creation of symbiotic collaboration [10]. Another approach to the symbiotic science is presented by Gains who envisioned symbiosis as a progression of knowledge science [11]. He defines symbiosis as a matter of developing “goal-oriented autonomous knowledge creating processes”, “increasing coupling of knowledge processing entities in social networks”, “development of techniques to facilitate the synergy between human and computer knowledge process” and “synthesis of both into a unified system”. Bradshaw in a detailed review paper on the developments of human-computer relationships bridges the gap between the developments of Licklider, Gaines and today’s developments and requirements [12]. He provides a review on the progress of technological requirements put forward by Gaines and concludes that it is time to pursuit wisdom in machines which will enable symbiotic relations. This mean human-machine symbiosis is within reach, which will have a significant impact in solving the current challenges in assembly systems.

2.3. Human machine collaboration in manufacturing

An area where machines and humans suffer from restricted collaboration is in manufacturing. Safety concerns for human-machine interaction have resulted in strict legislation that has pushed humans and machines away from real collaboration and limits it to a usually shielded interaction [5]. The strict and rule based interaction does not allow full exploitation of technological advances in contemporary machines and robots. Kruger et al., in a review study on human-machine cooperation types in assembly systems, state that cooperation is an important aspect for flexibility, adaptability and reusability [5]. The need for human-machine collaboration is also stressed in a number of other recent studies [3, 4].

More development has been achieved in robot specific applications which have attracted a lot of attention due to their wide use in manufacturing and commercial environments. Different solution designs such as assist-robots, collaborative-robots, portable-robots etc. have been introduced to enable human-robot collaboration [5, 13]. Previously the fundamental problem with the concept of true collaborative work was the lack of regulatory support. This changed with the introduction of the new ISO 10218 standard published in July 2011, which provides some leeway for machine operation in the presence of people. Nevertheless and despite the fact that research results indicate that safe human-robot collaboration is achievable, existing legislation industrial standards still require some clarification in their application in industry. This situation urges for further research and development in order to achieve the required level of safety.

Another aspect that needs to be noted for the design of collaborative systems is the perception of collaboration from the operator’s perspective. In a very interesting study Arai et al. investigate this aspect by measuring the human stress and strain during the collaboration as a factor that reduces productivity [14]. Strain is measured in response to robot-human distance, robot operating speed and time of notice. One of their conclusions is that not only physical support needs to be provided but also information support to enhance human awareness to reduce stress and allow closer human-robot collaboration.

All of the cooperative and collaboration-based systems aim to design a supportive mechanism for human operators.
Robots are treated as passive devices controlled by a human rather than an autonomous device build to sense, reason, and act in a symbiotic context. A requirement for future systems is the cooperation not only between two parties (human-machine) but with entities aiming to fulfil a common task [5]. The aim of a SAS should be on creating a symbiotic non-stressful environment without fear and surprise during collaboration. In such environment a machine would not be perceived as a harmful and strange object but as valuable partner which is critical for the success of operator.

2.4. Summary

New research approaches and projects include collaborative functionalities within their technical advances. Research calls include terms such as “…symbiotic human-robot collaboration…” in order to support such developments. The first collaborative robots enabling teaching and learning functionalities have appeared in the industrial market. To further support the requirement for a new type of automation based on collaboration, and enhance adaptive systems in industrial environment, it is required to aggregate the individual developments into a new paradigm. Symbiotic Assembly Systems (SAS) become a requirement in contemporary manufacturing for both the industry and the workers. It is no longer enough to address competitiveness in terms outputs, one requires the wider social view to understand the importance of SAS. Moreover, according to the requirements for symbiotic systems defined by Licklider it is now the time to push for such an environment since technology can support it.

3. Symbiotic Assembly System Paradigm

The first step in establishing SAS paradigm is to understand the nature of symbiotic systems. It is clear that nature had millions of year to evolve and fine tune its solutions. However, in the assembly domain we do not have the luxury of so much time. Therefore, it is important to understand how symbiotic systems emerge in the natural domain and when they do not. Critically, there is a clear separation between the design process of symbiotic systems and the actual occurrence of symbiotic relationships between individuals of different species. Natural occurring symbiotic relationships provide significant advantages for the species involved from which we can draw clear parallels with the assembly domain. However, the advantages of such relationships can only be harnessed if one understands the underlying principles behind the emergence of a symbiotic system. The emergence of successful systems in nature is regulated by the principle known as "survival of the fittest". Consequently, symbiotic systems only emerge in nature if the species involved both improve their chances to survive. Hence, it is critical to establish mutual gain or benefit as the criteria for the identification of symbiotic relationships within production systems. It is very important to understand the nature of the species within the system and comprehend the reason for their existence to ensure their symbiosis will be mutually beneficial and ensure their long term success.

The importance of understanding the underlying motivations and instincts of the partners in a symbiotic relationship can be well illustrated with the famous fable of the scorpion and the turtle, highlighting the challenges if the individual drives are ignored. A scorpion walking up to a river bank calls out to a passing turtle and says “I do not know how to swim, would you be so kind as to carry me on your back across the river?” The turtle confused by the request replied “Of course not, if I do you will sting me and I will die.” However the scorpion did not admit defeat, instead he said “If I do we will both die, because I do not know how to swim.” The turtle thought carefully on the scorpions answer and did not see any fault in its logic, so it decided to take the scorpion across. In the middle of the river the turtle felt a sting piercing its neck, and just before dyeing asked the scorpion “Why did you do this?” and the scorpion answer “Because it is my nature”.

The moral of this tale is that one cannot go against ones nature. Surprisingly, in the natural world one can find examples of symbiotic relationships that seem to contradict the primary instincts of the species involved. For example, the Egyptian Plover bird sits in the mouth of a crocodile and picks its teeth for food leftovers, while the crocodile does not eat it. This is because there is a symbiotic relation in place. Both parties benefit from this relationship. This is a critical in symbiotic systems. If the crocodile ate the Egyptian Plover it would not gain much nutrition, while it would not have any means to clean its teeth. On the other hand the Egyptian Plover is able to eat without having to hunt for food. In fact, when analysing the underlying reasons for symbiotic relations, such as this, one can see that the primary instinct is overruled due to a clear gain.

The concept of gain needs to be clear, but without the concept of trust it is irrelevant. If the Egyptian Plover did not trust that the crocodile would not eat it, would it go in the mouth of the crocodile? This is particularly important if the species involved in the symbiotic system are able to reason, which is the case for people.

So to establish a symbiotic system it is important to understand the nature of the elements in the system, to establish the gain for all parties and to enable a trust relationship. The concept of trust requires the ability of awareness, one needs to be aware of the another and oneself in order to establish a trust relation. It is important to stress that SAS involves people, who have attributes that are not found anywhere else in nature. One needs to bare this in mind when proposing this system, since the nature of the elements will play a critical role in the creation of a symbiotic relation. Moreover, the symbiotic relation tends to rely on the strengths of each element to compensate for the weaknesses of the others. Finally, one should also point out that in any symbiotic relation there is a choice to be made. This implies that the relationship is not enforced, but exists on the condition of mutual trust and benefit. Otherwise, an enforced relationship will not achieve the desired benefit of close collaboration and will have the tendency to break down.

In SAS there are two main categories of elements, humans and machines. These categories can be further broken down into more detailed roles, but there is a clear need to
differentiate between the two at a high level. Humans are great at adapting to change, making difficult decisions with incomplete data, learning from experience, sensing unexpected stimuli, etc. Machines are good in applications for repetitive tasks, in depth calculations, operating in hazardous conditions, operating with high payloads, making routine decisions quickly, etc. These relative strengths provide the base for the identification of promising symbiotic collaborations.

In addition, one needs to understand the intrinsic motivation and the gain of each element. It is important to state that each element is expected to have its own independent motivation. It is assumed, however, that each species in the system will be firstly motivated by its own survival and secondly by its need to do well. This means different things for each species. For the people in the system it means “adapt to changes to prevent becoming obsolete which would lead to decommissioning”. For the machine it means “adapt to increase productivity and efficiency to retain employment”. For the system this means “adapt to changes to prevent becoming obsolete which would lead to decommissioning”. For the machine it means “adapt to increase productivity and efficiency to retain employment”. For the system this means “adapt to changes to prevent becoming obsolete which would lead to decommissioning”.

SAS hypothesizes that the establishment of a real and measurable co-dependency between humans and machine will lead to long term sustainability even across different social-economic conditions in the world. If there is no balance between the two, we either will have no jobs which will lead to a destruction of our economic system, or we will have human exploitation as the only way to have viable economies. As Oscar Wilde put it: “The fact is, that civilisation requires slaves. The Greeks were quite right there. Unless there are slaves to do the ugly, horrible, uninteresting work, culture and contemplation become almost impossible. Human slavery is wrong, insecure, and demoralizing. On mechanical slavery, on the slavery of the machine, the future of the world depends.” What Oscar Wilde dismisses in his statement is the importance of work in the economy. SAS proposes an enhancement of machines beyond their slavery in order to establish a balanced and truly symbiotic system, where all elements are driven by their own benefit.

The SAS paradigm is intended to drive the next generation assembly systems by providing a truly agile environment where change is the rule and where dynamic reactions are human driven and machine executed. SAS will build on already existing symbiotic relations between human and machines, but it will formalize and structure these, while trying to optimize the relationships in order to establish clear and understandable gain. Machines will not be seen as the replacement of workers, but rather as the means for which workers can continue to work. An example of this is the paint shop in a car manufacturing where the robot is programmed to mimic the human. This is done because the task is too complex to fully describe, but it is quite easy for a human to verify the quality of the task. Once the pattern for painting is established the robot can repeat it. This means that the robot can only exist if the worker does as well, and if there is a constant change in products (cars) this dynamic relation needs to be enhanced and perfected into a close collaboration where the individual strengths of each species can be truly exploited.

The previous example really shows how the use of symbiotic systems will help particular for complex processes where the variation is quite high. Aerospace is an example of an industry which is characterized by high levels of variations compared to relatively low production volumes. SAS will provide real time collaboration between human and machines to achieve faster and more efficient production environment. The assembly of a wing component can be used to demonstrate this potential. The wing is a highly complex product, which currently requires humans to work in very small enclosed environments to carry out complex tasks such as applying sealant to bolts inside the wing. Some of these tasks involve hazardous materials which are currently handled with extreme care, but with a certain level of risk to the worker. Fully automatic solutions would eliminate the need for workers to work in such confined spaces. The skill involved to carry out the required processes is, however, very challenging to automate and would cause considerable quality concerns. Following the SAS approach would provide the worker with support through automation to avoid the confined spaces while at the same time utilising the required complex quick decision making skills from the worker. The worker would retain their job, which is currently at risk of being outsourced, while the machines would have higher utilization and achieve the desired purpose. This would lead to the maintenance of a quite stable economy with the necessary social concerns that should govern all humanity.

4. Symbiotic Assembly System Technological Requirements

The feasibility assessment of SAS is quite dependent on our ability to clearly define the necessary technology to enable it, and critically verify that it is within reach. As stated in the literature review, the high level requirements for the creation of symbiotic systems already exist. Despite the fact that the current state of the art of technology does not directly address all these requirements, it does provide the indication that they are within reach. One might argue that the lack of a structured and detailed technological requirements definition is critically at fault for the lack of focus in developments. Nevertheless, it seems clear that symbiotic systems are achievable with the current level of technology, which addresses both the requirements from Gains [12] and Licklider [8]. Fig 2 provides an overview for the SAS technological requirements.

The creation of a semantic model that is understood and shared across all elements in the system is the first step towards having a fully symbiotic environment. The need for this common language is critical to enable the communication between elements. This is of the utmost importance due to the critical role of people in the environment. The need to establish a trust relation requires clear communication, particularly if human elements are involved. Moreover, in order to establish gain, one has to possess the means to describe the system, which will also be provided by the common semantic model.

SAS aims to create an environment where machines and humans can interact closely, which implies that the systems need to be safe, predictable, and reliable. This will require the advancement of current safety systems and regulations to
allow for safe and effective cooperation between machines and humans. Machines and humans have to be addressed as intrinsic elements of dynamic shop floors that require high levels of in process adaptation. Thus, new step changing methodologies for rapid re-programming and behaviour adaptions through close interaction need to be introduced to overcome current practices which require huge amounts of time to perform any change in a system.

5. Conclusion

This paper proposes the creation the new Symbiotic Assembly System paradigm to not only address the need for higher levels of flexibility, but also to create an social-technical environment that is truly sustainable for both companies and workers.

The paper highlights the need for such systems and establishes that symbiotic assembly systems will be feasible in a near future. However, for this paradigm to become a reality, multiple technological advances need to occur. A preliminary view of these has been presented in this paper. Future work will focus on defining a full SAS reference architecture supported by a clear technology development roadmap which is expected to be the blueprint for future symbiotic systems enabling longer term sustainability.

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