PROACTIVE ASSEMBLY SYSTEMS-REALIZING THE POTENTIAL OF HUMAN COLLABORATION WITH AUTOMATION

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Abstract: Manufacturing competitiveness frequently relies on company ability to rapidly reconfigure their assembly systems. This paper introduces assembly system proactivity, a concept based on interrelated levels of automation, human competence, and information handling. Increased and structured human involvement contributes to increased system ability to proactively address predicted and unpredicted events. Correct involvement of human operators will utilize the combined potential of human and technical capabilities, providing cost-efficient assembly system solutions. The ProAct project is developing proactive assembly system models and evaluates proactive, feature-based solutions. Focus is on realising the potential of cost-efficient and semi-automated systems with relevant human involvement, i.e. highly skilled operators who add flexibility and functionality © 2009 Elsevier Ltd. All rights reserved.

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1. INTRODUCTION

Leading manufacturing companies must constantly develop their competitive advantages. Manufacturing strategies deployed should create ability for rapid and cost-efficient introduction of new products and product variants (Billington et al, 1998; Capon et al, 1996; Harmsen et al, 2000; Langowitz, 1989). Competitive systems for manufacturing, especially assembly systems, have to cope with frequent changes of external as well as internal demands, i.e. changes of product variants and increased variation in volumes, which require drastically shortened resetting and ramp-up times. At the same time, cost efficiency and “leaness” require correct quality, lower cost, and focus on value-adding activities. One approach is to introduce product customization as late as possible in the value-adding chain. As a consequence, the flexibility of the final assembly process becomes a critical factor.

Companies often develop assembly systems as a reaction to emerging external demands or new products. The assembly system designer reacts to occurring needs and solutions become responses to existing problems, i.e. highly reactive actions. Often, the introduction and ramp-up of a new product is a discrete and unique event rather than a part of the assembly system long-term development. It is questionable if reactive approaches alone are sufficiently progressive and competitive. Further, if it presents a cost-efficient solution contributing to stable and economical company growth. Rather, assembly systems need to be dynamic and evolvable to really constitute long-term assets for the manufacturing company (Onori et al, 2006a).

In summary, the preferred assembly system should have the ability to proactively meet emergent and long-term fluctuations, while not losing its capability to react to occurring deviations from planned behaviour. A general definition of proactivity is ‘taking action by causing change towards a state and not only reacting to change when it happens’. Another way to phrase this is ‘to be anticipatory and taking charge of situations’. Such a system consists of technical components efficiently integrated with human operators to constitute reliable resources in the manufacturing system. In that way, present and future requirements for sustainability, flexibility, and robustness could be met. Effects of predicted and unpredicted disturbances can be minimized. Hereby, availability of entire assembly systems will be increased (Flegel et al, 2005).

Presently, proactivity is generally not considered a competitive factor in assembly system design. This paper focuses the need for proactivity in assembly systems, complementing traditional, reactive system activities. We claim that proactivity can be influenced by a systems ability to change the levels of automation, information, and competence respectively, in a semi-automated assembly system. The paper presents results from the ProAct project, a collaborative effort by six Swedish industries and three Swedish technical universities, aiming at development of proactive assembly systems.
2. BACKGROUND

Assembly systems consist of human operators collaborating with technical and automated resources. Highly automated assembly systems frequently have limited flexibility and are primarily dedicated to single products. A major challenge is to minimize lead-time, while maintaining flexibility and robustness, thus absorbing late market requirement changes. This includes reduction of cycle and throughput times for individual assembly processes. Also, there is a need to minimize resetting time between batches, time to repair, time for disturbance handling, and time to prepare for new product variants in the assembly system. Time can be reduced by achieving proactivity through an efficient combination and integration of the respective levels of automation, information, and competence requires cross-disciplinary research efforts, e.g. development of measurement and visualization methods. Quantifications of the three parameters provide a structured description of the action space for proactive solutions in assembly system development.

2.1 Assembly Systems

Recent research and development within the area of assembly is characterized by approaches towards higher levels of automation (Onori et al, 2006a). Evolvable and reconfigurable systems (Barata et al, 2005; Lohse et al, 2005; Onori, 2002) and process-oriented, evolvable and reconfigurable systems (Onori, 2005), have been developed. Early efforts to develop highly flexible assembly systems have been complemented by reconfigurable assembly system concepts (Barata et al, 2005; Lohse et al, 2005; Mehrabi et al, 2000) with the ability of emergent behaviour, e.g. evolvable assembly systems (Barata et al, 2006; Maraldo et al, 2006). These projects underline the need for self-configuring, collaborative, and more autonomous assembly systems to enable quick change and reduce implementation time. Unfortunately, integration of human operator abilities into evolvable assembly systems is presently limited. Human ‘components’ are often delimited from the system, despite the fact that human cognition and control is often superior to IT solutions, in terms of e.g. investment cost and problem solving capability. Successful integration of human operators constitutes great potential in highly flexible assembly.

2.2 Human-Centred Automation

Automation is frequently used to improve productivity and efficiency in manufacturing systems and assembly. Despite tremendous development, there is still no evidence that manual labour has been surpassed as flexible resource in assembly systems. Further, human presence generally has few negative consequences on performance and quality (Ruiz-Torres & Mahmoodi, 2007), and it is rarely possible to meet necessary market requirements for flexibility and cost efficiency by automation only. As a response to technology-centred approaches to automation, e.g. ‘automate what can be automated’, human-centred automation has been suggested. Billings (1991; 1996) defines human-centred automation as facilitating a cooperative relationship in the control and management of a complex system with potential benefits for performance. Sheridan (1995) elaborates on alternative meanings of human-centred automation, e.g. ‘allocate to the human the tasks best suited to the human, allocate to the automation tasks best suited to it’ and in that way ‘achieve the best combination of human and automatic control, where best is defined by explicit system objectives’. This changes focus from a function-oriented to a process-oriented perspective. High performance of a human-machine system may be achieved through human-centred automation by ensuring that the human has the capability to monitor the system, that humans receive correct feedback on the state of the system, and that the automation functions in a predictable way (Billings, 1996).

Although highly efficient, concepts for emerging, evolving, and highly reconfigurable assembly systems previously described, rely on rapid adaptation to changing conditions. This paper suggests that even higher competitiveness can be achieved by a complementing proactive behaviour. Proactivity is not a new concept, as proactivity often can be observed in the behaviour of highly skilled and experienced workers. Experience, pattern recognition, and other human cognitive skills support the way working people prepare themselves and their workplaces for expected and planned events. A classical model for proactive behaviour, Situation Awareness (SA), was proposed by Endsley and Kaber (1999). The three levels of situation awareness were defined as:

- Perception of elements within the current situation.
- Comprehension of the current situation
- Projection of future state.

Thus, in addition to planned events, proactivity, as well as SA, involves anticipation of situations and events that have not previously been explicitly defined and described. Anticipation is primarily a human cognitive skill, not often efficiently mimicked by automation. Through efficient integration and collaboration between human operators and technical systems, proactivity for the complete assembly system can be achieved. Such cooperation relies on technology that can be changed and on human competence to act proactively. Finally, the information available influences the system’s ability to anticipate forthcoming events.

2.3 Information

A well functional information flow throughout the manufacturing process chain is a powerful and necessary prerequisite (Lumsden, 1998). Fjällström (2007) suggests that information related to the shop floor, particularly in assembly systems, should be either problem-related or domain-oriented. One challenge is to provide adequate information for performing the task required, thereby preventing frustration, confusion and time consuming activities (Almgren, 1999, Berglund et al, 2001). The information flow to the assembly system must provide the right amount of information to reduce uncertainty. Further, information has to fulfill several qualitative criteria (Kehoe et al, 1992):

- Relevance e.g. the users benefit in their decision or action because of it.
The role of people in the modern flexible production system changed when new system principles and technologies were introduced. Operator teams are now expected to behave agile and proactively, rather than just executing simple, repetitive tasks. MacDuffie & Krafcik (1992) stated the increasing need for understanding of the employee’s role in the production system due to the necessity to identify and solve problems the moment they arise on the line. Kaber & Endsley (2003) explored effects of different levels of automation on human performance and situation awareness. Bley et al. (2004) discussed appropriate human involvement in assembly systems. They focus on how the system should be adapted to the external constraints like products and internal human behaviour i.e. the operator is treated like a system component. Unfortunately, the possibility to really use the competence of the operator is not addressed.

Production employees require knowledge and training to solve problems on the production line, as they occur. They must be able to identify problems, isolate their occurrence, determine their root causes, and conduct remedial actions to prevent their reoccurrence. These requirements highlight the importance of information sharing and decentralising of the skills of specialised staff, such as those involved in maintenance and technical engineering. Further, this additional knowledge will assist operators when facing daily issues, and help integrate them into the concept of the ‘production system’ Barroso & Wilson (2000) recognise that although human operators can act as ‘contributors’ of defects, they could also be ‘recoverers’ of defects given necessary knowledge and skills. Clearly, there must be a balance between the operator’s perception to cognitive and social aspects of the production environment and changes that occur in their workplace due to new performance pressures. Support to understand, mandate to react and resources to allocate constitute the action space. This balance enables the workforce to intervene and handle defect occurrences effectively and efficiently. If an operator acts as a recoverer of defects in the system, it is equally possible that any human error that occurs can make recovery more difficult. For example, if errors have been introduced during a manual assembly process and the system relies on human inspection for defect control, then failure of the inspection process might result in the defect becoming further embedded and more difficult to detect and remedy. During operation, operators will assume different roles in relation to the system. Sheridan (1987) described human supervisory control of complex systems as five major and interrelated roles of system operators i.e. planning, programming, monitoring, intervening, and learning. Primary contexts for his description were process and aerospace industries. Stahre (1995a; 1995b) suggested a complementary re-definition of the monitoring and intervening roles, where more interaction with the physical process was included, as would be normal in manufacturing and assembly systems. In all the roles, the competence of the operator is crucial to normal operation and even more so during disturbances and breakdowns.

- Timeliness e.g. the information is available in time.
- Accuracy, information is free from error.
- Accessibility, information is readily available.
- Comprehensiveness, information is free from omissions and redundant data.
- Format e.g. effectiveness with which information is perceived and suits the individual users’ cognitive resources and subjective preferences (Rasmussen et al, 1990).

This demands a large amount of information to be exchanged in a short period if time. Moreover, the purpose is to ensure that the operator’s perspective is taken into account. This means that in the future there is a need to take the operator’s abilities and limitations into consideration, as well as the operator’s various ways of using information and making decisions in different working situations. Frequent exchange of information between different company levels is crucial to create quick ‘decision-loops’ which are correctly connected and updated with real manufacturing conditions (Bruch et al, 2007). In the proactive assembly system the operators are encouraged to take more responsibility, far beyond managing operation and disturbances.

The operator needs to be informed about all the resources available to perform the activity while at the same time, information defines the boundaries of possible actions for the operators. This implies that information should represent the functional structure and state of the process (Hollnagel, 2003).

Moving from a lower level of abstraction to a higher level means a change in representing system properties. However, it does not imply a removal of detailed information about the physical or material properties; rather information is added on higher level principles in terms of describing the co-functioning of the various elements at the lower levels (Hollnagel, 2003). Consequently, the concept and structure of information representation changes at the different levels of abstraction as well as that the information appropriate to characterise the current status will be varying. Information represents the resources (material, machines, operators, etc.) available and needed for all relevant activities in order to guide operators’ activities. Moreover, operators need information about above and the below levels. The former is related to the immediate purpose of the control decision, i.e. why it is made, while the latter one represents how a decision can be implemented (Hollnagel, 2003). The abstraction hierarchy implies that for each task the questions of why, what and how need to be answered.

2.4 Competence

The operator competence should consist of domain knowledge regarding the production process, assembly operations, and of skills based on experience as well as of a capacity for correct judgment and evaluation of the actual production situation. Proactive assembly operators’ work should approach ‘knowledge work’, in the true sense of the “Knowledge worker” as described by Drucker (1999).
Issues to be dealt with by competent operators are e.g. the ability to foresee planned and unplanned disturbances, identify technical errors, and find solutions to problems. These tasks are important in both short- and long-term perspectives. With Sheridan’s operator roles as starting point, an analysis could be made of the tasks carried out in an assembly system.

The analysis could be extended to cover also the behavioural levels as once phrased by Rasmussen (1986): skill-based level, rule-based level and knowledge-based level, the latter applicable to behaviour in new situations. As shown in Fig. 1 there are 15 tasks in an assembly system, which could be attached to the five roles in Sheridan’s terminology. Consequently, long-term and short-term planning (tasks 1 and 2) are carried out on a rule-based level. Programming (task 3) and process planning (task 4) are likely to be carried out on a knowledge-based level. Assembly (5), order handling (6) and material supply (10) are skill-based tasks. Set-up (7), monitoring (8), identifying deviations (9), maintenance (11) disturbance handling (12) and quality assurance (13) are rule-based activities. Finally the learning tasks (14 and 15) are carried out on a knowledge-based level.

Most of the assembly tasks are relevant in the light of proactivity. However the tasks of setting up, order handling, assembly and disturbance handling are dealing with the situation of today.

Figure 1 – Tasks within an Assembly System

This analysis is relevant when designing future proactive assembly systems. The described research on human supervisory control and situation awareness relates to decision making in dynamic system contexts. Sequenced decisions will be interdependent and often made in real time. An operator with a high level of understanding of the whole system will be able to manage the situation supported by comprehensive information. Automation within a human-machine system not only includes decision and execution tasks, it also covers functions that precede decision making and implementation, (Parasuraman et al, 2000). The model suggested by Parasuraman et al, (2000) is built on theories of human information processing.

3. PROACTIVITY IN ASSEMBLY SYSTEMS AND ITS PARAMETERS

In a proactive assembly system its human and technical resources are prepared for and may anticipate changes and disturbances during operation and planned, long-term, and sustainable evolution of the system. Proactivity is highly related to the time factor, specifically the reduction of time, thus time should be a main metric of proactivity. This implies a combination of short resetting time and robustness of the system as a whole and its resources. A major challenge is to reduce and minimise the lead time, which has a direct influence on order-to-delivery time, while maintaining flexibility and robustness to absorb late requirement market changes.
This includes throughput time and cycle times for individual assembly processes. Also, there is a need to minimise resetting time between batches, time to repair, time for disturbance handling, and time to prepare for new variants or products in the assembly system. Fasth et al, 2008 introduce the following criteria for the systems resources to achieve and maintain a proactive behaviour in an assembly system:

1) Anticipation of problems related to change.

2) Initiations of activities that lead to solution of change-related problems and improvements in work.

3) Resolution of change-related problems.

To achieve the design of a proactive assembly system, automation and manual knowledge work should be combined to achieve high performance and flexibility. We propose that the level of automation (LoA), the level of competence (LoC) and the level of information (LoI) will be decisive factors affecting system performance towards a proactive behaviour.

**Level of Automation - LoA**

LoA describes the inherent flexibility and quickly changeable level of automation in the assembly system. This applies to mechanical/physical as well as information/cognitive levels of automation.

**Level of Information - LoI**

LoI describes an efficient and dynamic flow of predictable as well as more or less unpredictable information between assembly, manufacturing production, preparation, suppliers, marketing etc.

**Level of Competence - LoC**

LoC describes the accumulated and combined knowledge of the group of operators working in the system. Efficient system operation relies on continuous and efficient competence development and adequate learning processes.

By combining appropriate levels of the LoA, LoI, and LoC parameters, proactivity can increase, provided that flexible automation as well as operator ability and awareness can be achieved. The ambition is to approach the context of rapidly reconfigurable assembly systems in order to increase efficiency, decrease reaction time, and reduce disturbances. The proactive concept is presented with arguments for focus on levels of automation, information, and competence as main drivers for the degree of proactivity. The ProAct project recognizes the need for rapid reconfigurability. However, an added value of ProAct is to emphasise human resources on the shop floor and the possibilities to dynamically and gradually deploy such resources to proactively resolve problems and to exploit market possibilities. The combination of skilled human operators, dynamically semi-automated assembly systems and the aspect of emerging and self configuring systems is set as the field of research.

4. APPROACHING PROACTIVITY - MEASURING THE LEVEL OF AUTOMATION (LOA)

Concepts for varying levels in manufacturing automation have been suggested by e.g. Williams & Li, (1998) and have also been integrated into the enterprise integration frameworks Purdue Enterprise Reference Architecture (PERA) and the Generalized Enterprise Reference Architecture and Methodology (GERAM), (Williams and Li, 1998). However, the LoA concept is from an information/cognitive perspective well established in e.g. aerospace and process industry, and in the IT research communities (Sheridan, 2002; Inagaki, 2003; Endsley & Kaber, 1999). LoA concepts were recently reviewed by Frohm et al, (2008). Core resources, such as humans and technical equipment, need special attention when designing and redesigning an assembly system. The balance between the human and automation can be used as a design parameter, by determining a specific LoA in the assembly system. LoA is defined as ‘the relation between human and technology in terms of task and function allocation’ (Frohm et al, 2006). LoA is an indicator of the allocation of tasks in an assembly system and is expressed as an index of physical as well as cognitive tasks. Choosing the wrong level of automation may result in considerable investments without sufficient gain in assembly system capability. To approach a proactivity assessment in assembly systems, the ProAct project has performed case studies in five Swedish industrial companies. Each case study includes an analysis of the present competence situation and a cognitive task analysis. The operators’ views of their work are acquired to provide product and system designers with information on critical issues in the assembly work situation. Further, the degree of long-term, proactive perspective among the operators on the development of their assembly system and active participation in product design and in the assembly development process is also assessed. A functional analysis is carried out, addressing expectations on the system and assumptions on which duties, tasks, and actions that will be included in the operator team responsibilities. The cognitive task analysis involves interviews of stakeholders at different levels in the organisation. Interviews focus on mental activities e.g. information handling, communication, and decision making in normal operation. This also involves a comparative analysis between novice and expert operator work. When considering the applicability of the three parameters automation, information and competence the ProAct project has been using an extended version of the DYNAMO methodology (Frohm 2008; Fasth et al 2008) which enables measurement of the level of automation both in terms of mechanical and information work tasks. The result of a measurement with the DYNAMO methodology is a matrix with an area with defined possible technical solutions for the assembly tasks, mechanical as well as cognitive tasks, shown in Fig. 2 (Fasth et al, 2008).
The tasks can be integrated in an automated system, semi-automated or manual and can be measured and analyzed at the same time (Fasth et al, 2007). The aim of the DYNAMO methodology is to measure and get an accurate picture of the span of possible solutions for LoA to perform the tasks. For example, a screw fastening operation can be done using a regular screwdriver (LoAmech = 2), by an automatic screwdriver (LoAmech = 4) or by a machine (LoAmech = 5). Setting minimum and maximum levels for both mechanical and information automation enables a square of potential improvements (SoPI). The analysis makes it possible to elaborate with different levels of automation ranging from the lowest possible to the highest possible, for cognitive as well as physical tasks. A larger span of possible solutions for replacement and in real time optimisation is an enabler for proactive behaviour. Equipment for automation for mechanical, cognitive tasks and information tools can be evaluated with the criteria anticipation, initiations of activities and resolution of change-related problems. Example is shown in Fig 3.

Figure 3 – Example of a LoA Span defined by using DYNAMO Methodology, Fasth, 2008.

The criteria support correct situation awareness for the operator team. This put requirements on the information to have ability to both provide correct information about the system, the resources and the system as a whole. Information also needs to be presented in a way that supports the operator team to have the correct situation awareness in a short time. The competence of the operator team is crucial because this realises the system’s proactivity that is built in. Competence is not replaceable with information but it could be reinforced with the right level of information. Without correct competence it is not possible to have correct situation awareness in a short time. The competence is the ability to do the right action and also to predict the consequences of the action taken.

5. Discussion

The authors’ approach to proactive assembly systems has been presented and aligned with the arguments to focus on automation, information and competence as main drivers for proactivity. A combination of skilled human operators, efficient information technology, and semi-automated assembly systems are proposed as enablers for time reduction and increase of flexibility.

In such systems the levels of physical and cognitive automation are decisive factors. When the level of automation (LoA) is measured on a detailed level, also task-related requirements for competence and information become clear. The ability to adjust the level of automation is a powerful enabler for proactive behaviour. Our case studies also indicate that changeability of information content, and competence levels are ways to increase system performance. This especially applies to system lead time, cycle time, and downtime. The competence of the operator team is the enabler to realise system proactivity and performance. Without the right operator competence level, automation cannot be utilised to its full extent.

Figure 2 – Possible Solutions of LoA for Assembly Tasks

The authors' approach to proactive assembly systems has been presented and aligned with the arguments to focus on automation, information and competence as main drivers for proactivity. A combination of skilled human operators, efficient information technology, and semi-automated assembly systems are proposed as enablers for time reduction and increase of flexibility.
Competence cannot be replaced by information but it could be reinforced by the correct level of information to rapidly achieve high situation awareness. The achieved proactiveness and situation awareness enable the operators to perform the correct action and also to predict the consequences of the action taken, i.e. being aware of the environment within a volume of time and space and understanding their meaning and the assembly systems status in near time and in the future. Fig. 4 illustrates a sequence of tasks initiated by a planned change (e.g. a new batch) or unplanned event (e.g. a mechanical equipment error).

Figure 4 – Sequence of Tasks Initiated by a Change
Automation, competence, and information have high impact on e.g. investment amounts. All three parameters may be crucial for company management decisions. In proactive assembly systems, changes of the level of automation enable quick response to variations. Further, in such systems changes in information levels will provide assembly operators with information matching their present knowledge level and increasing their situation awareness in rapid response to quickly changing market demands.

6 CONCLUSIONS
It can be concluded that increased proactivity in assembly systems will result in flexibility gains and reduction of total lead time in assembly. Proactivity in assembly also provides reduction of disturbances and higher situation awareness among assembly system operators. The authors have determined that contributions to proactivity can be made through changes in information, competence and automation. Such changes require quantification of levels of automation, information and competence. Proactivity enables human advantages with respect to automation as well as advantages in automation related to human abilities. The ProAct project has acquired empirical data from six case studies in Swedish small and medium-sized (SME) companies, to substantiate and test the applicability of proactivity in assembly. With a proactive approach, companies will potentially have better control of their assembly system during an unforeseen occurrence or incident. A proactive, semi-automated assembly system will quickly be able to absorb emergent changes within its constraints and thus demonstrate superior sustainability in its long-term development.

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