Current status of reconfigurable assembly systems

Z.M. Bi*, Lihui Wang and Sherman Y.T. Lang
Integrated Manufacturing Technologies Institute
National Research Council of Canada
800 Collip Circle, London, ON N6G 4X8, Canada
E-mail: Zhuming.Bi@nrc.gc.ca
*Corresponding author

Abstract: Reconfigurable Manufacturing System (RMS) is one of most promising paradigms that provide an effective solution to changes and uncertainties in a competitive manufacturing environment. A Reconfigurable Assembly System (RAS) is a key component of an RMS. In this paper, our survey on the development of RAS has been summarised. The objectives of this literature survey are to:

• clarify the needs and drivers in developing reconfigurable assembly systems
• identify both academic and practical issues critical to the development of reconfigurable assembly systems
• understand the state of the art of R&D related to the studies on the critical issues
• reveal the future research directions, which are mostly beneficial to manufacturing industries.

Keywords: Reconfigurable Assembly Systems; RAS; modular assembly; flexible assembly; robotics and automation; system reconfigurability.


Biographical notes: Dr. Z.M. Bi is a Research Officer of Integrated Manufacturing Technologies Institute at National Research Council of Canada. He received a PhD degree in Mechatronic Control and Automation from Harbin Institute of Technology, China, in 1994, and a PhD degree in Design and Manufacturing from University of Saskatchewan, Canada, in 2002, respectively. His current interests include mechatronics, automatic robotic processing, reconfigurable manufacturing and assembling systems. He has published over 60 technical articles on robotics and automation, parallel kinematic machines, advanced manufacturing systems, planning and scheduling, and software development and testing.

Dr. Lihui Wang is a Senior Research Officer of Integrated Manufacturing Technologies Institute at National Research Council of Canada. He received PhD and MSc from Kobe University, Japan in 1993 and 1990, respectively, and BSc from China in 1982. His research interests are focused on adaptive process planning, web-based monitoring and control, and reconfigurable assembly systems. He has authored in excess of 150 book chapters, archival journal papers, and peer-reviewed conference articles. He is now
1 Introduction

In a recent review on Reconfigurable Manufacturing Systems (RMS), Bi et al. (2007) have discussed some key requirements of today’s manufacturing systems and classified the strategies to meet these requirements. RMS has been identified as one of the focused areas, based on the state-of-the-art review of RMS and its comparison with other popular manufacturing systems. However, RMS is a very broad concept. It consists of many elements, each of which poses its own research challenges. It was difficult to cover everything of an RMS in a single review. In this paper, both in-depth review and analysis are given to one of the key elements of RMS – Reconfigurable Assembly System (RAS). In particular, a comprehensive literature survey is conducted on RAS to:

• clarify the needs and drivers in developing reconfigurable assembly systems
• identify both academic and practical issues that are critical to the development of an RAS
• understand the state of the art of R&D related to these critical issues
• reveal future research directions, which are mostly beneficial to manufacturing industries.

The remainder of this paper is organised as follows: in Section 2, the concept of RAS, as well as its variations, is introduced; in Section 3, the rationales of developing an RAS are discussed; in Section 4, some critical issues involved in RAS are clarified, and the previous efforts towards addressing these issues are reviewed; in Section 5, the difficulties in developing an RAS are summarised; and finally in Section 6, some future research directions of RAS are identified.

2 Concept of reconfigurable assembly system

Assembly includes all assembly/subassembly processes and equipment required to (a) bring together, configure, align, orient, and adjust components and materials to form the end-product, (b) physically attach parts, materials, and components, such as
screwing, riveting, stapling, nailing, gluing, wrapping, interlocking, tying, fusing, sewing, welding, soldering, bonding, pegging, coupling, laminating, insertion, sealing, and similar activities (IMTI Inc., 2000; Yahya and Muhamad, 2004).

Assembly is an essential part of the total manufacturing process. Assembly costs are typically 25% to 50% of the total cost of manufacturing. The percentage of workers involved in assembly operations ranges from 20% to 60%. For an example of electronics industries, 40% to 60% of total wages are paid to assembly workers (Kalpakjian, 2001). Assembly often constitutes the last stage of a discrete manufacturing process. The accumulated processing value of the product is therefore high compared to other manufacturing processes at previous stages (Bellgran and Johansson, 1995).

An assembly system is a portion of a manufacturing system, which carries out the assembly processes. Assembly systems can be classified in terms of different criteria. Based on system reconfigurability, assembly systems are classified into dedicated, reconfigurable, and flexible (Bukchin et al., 1997; Koren et al., 1999). According to Mehrabi et al. (2000), a dedicated manufacturing system is designed for productions of a specific part, which uses transfer line technology with fixed tooling and automation. A flexible manufacturing system is designed for productions of a part family, which consists of fixed hardware and fixed, but programmable, software to handle changes in work orders, production schedules, part-programmes, and tooling for several types of parts in the family. A reconfigurable manufacturing system is designed at the outset for rapid change in structure; as well as in hardware and software components, in order to quickly adjust product capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements.

RAS is a portion of the entire manufacturing system; it is an RMS for the assembly processes.

It should be noted that the terminology ‘reconfigurable’ has many alternatives such as ‘flexible’, ‘modular’, ‘agile’, ‘recomposable’, ‘recomponentable’, ‘retransformable’ (Tsaryev, 2005; Bi et al., 2007); although these terminologies have slightly different meanings, their creators have had the same motivation for them to deal with changes and uncertainties of the system. In this survey, these terminologies are used alternatively, with due respect to the original sources.

3 Drivers of RAS

It is important to clarify the drivers and needs in developing an RAS so that one can justify whether or not an RAS is appropriately to be developed.

Current manufacturing systems endure a great pressure to deal with the changes and uncertainties in aspects of product functions, variations, product volume, delivery time and quality. It is unambiguous to the academia and industry that an RAS paradigm is becoming more and more promising due to its capability to deal with changes and uncertainties. The rationales of developing reconfigurable systems have been identified by many researchers (Koren et al., 1999; Yusuf et al., 1999; Michelini et al., 2001; Edmondson and Redford, 2002; Weber, 2004). However, these rationales have to be justified economically when an RAS is actually considered. Few practical systems are available to demonstrate the potentials of the RAS. Moreover, due to unreliable
The performances of available RAS, companies have to use manual systems or man-machine hybrid systems to deal with the turbulent manufacturing environment (Edmondson and Redford, 2002).

Note that the requirements of a manufacturing system have many aspects. It is crucial to distinguish some key drivers and needs from the remainders so that the research efforts on RAS can be more focused and some typical and efficient RAS can be developed. Based on a comparison of the drivers discussed by other researchers, in particular by Tichem (2000), two of them, i.e., (a) changes and uncertainties, and (b) needs for reducing cost and improving productivity via automation, are identified as the most critical ones, and they are explained below.

### 3.1 Changes and uncertainties

A manufacturing system transfers raw materials into products. Its ultimate objective is to gain values such as profit, reputation, and market sharing. A manufacturing enterprise can survive only if this objective is achieved appropriately. Manufacturing environment has a great impact on the performance of a manufacturing system. Current manufacturing environment has brought many changes to manufacturing systems. These changes happen both in internal manufacturing system itself and external manufacturing environment (Wadhwa et al., 2005). A manufacturing system has the requirements of flexibility in many aspects (Feldmann and Slama, 2001; Koren et al., 1999; Sethi and Sethi, 1990; Kumar, 1995; Handfield and Pagell, 1995):

- **Product variants increase** – products become versatile and customised. Versatility implies that a product needs more components for additional functions and features. Customisation means that a product has options for individual tastes (Tseng and Du, 1998; Fralix, 2001). A manufacturing system is forced to produce more product variants to meet fragmented, sophisticated, and personalised needs.

- **Product volume becomes lower and fluctuated** – the volume of a specific product tends to be low since:
  a. the limited market niches are shared by global competitors
  b. the life cycle of a new product becomes shorter and the durability of the product becomes longer. Different-generation products exist on the market at the same time
  c. product customisation has fragmented the entire market demands into small portions.

- **Product lead-time becomes shorter** – product lead-time affects the performance of a manufacturing system in different ways (Smith and Reinertsen, 1997): (a) if a product is introduced early, it is an advantage over the competitors since their lag in matching or surpassing is larger; (b) early product introduction increases peak sales. The earlier a product is made, the better its prospect is for obtaining and retaining a large share of the market; and (c) a new product brings a higher profit margin.

- **Product price becomes more competitive** – the product price is a primary feature to most of the customers. On the one hand, the globalised market offers customers with more windows to purchase low-price products with the same quality and service. On the other hand, the price is heavily time-dependent, and the price margin can reach its limit very soon after the product is introduced into the market.
• Manufacturing system becomes more dynamic and turbulent – versatility of a product usually implies more components and advanced controls; it makes the planning and scheduling of assembly processes very complex. The changes and fluctuations of products cause dynamic changes of manufacturing hardware and software resources.

3.2 Needs of improving productivity and reducing cost

Generally speaking, assembly processes are the most complex and varying processes in a production line. Intensive labours are currently involved in executing assembly tasks. However, human operators raise many issues such as low productivities, increasing labour cost, and health and safety concerns. Assembly tasks have to be operated by machines (Bodine, 1998; Tichem, 2000) to:

• Reduce cost

Labour cost is a significant part of entire production cost. The production cost can be reduced when the assembly labour is replaced by machines. However, the pre-condition of the cost reduction is to obtain a cost-effective automated assembly solution. The cost of an automated solution consists of development and investment cost, operation cost and maintenance cost. The development and investment cost are higher in the case of automated assembly, and must therefore be balanced by, for instance, improved productivity. Traditional investment evaluation methods are often unsuitable for evaluating investments in assembly automation, where frequent changes occur to the system. Efforts have been made to justify the contributions of system flexibility and automations (Kumar, 1995).

• Achieve high and constant quality

On the one hand, operational errors are unavoidable in manual assembly. For example, parts are sometimes assembled in the wrong way or even not assembled at all. On the other hand, quality and productivity is inconsistent since they may change depending on operators’ experiences. An automated system can eliminate manual errors and achieve repeatable and constant quality once the system is successfully tested and calibrated.

• Meet technology challenges

New products become very versatile and complicated. As a result, some products become extremely huge and heavy, while some others become extremely tiny and precise. Operations on these components are often beyond human being’s capability. Machinery automation will be essential to assist or replace human operators to accomplish the assembly processes, in particular, when the products could be modularised and a certain type of components can be processed for different products in a large volume.

• Overcome the labour shortage

The issue of labour shortage has drawn lots of attention. Macnamara (2002) has predicted that Canada could lack as many as 1.5 million skilled workers by 2010. Recently in December 2005, Ontario province in Canada passed a new legislation
that eliminates mandatory retirement at the age of 65. In Japan, Milberg and Schmidt (1990) and Arai (1993) estimated that the country has an employee shortage of 30% in the year of 2000.

- Prevent workers from poor working conditions
  
  Government regulations on safety and environments become more and more strict. A Swedish law is being enforced, which puts the cost of rehabilitation of injuries caused by bad working conditions on the shoulders of the companies (Tichem, 2000). Some assembly processes, such as final painting operations, have a poor working condition for human operators. The protection facilities and technologies have already reached their limits to protect the operators, economically.

3.3 RAS as a solution

The role of an RAS will be justified in terms of its functions to meet the aforementioned drivers.

3.3.1 Changes and uncertainties

Changes can only be dealt with by changes. Two ways to bring changes in a manufacturing system are the concept of flexible system and modular system (Bi and Zhang, 2001; Correa, 2001). The flexible system concept is to use internal adjustable components in an integral system. These system components can change their behaviours to meet the requirements. Changes can be made by control parameters. One example of the system developed following the flexible system concept is an industrial robot. A robot has some actuated joints, whose positions, speeds, and accelerations can be changed to generate different motion profiles. The modular system concept is to use modular components under a modularised architecture. A modular system is capable of generating different system configurations. System configurations vary with addition or removal of modules, and the changes of the topology or permutation of the assemblies. The modular system concept implies that the system topology can be changed by removing or adding modules. As such, the space of tasks that may be fulfilled increases nearly indefinitely (Ulrich, 1995). Commercial modular fixtures are typical systems designed based on the modular concept.

The above-mentioned two concepts have been integrated in an RAS. On the one hand, an RAS consists of the modules such as industrial robots and flexible fixtures. These modules are flexible themselves to meet different requirements at the machine or tool level. On the other hand, an RAS is modular; the system modules can be added or removed based on the capacity requirement. The implementation of the two concepts in an RAS will enhance system capability to meet the changes and uncertainties.

3.3.2 Improving productivities and reducing cost

Automation is a right solution to improve productivity and reduce cost. Automation has three paradigms: dedicated hard automation, reconfigurable system, and flexible system.
Dedicated hard automation is based on inexpensive fixed automation and can product parts at high volume. Each assembly line is typically designed to produce a single product at high production rate achieved by the operation of several tools, simultaneously, in several stations. Its drawbacks, however, have been summarised (Bukchin et al., 1997) below:

- Low flexibility – assembly lines are characterised by low flexibility with respect to changes in demand. In addition, any changes in product design, affects the entire system, and a line re-balance is necessary. Workers in assembly line are generally narrowly trained, which creates difficulties in transferring them between stations.

- High balance loss – balance loss results from imperfect balance of the line caused by stochastic task times or different task times due to model variations in a mixed model assembly environment. The symptoms of the imperfect balance are blockage and starvations that impair performance.

- Poor quality – there is no direct link between a worker and a final product. No direct feedback is given and the worker cannot learn from his or her mistakes. It is not always possible to identify the worker who causes a defect, especially when others work on the incomplete product. All these issues lead to a poor quality.

- High work-in-process – assembly lines are characterised by long product flow time, which is an outcome of the sequential order of the assembly operations. Additional safety stocks are required due to low flexibility with respect to demand fluctuations.

- High costs of material handling – an assembly line consists of stationary workers with products passing between them. Such a configuration requires costly material handling systems, especially when a single synchronous system is used for assembling the entire product.

A flexible system consists of several machines along with part and tool handling devices such as robots. It is so arranged that it can handle all parts in a product family, for which it has been designed and developed. The components are usually expensive general-purpose Computer Numerically Controlled (CNC) machines and other programmable automation equipment. Because of the single-tool operation of the CNC machines, the system throughput is low. The combination of high equipment cost and low throughput makes the cost per part relatively high. High cost is one of the major reasons for the low level of acceptance or satisfaction with flexible systems (Koren et al., 1999). The survey by Mehrabi et al. (2000) concluded that a flexible system seemed to be the only alternative to manufacture the parts for a part family; however, some of the manufacturers did not need the flexibility and extra functionality that came with the flexible systems when they were purchased.

A reconfigurable system is something in between – dedicated hard automation and flexible system. The system is designed for a part family with enough flexibility to handle any member of that part family, but not general flexibility where you can produce just about anything that can fit on the machine (Mellor, 2002). The system and its components have adjustable structure that enables system scalability in response to market demands and system adaptability to new products.
3.4 RAS in practice

It is evident in Section 2.3 that an RAS is the right solution to meet the above-mentioned challenges. However, the precondition is that the methodologies and technologies for the design and development of such an RAS are mature enough, so that a cost-effective RAS can be developed to meet the demand of changes and automations.

The choice of system paradigms depends on multiple factors, e.g., cost, complexity, schedule, safety, labour rate, and labour agreements. Sometimes, an RAS is chosen to assemble a repeatable product or to get human operators out of the process for health or safety reasons. However, due to the limits of technologies and the complexity of assembly processes, manual assembly still dominates the low-volume or mixed-technology products, where the assembly processes are highly variable or not consistently predictable or controllable, or where proper assembly relies on individual experience and proficiency. Assembly of simple precision products such as electronics normally involves a high level of automation, while electromechanical assembly is largely manual (IMTI Inc., 2000).

Figure 1 summarises application scenarios of different assembly systems. The application domains can be segmented in terms of the demand of changes and automations. The assembly processes with complicated changes have to be accomplished by a manual assembly since current manufacturing technologies are not intelligent enough to deal with complicated processes and human being is the most flexible resources ever known. An RAS could be the best solution when the products have considerable changes and automations can be implemented economically. With the development of new technologies, RAS will gradually replace manual assembly systems for complicated assembly processes. Flexible assembly systems still stay alive where flexibility for system capacity is not so critical. Dedicated automated systems keep occupying certain markets for high-volume parts or modules, since products can usually be modularised and the same type of modules can be fabricated in mass production for different products.

Figure 1 System paradigms versus changes and automation
4 Enabling technologies to achieve reconfigurability

It is shown that the goal of an RAS is to meet the demand of changes and automations. In order to reach this goal, an RAS can integrate flexible components into a modular architecture to maximise its reconfigurability. In this section, relevant enabling technologies are reviewed.

4.1 Design for assembly

The first task of RAS design is to determine the system requirements, e.g., the required assembly processes and predictable and unpredictable changes. The challenges of this task will be underestimated if assembly processes are isolated from other processes, in particular, product design and manufacturing.

Rampersad (1995) has indicated that the design cost of a product amounts to only approximately 5% of the manufacturing cost on average, but the product design influences approximately 70% of total production cost. By examining the design activities in the life cycle of a product, system adaptability for changes can be met by two approaches:

1. to modularise products to make them as similar as possible, in order that the components of different products can be manufactured or assembled in the same process

2. to employ reconfigurable systems, which are capable of accommodating various process variations, in order that the products with different processes can be handled in the same system (Bi et al., 2004; Bi and Lang, 2005).

However, the two approaches are mutually influential to each other. In other words, the design of an RAS can take a great advantage of a good product design. This is the reason why Design for Assembly (DFA) is treated as an enabling technology for RAS.

The assembly model is presented in Figure 2, which illustrates the interactions between a set of assembly variables. The variables are subdivided into product, assembly process, and assembly system.

- Product – design for manufacturing/assembly, a short development time, a more frequent development of new products.
- Assembly process – improved controllability, shorter cycle times and minimal stocks.
- Assembly system – the use of universal, modular, and reliable system components, high system flexibility, and the integration of product systems in the entire production (Rampersad, 1995; 1996).

The objective of DFA is to optimise a product design with consideration of its production system including supplies, material-handling systems, manufacturing and assembly processes, labour force, distribution systems and customers (Manzini et al., 2004). The DFA process is based on a large set of supporting and optimising rules and techniques, and attempts to rationalise the assembly activities, especially for products in small batches and a great number of varieties. Fujimoto et al. (2003) have reviewed the methodologies for assembly process design to handle variety and presented a new approach to strategically managing manufacturing complexities due to product varieties.
In Figure 3, an example has been given to illustrate how product design eliminates assembly processes. Becker et al. (2005) have further predicted that a lot of products of today and especially of tomorrow could be produced by the new rapid manufacturing processes today and at a competitive cost.

**Figure 3** An example of reducing assembly via design

*The new optimized design of the part (it is no longer an assembly...)*

Utilizing the advantages:
- Reduced number of parts
- Less assembly effort
- Advanced functionality

---

**Source:** Becker et al. (2005)
Since the cost of an RAS is a primary factor, Tichem (2000) has suggested to reduce the cost of an RAS by:

- reducing the number of assembly processes
- reducing the number of parts to be assembled and redesign of parts and connection for the ease of assembly
- optimising the layout of the assembly workstations
- reducing manual involvements.

4.2 System modularisation

System modularisation brings significant benefits to companies, including flexibility for product changes, scalability for capacity changes, lead-time reduction, simplicity due to decoupled tasks, and easiness of product upgrade, maintenance, repair, and disposal (Gunnar, 1998; Blackenfelt and Stake, 1998; Martin and Ishii, 2002).

A German company has applied the modular component-based approach for the implementation of one full-size assembly machine. Its commissioning engineers have expressed that about 80% of the controls and equipment for assembly are standard, and tremendous effort can be saved if the design, development and implementation for such control elements can be encapsulated and reused. It is estimated that 70% of the engineering teams’ effort is involved in re-implementing the control and related electrical systems each time a new machine is implemented on a new project (Harrison et al., 2005).

To modularise a system, modules are established by reviewing the similarities among system components, and modules are kept as much independent from others as possible. Under a modular architecture, a finite set of system modules can meet the infinite changes of the environment (Bi and Zhang, 2001). Take the RAS in Figure 4 as an example. The system has interchangeable hardware and software modules, such as a tabletop, a basic energy supply, the mounted handling devices, the internal conveyor system, and a safety device. These modules are connected by the flow of materials and information (Heisel and Meitzner, 2003; Feldmann and Slama, 2001).

Another example is the RAS in Figure 5 developed by Chen (2001). The system consists of standard and interoperable components including actuator modules, rigid link connectors and tools that can be assembled into robots with arbitrary geometry and degrees of freedom. The system is capable of being configured rapidly to perform a specific manufacturing task.

Sandin et al. (2002) have proposed a modular assembly platform. The objective is to contain all of the possible modules used for assembling products; the platform enables a process-oriented product design since the available technological solutions are known a priori to the state of the product design.

Sugi et al. (2001) proposed a holonic robot system that aims at assembling activities of real manufacturing devices. This system assembles products by negotiations between production management agents and device agents. Furthermore, their paper proposed Plug & Produce, a system function that enables easy addition/removal of devices.

Bourn (2001) has argued that the modularisation of the design process is more advantageous than that of hardware components itself. Few assembly operations are the same. It implies that the assembly machines usually differ depending on the assembly
operations. Many designs are different in terms of appearance, functions, and styles or preferences. However, not all differences are necessary. An efficient approach is to collect together a selection of standard parts and assemble them together rather than build a totally new machine. Modular assembly is a process rather than an engineering technique.

**Figure 4** An RAS architecture

![An RAS architecture](source: Feldmann and Slama (2001))

**Figure 5** Modular reconfigurable assembly system at NUT

![Modular reconfigurable assembly system at NUT](source: Chen (2001))
4.3 Flexible assembly machines

Assembly machines include all machines or devices used in assembling a product including various types of assembly activities: assembling, fixturing, material-handling, calibrating, and inspecting. A flexible assembly machine is capable of adapting assembly changes by manipulating its adjustable components or processes. Hundreds of literatures have been found in improving the system flexibility.

4.3.1 Rapid manufacturing as a new assembly processes

Rapid manufacturing is occasionally used to create a whole product with assembly. Laurentis and Mavroidis (2004) applied rapid prototyping in fabricating a non-assembly multi-articulated robotic hand with inserts. The development of robotic systems that have all necessary components inserted, with no assembly required, and ready to function when the manufacturing process is complete is quite attractive. In Figure 6, a prototype of a universal joint is fabricated via stereolithography (SL).

Figure 6  A joint made directly from rapid manufacturing


4.3.2 Robots for reconfigurable assembly

Industrial robots are widely used for assembly automation. Robots can be reprogrammed to accomplish different assembly tasks. Today, most RAS are developed using industrial robots (Giusti et al., 1994; Arai et al., 2002; Heilala and Voho, 2001; Jorg et al., 2000; Sugi et al., 2001). System scale can be adjusted by the number of robots in the system. For example, the RAS at Tri-Way in Canada has five machine cells, each of which includes two or three workstations devoted to a particular task (Mellor, 2002; Degaspari, 2002).

An example has been illustrated for reconfigurable riveting processes in Figure 7. It consists of a comau H4, an S2 robot, and a Tricept robot. The system is capable of inserting a solid rivet in a cycle time of seven seconds. A re-configurable assembly end-effector is used to eliminate the need to change grippers during assembly. This robot tooling was capable of handling all the stringers and frames needed to assemble the fuselage panels for a product family.

As shown in Figure 8, a flexible welding system for truck cabs at DaimlerChrysler has been developed and applied for ten years. The system produces four models in multiple variants with the accuracies of 0.5 mm. The advanced vision systems have been integrated to deal with the changes in the welding processes.
System reconfigurability can be further improved if a robotic system itself has been modularised. In fact, modular robot design is one of the main research threads in the robotics community (Bi et al., 2004); for example, The RAS developed by Chen (2001) proposed an RAS concept using various modular robots.

4.3.3 Fixtureless assembly processes

The most flexible assembly tooling is no tooling, that is, fixtureless assembly (Walczyk et al., 2000). To align parts together, fixtureless assembly relies on carefully tolerated alignment holes that are CNC machined into the parts at fastener locations. Parts are temporarily fastened at these alignment holes for their proper alignment together into the assembly and then permanently fastened at all rivet and bolt locations. Even though fixtureless assembly requires individual parts to be fixtured to the CNC workbed and then accurately CNC machined, this should require no more time than the CNC machining or manual layout of parts associated with conventional assembly methods.
Fixtureless assembly refers to the performance of assembly tasks using robots without fixtures. The elimination of fixtures is expected to reduce the cost and lead-time associated with retooling greatly. Bandyopadhyaya et al. (1993) designed a fixture-free machining centre for the machining of block-like component.

### 4.3.4 Material-handling system

A material handling system is functioned to deliver parts or components to the station where they are assembled. A few of reconfigurable material handling systems are under development.

Fukuda and Takagawa (2000) have designed a system for a large number of product variants. It consists of autonomous robotic modules, which transfer a palette carrying machined parts. Figure 9 shows the structure of a system module. It allows the part move in different directions. Two modules can be connected easily. Ho and Ranky (1997) have developed a reconfigurable conveyor system which allows to change the product volume in real-time. Automation Tooling System (ATS) in Canada has developed a programmable conveyor, which allows the conveyors to turn pallets from one section to another (Mellor, 2002).

**Figure 9** Module and pallet of a Flexible Transfer System (FTS)

![Module and Pallet](source: Fukuda and Takagawa (2000))

### 4.3.5 Flexible fixturing

Flexible fixturing systems can be classified into two categories: modular fixtures and dedicated flexible fixtures. A modular fixture system consists of many elements such as base plate, locators, clamps and connections. By selecting and assembling different elements, a customised fixture can be designed for a specific product. Many modular fixture tools are commercially available. For a modular fixturing system, the development of CAD tools is crucial. The design tool should be capable of generating optimal fixture configuration efficiently. The reconfiguration in building modular elements into a fixture configuration is also an assembly process itself. This reconfigurable process can be automated. Some prototype systems have been developed to use industrial robots as reconfigurable tools.
Dedicated flexible fixtures are usually designed for a specific application domain. Intensive efforts have been made to develop different flexible fixtures, including flexible grippers, PKM-based fixtures, phase-change fixtures, reconfigurable dies, and conformable clamp using shape memory alloy.

4.3.6 Auxiliary machines for reconfiguration

System ramp-up, calibration, and inspection should be treated as regular tasks in an RAS. Sophisticated devices for these tasks are needed to support frequent reconfiguration. A few papers can be found towards this goal.

In a reconfiguration process, calibration of assembly robots is highly important. This is because they need to measure the characteristics of related agents to set up good collaboration among physical agents. Arai et al. (2002) proposed an automatic calibrating system. The calibrations are accomplished by industrial robots. Mehrabi and Kannatey-Asibu (2001) have presented a multi-sensor monitoring system to increase system diagnosibility.

After a reconfigurable process, it is likely that there will be many quality problems to be addressed as a result of the reconfiguration process. For example, with each module that is rearranged in the system, there are new opportunities for misalignments and subsequent dimensional errors. These quality problems cause system down time and slow down the process of system ramping-up to full production after reconfiguration. Hence, the rapid elimination of such quality errors is essential to the ramp-up and operation of reconfigurable systems, and all high volume manufacturing systems in general. As shown in Figure 10, Barhak et al. (2005) developed an inspection machine capable of examining parts efficiently.

4.4 System configuration design

An RAS has a large number of system configurations. Configuration design determines optimal system configuration under given system architecture for a specific task. Configuration design is involved at the phase of system application. It is repeatable within a life cycle of the system application.

A challenge to the formulation is to identify and quantify design requirements. Many criteria (e.g., productivity, quality, and cost) and responsiveness issues (e.g., convertibility and scalability) should be taken into considerations. The Analytic Hierarchy Process (AHP) is often applied to trade off the design criteria (Maier-Speredelozzi and Hu, 2002; Webbink and Hu, 2005; Abdi and Labib, 2003). AHP is also applied to group products to identify and allocate corresponding assembly facilities. Manzini et al. (2004) developed a conceptual framework for the simultaneous design and control of flexible, agile, reconfigurable and robust assembly system in conjunction with the analysis and optimisation of product, process, system structure, material-handling devices and plant layout. Yigit and Allahverd (2003) formulated the RAS configuration design as an integer nonlinear programming problem to find a trade-off between the quality loss due to modularity and the cost of reconfiguration for a given set of customer requirements. To identify the reconfigurable need, an interface between market and manufacturing resources called reconfiguration link is presented by Abdi and Labib (2004).
Different mathematical tools can be applied in the optimisation process after the RAS design problem is formulated. Ho (2005) used genetic algorithms to solve the design problems of flexible assembly line. Sawik (2000) applied heuristic algorithm for the loading and assembly plan selection problem in a flexible assembly line. Tang et al. (2004) implemented a search engine for the reconfiguration plan and reconfigured system that best satisfies the new performance goals. This search engine is developed using an AI-based framework, which is designed to assist manufacturing engineers in making reconfiguration planning decisions. Compared with other design issues, the layout of assembly equipment lags behind. In this area, Michelini et al. (2001) and Kamrani (2003) have developed a template-based approach for layout design.

Simulation-based optimisation is advantageous when high degree of uncertainties and changes are involved. A virtual assembly environment provides not only an intuitive and interactive interface for virtual product design, but also an efficient method to analyse or verify assembly performance of these products. Virtual assembly systems have been explored by some researchers (Liu and Yao, 2004; Moore et al., 2003; Park, 2005; Yuan and Ferrira, 2003). For internet-enable assembly line modelling, simulation is essential for creating hardware and software independent system designs that can be implemented on a global-basis in different countries, based on constraints such as cost and quality.
Sunil and Pande (2004) developed an internet based assembly planner called webROBOT for intelligent task level programming of assembly robots. To support the simulation of RAS, Ji et al. (2002) established a library of standard mechanical fastening parts, so that a great deal of work can be eliminated during the product modelling stage.

4.5 System control

An RAS has two classes of variables for changes: reconfigurable variables and process variables. Reconfigurable variables are determined during configuration design while process variables are manipulated when the system is running (Bi et al., 2007). Due to system reconfigurability, a new configuration has to be calibrated and verified before it is applied. The control problem during the ramp-up period is also raised so that the configurations can be shifted smoothly. Note that the system should also be able to identify reconfigurable factors, such as the failure of joints and the change of a task, so that the system is reconfigured at the right time. Once the system is running, the RAS control is similar to that of a distributed manufacturing system.

Sugi et al. (2003), Tang and Wong (2005), and Wang et al. (2005a) have used agent-based control architecture. System components are autonomous manufacturing devices. They are dealt with by agents who communicate with each other to accomplish production tasks. Lohse et al. (2005) applied a similar concept called ontology for the control of an RAS. They used ontology to define the assembly system requirements in terms of product and assembly process descriptions and the capabilities of assembly requirement modules in terms of the equipment functions, behaviour and structure.

Qiu et al. (2004) applied non-cooperative game theory for facilitating the decision process during reconfiguration decision-making at the machine controller level. It is argued that the application of the non-cooperative game theory is the absence of a fully-integrated information system and the gaining popularity of distributed computing. A machine reconfiguration decision is made by machine controllers on the shop floor where heterarchical control architecture is typically used. Zhang et al. (2005) and Seeluangsawat and Bohez (2004) studied the optimisation of scheduling and sequencing for RAS.

Assembly systems are discrete event dynamic systems. Petri net is one of powerful tools for modelling, simulation and control of such systems. Knowledge-based timed coloured object-oriented Petri net is presented as a modelling method for an RAS. The configuration of an RAS will allow flexibility not only in assembling a variety of products, but also in changing the system itself. Combining knowledge and object-oriented methods into timed Petri net, allow the characteristic of an RAS to be fully expressed (Yu et al., 2003; Kuo et al., 1999).

4.6 Human being in assembly

Human being has great flexibility and agility to deal with changes and uncertainties. Assembly labours can increase system reconfigurability and flexibility greatly. The development of RAS does not imply to eliminate human being from an assembly system completely. Instead, the system should be designed to be friendly to human operators, so that they can efficiently accomplish the tasks that otherwise can not be automated cost-effectively.
For today’s environment, an optimal assembly system is usually a semi-automatic system, which includes fully-automated machines and manual workstations with automated material handling. The design requirements of these systems have been discussed by Heilala and Voho (2001).

Conventional assembly systems have the difficulty of real line balancing. Any variance at any link in a theoretically balanced production chain will result in disruptions in production and even stop of the entire production line. Bukchin et al. (1997) developed a new design methodology for team-based assembly systems. Team-oriented assembly systems support the objectives of modern assembly systems, which creating a more satisfactory working environment. Each team is defined as semi-autonomous with well-defined responsibilities. Wang et al. (2005b) proposed walking-worker assembly lines, where each worker builds a product completely from start to end. The goal is to sustain the flexibility of the workbench system in terms of production capacity.

To assist operators, Vauxhall has installed more than 300 error-proofing stations that facilitate the correction selection of a part from the numerous variants that are often identical-looking (Kochan, 2003). The core of the human interface production system consists of manual and automatic workstations equipped with automated material-handling and intelligent control features (Heilala and Voho, 1997).

5 Difficulties in developing RAS

Many assembly systems have been proposed and implemented; however, only a limited number of them have been successful (Lee, 1997). It has been shown that the implementations of RAS have encountered some bottlenecks. Rampersad (1993; 1995) has summarised some of the technical bottlenecks, as well as their corresponding tendencies.

Detailed discussions on the bottlenecks of RAS have been reported in the literature (Tichem, 2000; IMTI Inc., 2000; Rampersad, 1993; 1995; Manzini et al., 2004). Some typical issues involved in the development of an RAS include:

- Separation from product design – design of an RAS is separated from that of a product, and the RAS is designed after the product is finalised. It leaves less room to optimise the RAS.
- Pre-mature technologies – assembly automation is expected to eliminate human operators. However, technologies to develop an RAS are not mature enough to quarantine system reliability and fully automation. Many problems have to be solved by the developers manually.
- No modelling and simulation tools – few modelling and simulation tools are available to support the design and optimisation of an RAS.
- Attitudes towards RAS – the complexity related to assembly automation and the lack of knowledge on these technologies results in a negative attitude towards the application of assembly automation. Even more importantly, the strategic importance of assembly and assembly automation is not recognised by many companies.
- Low production volumes – productivities of automation is often proportional to the product volumes; however, most of the RAS are designed not good enough to bring profits for low production volumes.
Definition of uncertainties and changes – the design of an RAS is based on well-defined system requirements corresponding to uncertainties and changes, so that right mechanisms can be selected to meet these requirements. However, some uncertainties and changes cannot be represented reasonably in a mathematical form, and others cannot be predicted accurately.

RAS as a wrong solution – not all problems related to changes, uncertainties, and human operators can be solved by an RAS. Holmstedt et al. (1997) identified some reasons that cause the difficulties of applying an RAS:
   a the team has insufficient technical competence
   b the team has insufficient focus on the project
   c the company does not adapt to manufacturing strategy
   d insufficient training of operators
   e no system care.

6 Future research directions

An RAS is one of the solutions that have been put forward to meet market demands on increased product diversity and smaller lot-size, improved product quality, reduced delivery time, and shortening product life cycle. RAS is recognised as a high priority technology. However, significant research is needed before its widespread use in industry (Mehrabi et al., 2000).

The development of RAS involves product design, assembly processes, sensor technology, ergonomics, material-handling, fixtures, and so on. Due to the nature of assembly systems, the research on RAS is expected to be diversified. By examining the available technologies and current bottlenecks in system developments and by summarising some conclusions from the literatures (Tichem, 2000; IMTI Inc., 2000), research directions that have significant impacts on the evolution of RAS are introduced below.

6.1 Design for assembly

Most of the design requirements of an RAS are determined at the stage of product design. A product design without the consideration of the constraints of assemblies could reduce the design candidates of an RAS greatly. A good RAS design will become difficult to be achieved, since the system has to meet extra requirements for compensating a poor product design. DFA provides improved design and analysis tools for assembly processes and equipment to drastically reduce the number of the parts, enabling greater use of unitary design and simplifying assembly (IMTI Inc., 2000). Although intensive works have been done on DFA, few of them have been taken into consideration of the requirements of the changes and system reconfigurations.

6.2 New assembly processes and machines

One of the hurdles to adopt an RAS is the versatility and flexibility of human being in comparison to automated machines in traditional assembly processes. The situation would be changed dramatically if a new process can replace the traditional processes
Current status of reconfigurable assembly systems

cost-effectively, or the operation of this new process is beyond the capability of human being. A good example is mini- and micro-assembly. Research in mini- and micro-assembly has just begun and has focused on the long-term future possibilities rather than the direct industrial requirements (Onori, 2001). Since the manual assembly of micro-sized parts is difficult, there is a need to develop techniques, tools and methods that can facilitate the efficient and rapid assembly of micro-sized parts (Cecil et al., 2005). Therefore, research studies on fixtureless assembly, new joining technologies, reconfigurable fixtures, and rapid manufacturing in assembly are also very promising in certain manufacturing domains.

6.3 Modularisation and standardisation

Modularisation allows a system to generate a large number of system configurations with the minimised set of the modular components. It should be noted that efforts towards modularisation are not limited to an individual company or the design of individual RAS. It is rare that a single vendor provides the best-in-class solution for all applications. An RAS typically combines subsystems from several vendors (Faulkner et al., 1999). Standardisation allows any vendor or user to design add-on products and assure common communication protocols for all assembly equipments and operations (Grondahl and Onori, 2000).

6.4 Automated robotic programming and intelligent control

A large amount of programming tasks will be involved in reconfiguring automated machines. Time will be a critical factor for a successful reconfiguration. Traditional manual teaching approaches will become obsolete, and robotic programmes should be CAD and sensor-based (Ahrens and Pageau, 2002). They have to be automatically generated when new task requirements are defined. Robotic programmes will not be a standalone task any more. A programming procedure will be open so that the devices can respond online changes appropriately. System reconfiguration changes the number, types and distributions of system components, and it brings more uncertainties at the phase of system ramp-up and running. Sensors and closed-loop controls are required to enable flexible, adaptive assembly operations and implement intelligent, reliable, and robust control.

6.5 Integrated modelling and simulation

Simulation is profitably used at the design stage for a beforehand evaluation of alternative facilities; it becomes permanent consultation aid, during exploitation, to select or to restore the best choices (Michelini et al., 2001). Modelling and simulation will enable ‘intelligent assembly’ where every operation is the result of ‘best choice’ decision processes. Further efforts are needed towards:

• quantifying and evaluating reconfigurable requirements
• analysis and synthesis of system solutions
• modelling and simulation of reconfigurable processes
• modelling of system design and optimisation for high reconfigurable assembly systems
• modelling and simulation of human’s roles in RAS.

References


