Evolution, principles and recent trends in reconfigurable manufacturing system

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Abstract. In today’s era, the companies need to respond rapidly to the new product introduction, mix and demand changes to stay competitive. It has been very well accepted that traditional manufacturing systems are not suitable to offer an edge in such a competitive market. Reconfigurable manufacturing systems (RMS) appear to be a most promising mechanism for enabling the manufacturing sector to be more competitive and sustain itself in the tough global scenario. This manuscript attempts to survey the characteristics of RMS and evolution of research to improve the practical applicability of RMS. Further the recent trends of reconfigurable manufacturing system in the present context have also been discussed along with the future research directions.

Keywords. Reconfigurable manufacturing system, Scheduling, Modelling, RMT

1. Introduction

Manufacturing, as the wealth creation sector of an economy, plays a key role in the overall growth of countries. Now a day, modern industry is facing fierce competition and ever-changing demand coupled with the customized products. Today’s market is customer centric where customer desires customized product with low cost, high quality and that too with least lead times. These changes are both a threat and an opportunity for the manufacturing enterprises. To capitalize these opportunities, industries need to adopt a manufacturing system which can produce the products with ever-changing functionalities and capacities [1-3]. By advances in automation, information technology, soft computing, the implementation of these manufacturing strategies has been made possible. Traditional manufacturing system such as Dedicated Manufacturing Systems, Job shops, Flow lines, Cellular Manufacturing Systems as well as Flexible Manufacturing System all have their own limitations and difficulties to run as per the expectations of business portfolio [4-5].

According to a recent NRC study [6], the Reconfigurable Manufacturing System (RMS) has been identified as a top priority for future manufacturing model research and is considered one of the six major challenges faced by manufacturing enterprises in the year 2020. At the University of Michigan, Engineering Research Centre for RMS (ERC/RMS) has already been established. RMS is a modular architecture design-based manufacturing system that selects two basic process modules, hardware and software, for further rapid, economical, and reliable reconfiguration or replacement [7-10].
Reconfiguration will permit including, deleting or replacing the modular machine structure and software to modify the production capacity in response to ever changing market conditions. These systems provide customized functionality and capacity to cater the necessities of a part family which can additionally be enhanced, redesigned, and reconfigured, instead of replaced. The major source of reconfigurability is the Reconfigurable Machine Tool (RMT) which lies at the core of RMS, and is having changeable structure, customized capacity and functionalities [11-13].

2. Evolution of a better manufacturing system

The logical arrangement of resources (equipment along with computer systems and workers) is referred to as the Manufacturing System in the factory. The historical roots of development of manufacturing systems can be traced back to the end of 18th century when Ford developed a ‘DMS’ to fulfill the demand of cars from the increasingly affluent population of America. Ever since, several different manufacturing system paradigms have been proposed [14]. Figure 1 shows the mapping of several types of manufacturing systems.

Traditional manufacturing approaches are not fulfilling the requirements of unpredictable market changes in terms of big fluctuations in the demand of product as well as the change in desired functionality. In recent times, RMS has been acknowledged as the most promising solution to these challenges. Table 1 presents the comprehensive comparison on various important aspects of RMS with the conventional manufacturing systems [7, 15].

Table 1- Comparison of DMS, FMS and RMS

| S.N. | Aspect               | Traditional Mfg. System (DMS) | Conventional Mfg. system (FMS) | Advanced Mfg. (RMS) |
|------|----------------------|-------------------------------|--------------------------------|---------------------|
| 1    | Manufacturing policy | Pushing                       | Pulling                        | Customizing         |
| 2    | Process technology   | Fixed                         | Adaptable                      | Responsive          |
| 3    | System Structure     | Fixed                         | Adjustable                     | Adjustable          |
| 4    | Scalability          | Nil                           | Yes                            | Yes                 |
| 5    | Machine structure    | Fixed                         | Fixed                          | Adjustable          |
| 6    | Flexibility          | Nil                           | General                        | Customized          |
| 7    | System focus         | Part                          | Machine                        | Part Family         |
From the comparison, it is evident that the RMS can achieve several key objectives including reduction in manufacturing system lead time, flexible capacity and functionality, redesign of existing systems, fast manufacturing system modification, rapid implementation of newer technologies.

3. Reconfigurable manufacturing system
Reconfigurable manufacturing is a novel manufacturing system paradigm that offers cost effectiveness along with the quick responsiveness to market and item changes [14]. The Next Generation Manufacturing (NGM) venture [16] has done a thorough investigation of the goals of future production systems, according to which the responsiveness of manufacturing firm is assumed to play a pivotal role in the accomplishment of the objectives such as economy, mass customization and responsiveness. The Reconfigurable manufacturing systems are known for managing the scalabilities on the system level [17]. Figure 2 shows the various characteristics portrayed by an RMS along with other capabilities.

3.1 Characteristics of RMS
Reconfigurable manufacturing system frameworks must be very well structured at the beginning with modular equipment and software architecture modules that can be configured rapidly and dependably to accomplish reconfiguration. The survey of literature reflects the following six key characteristics i.e. Customization, Scalability, Convertibility, Modularity, Integrability, and Diagnosability to be incorporated at the system level and machine level in an ideal RMS [2, 9].

| Characteristics | Description |
|-----------------|-------------|
| Modularity      | The term modularity describes the use of common system components to produce variation of a product. |
| Integrability   | Integrability means the ability of systems/modules/components to integrate precisely and rapidly. |
| Convertibility  | Convertibility permit fast changeover between existing parts and fast system adaptability for future parts. |
| Diagnosability  | After reconfiguration diagnosability detecting rapidly the reasons of bad quality products. |
| Customization   | Customization aims at reducing the cost of reconfiguration. |
| Scalability     | To change manufacturing volume by reordering a present production system and/or changing the manufacturing capacity of reconfigurable places. |

3.2 Principles of reconfigurable manufacturing system
- The reconfigurable manufacturing system is proposed for reconfigurable production resources for fulfilling the need of the customer which are changing over time.
- Reconfigurable manufacturing system’s key features like modularity, scalability, customization, integrability, convertibility and diagnosability should be exercised on the system level and also on the machine level for the enhancing the speed of responsiveness for reduced ramp-up time.
- Part family formation is a very crucial step in designing an RMS with enough flexibility for increasing the production and minimizing the lead times.
The productivity can be maintained despite the volatile environment by need based reconfigurations and by reallocating tasks of the machines.

The RMS can respond effectively and reliably to the unpredictable events — both intrinsic events (machine failure) and external (market changes).

4. Reconfigurable Machine Tool (RMT)
Reconfigurable Machine Tool (RMT) lies at the core of the RMS, which gives RMS its key feature of achieving reconfigurations at a very low ramp up time. Reconfigurable equipment and open-design controllers are the key empowering advances for RMS. The major components of an RMS include reconfigurable machine tools, CNC machines, reconfigurable inspection machines and material transport system [12-13] to connect the machines to form an integrated system. The main component in the RMS is the RMT, which plays pivotal role in achieving the “exact functionality and exact capacity exactly when needed” by its modular structure and open architecture controllers.

An RMT has a reconfigurable structure composed by assembling one or a combination of few Basic Modules and a combination of some Auxiliary Modules in a well-defined fashion to perform an operation or an operation cluster.

A basic module is structural in nature like bed, base, column, table, knee etc. with all necessary provisions to put-in on it various auxiliary modules. An RMT may have features designed into it to reposition or reorient its modules without changing its topological characteristics [18]. This reconfigurability feature is helpful in accommodating quick changes in part design or to accommodate various sizes or variants.

An RMT is configured to suit the functionality and capacity by selecting the required auxiliary and basic modules from the module catalogue, which consists of kinematic as well as structural modules. The RMTs are developed as modular machines comprising of various modules and the required controllers[19, 20]. An RMT developed at the ERC/RMS, University of Michigan is named as arch-type RMT as shown in Figure 3. RMTs are supposed to offer customised flexibility in various machining operations like drilling and milling processes on inclined surfaces. Figure 4 shows the reconfigurable power spindle mechanism for transmitting power between the spindle head modules.

5. Design and Modelling of Reconfigurable Manufacturing System
The main difference between RMS system design and other manufacturing system design is that the system configuration of RMS evolves over time. The capacity and functionality of DMS and FMS are designed for the expected future needs in advance. But covering all the future requirements of capacity and functionality leads to over capacity and/or over functionality. With the fast pace of developments in the enabling technologies, the issues related to the RMS system design need to be addressed for the effective implementation of this new technology on the shop floor level. Among the key research issues in RMS design include the Reconfigurability and configuration design, Part family formation and Scheduling in reconfigurable manufacturing environment.
5.1 RMS reconfigurability and configuration design

Urbani et al. proposed the reconfigurability as capacity of a framework to adjust to expected or sudden changes through the adjustments in the framework or framework segment's structure ensuring the productive utilization of functionalities [21]. Goyal et al. presented an approach to measure the responsiveness of RMTs through reconfiguration measurement during the configuration change of reconfigurable machines [22]. Youssef and ElMaraghy addressed optimal configuration selection in reconfigurable manufacturing system through a two phase algorithm. First stage of the algorithm enlists the k near optimal solutions through applying the real coded genetic algorithm and tabu search considering the cost as the sole objective and then during second phase the reconfiguration smoothness has been considered to select the best configuration for each demand period through applying the tabu search and integer coded genetic algorithm [23]. Youssef and ElMaraghy developed the reconfiguration policy along with the reconfiguration metrics on the market level, system level and machine level. In the present work a novel algorithm based on dynamic programming is proposed to find the maximum number of stages to be retained during the reconfiguration process between two reconfigurable flow lines [24]. Garbie proposed a methodology for the reconfiguration planning of RMS based on the analysis of the reconfiguration issues including reconfiguration level, reconfiguration methodology, and performance measurement [25]. Goyal et al. have proposed the methodology to design the reconfigurable flow lines combining the metaheuristic like NSGA and MOPSO with the multicriteria decision making techniques [26-28]. Hees et al. demonstrated the potential of RMS by developing a production planning approach to design a viable configuration that uses hybrid integer linear programming (MILP) to achieve capacity scalability and functional changes during planning [29]. Asghar et al. presented an approach to co-evolution of process planning and machine configurations during production changeovers considering optimal machine capabilities applying multi-objective genetic algorithms [30].

5.2 Part family formation issues in RMS

According to Koren et al. the reconfigurable manufacturing system is considered as a system designed to satisfy the requirements of a part family by reconfiguring its software and hardware components rapidly in response to the volatility of the market. In RMS each part requires a particular system configuration depending upon the operations to be performed and the precedence constraints [3]. Xiao et al. have considered the RMS as a manufacturing system configured to produce a part family, which shares some similarities [31]. Abdi and Labib concluded that grouping of products into part families in RMS has a positive impact on the launching of new product [32]. Eguia et al. proposed a hybrid integer linear programming model to simultaneously solve the problem of cell formation and partial scheduling in reconfigurable cellular manufacturing systems, taking into account the underutilization costs from one family to the next and not using RMT resources [33]. Considering the operation sequence similarity in developing the part family has been very crucial, thus various methodologies have been proposed for part family formation in RMS considering operation sequence similarity [34-35]. In nutshell, an efficient methodology for part family formation, considering the constraints and core features of RMS, is very important in harnessing the benefits from reconfigurable manufacturing system.

5.3 Scheduling in RMS

The design of reconfigurable manufacturing systems involves configuration design of reconfigurable flow lines which is capable of producing multiple parts contained in a part family simultaneously, the optimal design of system configuration and proper implementing the scheduling algorithm for shop floor control are very crucial for the cost-effective handling of a reconfigurable flow line. Azab and Naderi studied the problem of production operation scheduling in RMS, and a mathematical model is proposed [36]. Valente and Carpanzano investigated reconfiguration problem of a real-time automation system and presented a dynamic algorithm to schedule automation tasks over time in robotic cell operating in a pilot assembly line [37]. Yu et al. proposed priority rule-based approach to
solve the integrated input sequencing and scheduling problems considering three decisions i.e. part sequencing under various dispatching rules, operations and the machine selection [38]. Parsad and Jayaswal proposed scheduling of the products in considering reconfiguration effort, profit over cost and due date [39]. Dou et al. proposed a multi-objective mixed integer programming approach of configuration generation and scheduling for the optimization of an RMS. The total cost containing the sum of capital cost and reconfiguration cost along with the minimization of tardiness in the system are considered as two conflicting objectives to design the RMS Schedule [40].

6. Conclusion

RMS is an upcoming manufacturing paradigm which emphasizes on enhancing the system responsiveness to fluctuating demands and introduction of new products through rapid and cost-effective configuration changes. In this article characteristic, principles and enabling technologies of RMS have been discussed. A comparative assessment of RMS with various other conventional manufacturing systems such as DMS, CMS and FMS has also been carried out. A brief overview of the key reconfiguration enabler i.e. Reconfigurable Machine Tool has also been presented. It has been observed from the reviewed literature that the researchers have shown tremendous interest in the modelling of reconfiguration efforts, part family formation, scheduling and control policies of RMS in the last decade.

Future research ought to be directed on the simulation of the RMS under various exceptions and uncertainties. The verification of RMS modelling approaches through the simulation strategies may prove an added attraction to the modern industries for implementation of RMS. Further, the shop floor control algorithms also need to be developed in the presence of RMTs in a manufacturing environment.

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