Review and Framework for Task Allocation for a Robot in Digital Manufacturing: a Simulation Approach

Yarram Srinivas[1], Dr. Kolla Srivinivas[2], Dr. Sridhar CNV [3], Peddi Sreenivasa Rao[4]

Abstract- Digital manufacturing is the use of an integrated, computer-based system comprised of simulation, three-dimensional (3D) visualization, analytics and various collaboration tools to create product and manufacturing process definitions simultaneously. Digital manufacturing allows feedback from actual production operations to be incorporated into the product design process, and allowing companies to take advantage of shop floor realities during the planning stage. Also, simulation of production processes can be performed, with the intent to re-use existing knowledge and optimize processes before products are manufactured. The simulation capabilities of digital manufacturing help to reduce commissioning costs by validating robotics and automation programs virtually. Thus the objective of this paper is to design a framework to implement a task allocation model for a robot in Digital manufacturing, and an empirical investigation on the performance of the system.

1. INTRODUCTION

The speed-up of a manufacturing process consists of two aspects: one is the speed-up of product development to reduce development lead time and the other is that of production to reduce production lead time. Nevertheless, Digital Manufacturing (D-Mfg) needs to be exploited in order to close the gap between the product definition and the actual manufacturing production activities within the enterprise. The industries that benefit the most from utilizing these methodologies are those with capital-intensive manufacturing and those with very complex products but very low production, even single-unit production. Defining D-Mfg "It is the use of an integrated, computer-based system comprised of simulation, three-dimensional (3D) visualization, analytics and various collaboration tools to create product and manufacturing process". D-Mfg evolved from manufacturing initiatives such as design for manufacturability (DFM), computer-integrated manufacturing (CIM), flexible manufacturing, lean manufacturing, e-manufacturing and others that highlight the need for more collaborative product and process design.

Yarram Srinivas, Research Scholar, Department of Mechanical Engineering, Acharya Nagarjuna University, Guntur, AP, 9703039999, yarram.cnu@gmail.com
Dr. Kolla Srivinivas, Professor, Department of Mechanical Engineering, RVR & JC College of Engineering, Guntur, AP, 9866281628, drks@rvrjcce.ac.in
Dr. Sridhar CNV, Professor, Department of Mechanical Engineering, Narasimhareddy Engineering College, Secunderabad, Telangana, drcnv1970rjpt@gmail.com
Peddi Sreenivasa Rao, Department of Mechanical Engineering, Guntur Engineering College, Guntur, AP, 9581173379, sreenivasa.peddi@gmail.com

Digital manufacturing takes a slow, manual, resource-intensive process and brings it into the 21st century. At present, many leading automobile manufacturing companies in the world are persistently promoting the application of D-Mfg technologies, which is resulting in encouraging returns on investment. Also, up to 60 per cent of the value of automobiles and fighter aircraft are sourced from suppliers, the digital manufacturing environment must be accessible across the supply chain to support today's business-to business method. However, the application of digital manufacturing is rather hard mainly for: (1) it is hard to manage data due to the huge amount of information. According to GM statistics, the data related to the product production process is 100 - 1000 times of the data flow for design. (2) Integrated digital design has to be taken as the base. (3) It involves many parties (such as design, planning, production, logistics and other departments of such manufacturers), it raises high and comprehensive requirements for manufacturers, and they need to reconstruct the process. So, it is very important to choose an excellent DM solution and take reasonable implementation strategy. Simulation is a problem-solving methodology for analyzing complex systems and Schriber (1987) defines simulation as "the modeling of a process that mimics the response of the actual system to events that take place over time". With complex manufacturing environment and production processes in Automotive production systems of Digital Manufacturing (D-Mfg), Task allocation for a robot and robotic simulation has become nearly mandatory to manage and implement the complexity of the work cells and assembly lines; and subsequently improve cycle

time and manufacturing productivity. Thus the objective of this paper is to design a framework to implement a task allocation model for a robot in D-Mfg arena, and an empirical investigation on the performance of the system.

1.1. Task Allocation

A central problem in multi-robot systems in D-Mfg is to solve the multi-robot task allocation problem. Over the past few years, multi-robot systems have been successfully employed to solve problems in several robotic domains. Multi-robot teamwork is a complex problem consisting of task division, task allocation, coordination, and communication. The most significant concept in MRS is cooperation. It is only through cooperative task performance that the superiority of robot groups can be demonstrated. This type of group behavior is also called asynchronous cooperation, as it requires no synchronization in time or space simultaneously. Regardless of the type of cooperation, the goal of the team must be transformed in to tasks to be allocated to the individual robots. The explicit cooperation is the case where robots in a team work synchronously with respect to time or space in order to achieve a goal. The various issues and methodologies related to task allocating have been in the research and application domain since long. However the best performance is obtained through homogenous task allocation. The static task allocation usually works well if formation is treated like a coordination problem Arkin et.al (1998) and Gerkey et.al (2000) proposed a method of team formation where the task allocation takes place during system design. The common approach in all these work is that all of the robots have a predefined and similar task. Task assignment is done for a limited time horizon, using a goal directed search. Sahu et.al (2007) made an attempt to solve the generalized "Assignment problem" through genetic algorithm and simulated annealing. The generalized assignment problem is basically the "N men- N jobs" problem where a single job can be assigned to only one person in such a way that the overall cost of assignment is minimized.

2. RELATED EARLIER RESEARCH TASK ALLOCATION IN MULTI ROBOT SYSTEM

Most classic optimal assignment algorithms that reach the global optimal are centralized. A review of the literature shows that a large set of decentralized multi-robot task allocation methods employ auctioning mechanisms; representative examples include: the distributed market-based paradigm Michael N et.al(2008), the auction-based MURDOCH model proposed by Gerkey et.al (2002), and cooperative auctions Nanjanath M et.al(2006). These techniques have

been extended to a wide range of multi-robot scenarios, applied to NP-hard problems like routing, planning, scheduling, or used to address problems where partial knowledge is assumed or local information employed by Lagoudakis M. G(2005). For these reasons, most often the global optimum will not be obtained (see review in Dias M D et.al (2006); often the resulting allocation quality remains unknown. Other methods for task assignment operate by partitioning the robots and/or tasks into subgroups and repeating the process recursively Liu L et.al (2011) as well as behavior-based or role based strategies Parker L E et.al (1998).

In addition, Dahl et al., (2009) presented an algorithm for task allocation in groups of homogeneous robots, which are based on vacancy chains, a resource distribution strategy common in human and animal societies. This algorithm uses local task selection, reinforcement learning for estimation of task utility, and reward structures based on the vacancy chain framework. Hanna (2005) proposed an approach which allows robots to take into account the uncertainty of task execution. Shiroma et.al, (2009) proposed a framework called CoMutaR, which is designed to both tackle task allocation and coordination problems in MRS. This framework enables the single robot to perform multiple tasks concurrently by periodically checking and updating task-related information during implementation. Eventually, the task allocation for heterogeneous and homogeneous systems may be different. In heterogeneous systems, task allocation may be determined by individual capabilities. Parker (1994) introduced the concept of task coverage, which measures the ability of a given team member to achieve a given task. This parameter can be used as an index to organize a robot team to perform a mission from the available pool of heterogeneous robots. Task coverage reaches the maximum value in homogeneous teams, and decreases as teams become more heterogeneous. But in homogeneous systems, agents may need to differentiate into different roles at design time or dynamically at run time Yan et al. (2011). Finally it is believed that there is promising avenues in task allocation environments where robots work in are usually dynamic. Due to the unpredictability and uncertainty of the environment, the revenue and cost functions for task allocation will be difficult to define. For the purpose of maximizing system performance, robust definitions and metrics for various scenarios should be developed.

2.2 Simulation in Manufacturing

Simulation is a very helpful and valuable IT instrument in manufacturing. Hosseinpour, et.al (2009) said that simulation can be used in an industrial

environment, allowing the system's behavior to be tested. It provides decision-makers and engineers with a tool for low-cost, secure and fast analysis to investigate the complexity of their systems and the way that changes in the system's configuration or in the operational policies may affect the performance of the system or organization. Simulation is used both during a manufacturing system's design and operation. Web-based technologies are changing the manufacturing processes that are currently in place and in a new era of collaboration between the factory floor and enterprise supply chains. The internet has already transformed the business world, with the web-centric customer mandating the flow of business given by Sridhar CNV et.al (2010). Usually it is referred to as offline and online simulation, respectively Mirdamadi, et.al(2007). Computer simulation offers the great advantage of studying and statistically analyzing what-if scenarios, thus reducing the overall time and cost required for taking decisions. On the other hand, the system's operation involves short-term decision-making and as such the simulation runtime is an important factor, Smith (2003).

Rao et al.(2008) present an approach of an online simulation system for real-time shop floor control in a manufacturing execution system (MES). The simulation system can collect data from a physical shop floor through the MES, and the MES can also execute the shop floor control strategy, which is resolved by the simulation system. There are several aspects that need to be addressed by the simulation community for the endorsement of a widespread use of modeling and simulation for decision support in current and future manufacturing systems.

According to Fowler (2004), New or improved simulation approaches to be used in manufacturing for operational/real-time decisions. Today, due to the increased amount of data and information collected and maintained by the current shop floor information systems, the application of such simulation models is feasible. In this context, the development of simulation/virtual and synchronized counterparts of the real factory should also be considered. At the same time, statistical models such as ANOVA have long been used for identifying critical process parameters in simulation experiments. Modern data mining techniques may also be used for detecting the most important parameters in the design process, as well as for focusing on specific areas of the solution space Huyet, (2006). Knowledge maps may also be constructed with the aid of process experts, Rentzsch et al. (2005). Using these tools, simulation models may be simplified and be focused on

the study of the most important aspects pertaining to specific manufacturing processes.

2.3 Digital Manufacturing and Simulation

The benefits of digital manufacturing have received much attention, resulting in numerous research studies and applications over the last decade and from recent simulation-based developments on the digital manufacturing concept with applications in a variety of industrial domains are identified. In 2000, Chryssolouris et.al proposed an approach that involved the generation of scheduling alternatives, their transformation through a rule based mechanism into nesting solutions. Based on a pilot case from the ship repair industry, Mourtzis, in 2005, proposed a concept that supported the management of a ship repair yard by integrating, in a modular, open, platform-independent and flexible system, a number of important business functions, including estimating, tendering, purchasing, contract preparation/monitoring and invoicing with the production planning, scheduling and control. In 2005, Sun et.al presented a framework for Critical Success Factor (CSF) assessment of ERP system implementations and proposed a structured approach to help an SME identify the key requirements and measurements that determine its achievement of ERP implementation through simulation shown in Fig.1.
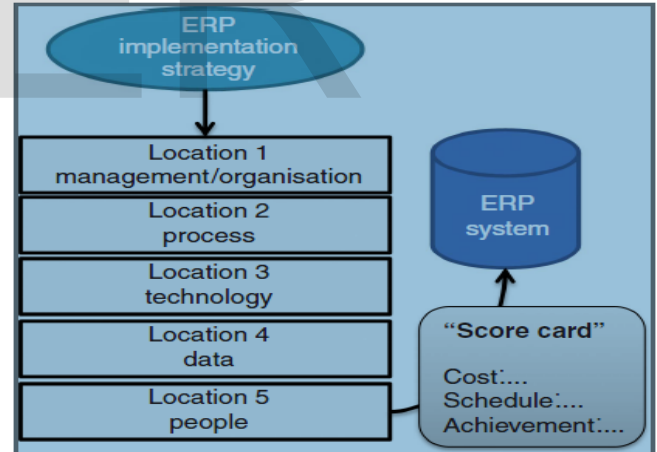

Fig.1 Simulation model -ERP integration for CSF assessment: Source: Sun et.al, 2005
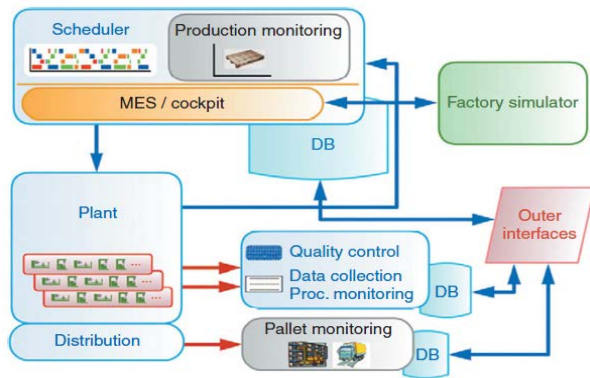
Fig.2 scheduling system with real-time feedback:
Source: Monostori et al. (2007)

A simulation-based hybrid backwards scheduling framework for manufacturing systems was proposed by Lalas et al.,(2006), referred to as HBS and mainly addressed as discrete manufacturing environments involves making long-term decisions, such as facility layout and system capacity configuration. A planning methodology and its application to the food industry were presented by Mourtzis (2006). This method included a four-level hierarchical model of the system's resources and their workload. Monostori et al., in 2007, proposed a scheduling system capable of real-time production control shown in Fig.2. This system received feedback from the daily production through the integration of information coming from the process, quality and production monitoring subsystems. The system was able to monitor a series of deviations and problems of the manufacturing system and to suggest possible alternatives for their handling.

Further to that, Michalos, et al. (2010), proposed a job rotation tool that, at the planning phase, could be able to determine and evaluate the possible alternatives for the next operator rotation by accounting for a set of user-defined criteria. This work was further extended by Michalos, et.al,(2011) by implementing the method in a web-based tool, able to generate job rotation schedules for human-based assembly systems and to test the tool on a truck assembly case. A web-based collaboration framework among manufacturing companies with reference to planning and coordinating their manufacturing activities was presented by Mourtzis (2011). A flexible agent-based system called RIDER (Real tIme DEcision-making in manufactuRing) was developed in Papakostas et al. (2012). The system encompassed both real-time and decentralized manufacturing decision-making capabilities. The overall schedule for the manufacturing procedures was generated by a backward scheduling algorithm, by obtaining real-time information through a special data

exchange mechanism, besides communicating with other manufacturing IT systems.

Research approaches such as those given earlier, in most cases, comprise standalone software components, which either act as an extension to the capabilities of commercial ERP platforms or may function in a complementary manner. Commercial ERP solutions that manage and integrate business processes across the function of an organization may cost millions of euros to purchase, several times more to implement and maintain, and may necessitate disruptive organizational changes as given by Soh, et.al (2000). The ERP solutions, whether in the form of software package or in customized on-demand solutions, will continue to play a major role in the realization of digital manufacturing. Digital manufacturing would allow for (a) the shortening of development time and cost; (b) the integration of knowledge coming from different manufacturing processes and departments; (c) the decentralized manufacturing of the increasing variety of parts and products in numerous production sites and (d) the focusing of manufacturing organizations on their core competences, working efficiently with other companies and suppliers, on the basis of effective IT-based cooperative engineering expressed by Chryssolouris, et.al (2008)

3   PROPOSED FRAMEWORK FOR TASK ALLOCATION

In particular, there is sufficient flexibility is assumed within the problem space to allow more simple variations to be implemented in the early stages of research, and to build and test more complex instances as the work progresses, for example beginning with equal numbers of identical tasks and identical robots, incrementally building up to the inclusion of online assignments, time-extended assignments, unequal numbers of tasks and robots, heterogeneous tasks and robots, multi-task robots, multi-robot tasks, and real-time, real-world implementations that require additional features requires for D-Mfg. In this paper, research begins with the problem of assigning a known number L of identical, to a known number N of homogenous robots in simulation. The assumptions made are:

3.1   Assumption made for Robot Task Allocation

The following assumptions are made for task allocation for robots in conjunction with D-Mfg:

- The robots have equal capabilities and travel at the same, fixed speed;
- The locations are equally accessible to all the robots,
- The level of risk is equal for all locations and constant throughout the operation;
- The number of locations L does not change at any time during the operation
- The number of robots N does not change at any time during the operation The number of robots available is always equal to the number of locations need task to be completed i.e., $N \equiv L$.
- Once assignment has taken place, treat all work is done.

3.2 Problem Formulation

We represent the probability of a robot to select task j after it has serviced task i as an *inter-task transition matrix M* given by:

$$M = \begin{bmatrix} \pi11 & \cdots & \pi1n \\ \pi21 & \ddots & \pi21 \\ \pi n1 & \cdots & \pi nn \end{bmatrix} \quad (1)$$

$$\text{Where } \pi ij = \frac{1/dij}{\sum_{j \neq i} 1/dij}, \quad (2)$$

Note that $\pi i j = 1$. Also, since a robot needs to service a task's demand at most once, $\pi i = 0$. Using this inter-task transition matrix, a robot has a higher likelihood of selecting available tasks that are closer than those that are further away. The problem facing robot ri is to select a task using the probabilities in the inter-task transition matrix. However, selecting the probabilities from M does not incorporate the dynamic nature of the system manifested through robots servicing and accomplishing tasks. Therefore, each robot ri maintains a local copy of M denoted by $M ri$ and updates it using its own task servicing information. To select tasks, each robot ri represents its probability of selecting a task at time t as a vector state matrix Vri, robot ri's initial vector state, Vri (0), is given by:

$$Vri(0) = (\hat{\pi}i1 \ \hat{\pi}i2 \ldots \hat{\pi}in) \quad (3)$$

Vri is updated using the equation:

$$Vri(t) = Vri(t-1) \times M ri(t) \quad (4)$$

Robot ri makes a decision about the next task to process by selecting a next task according to the highest probability of tasks in Vri (t). Since the robots select tasks in a distributed manner, more than one robot end up selecting the same task. In that case, the task is allocated to the robot with the higher probability of performing the task. If more than one robot has the same probability, the task is allocated to the robot with the highest

identifier. Since this research focuses on task allocation we do not deal with localization or path planning issues.

3.3 Future Work

Future work will aim to develop optimum criteria to test more complex scenarios, where extended assignments are required; there are heterogeneous tasks and robots, multi-task robots and multi-robot tasks. Real-world implementations that require additional features will also be carried in the context of D-Mfg. Integrating a robotics simulation study with a discrete-event simulation study benefits both in various ways.

4. CONCLUSIONS

Digital manufacturing solutions have already become an integral part of all engineering activities taking place in a typical manufacturing organization. Simulation is a core part of these solutions in the form of feature-rich 3D collaborative environments, allowing for the realistic validation of alternative solutions. In the future, it is expected that digital manufacturing tools and applications will be capable of generating and simulating more accurate and detailed alternative solutions for a multitude of product and process design activities. It is expected that future simulation-based digital manufacturing tools will make use of idle computing resources, allowing for the experimentation with much more detailed and complex simulation models, thus leading to a reduced number of design and development cycles. All these concepts are part of the ongoing research and are anticipated to virtually improve every aspect in the context D-Mfg.

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