A Literature Review of Robot Agility Methods, Use Cases, and Metrics for Manufacturing Assembly Applications

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Chapter 1

Introduction

In recent years, the evolutionary progress and paradigm shifts of manufacturing systems have been moving towards agile manufacturing systems. The agile manufacturing paradigm was formulated in response to the constantly changing environment and as a basis for returning to global competitiveness. Agile manufacturing can be defined as the capability of surviving and prospering in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services [Cunha 2007, Cho 1996, Gunasekaran 1999].

Having the ability to adapt quickly, an agile manufacturing system (AMS) can handle the variations in realistic production environments as well as the changing market needs. Agile manufacturing requires high responsiveness at all levels of a company, but is especially challenging on the shop floor level. One of the most important requirements for the implementation of an AMS is to enable its control system to respond and adapt to changes in production variables. These variables may be caused by expected events such as the introduction of new products, changes in the product design or high product customisation, as well as by unanticipated events such as machine failures during manufacturing, equipment drop-outs, rush orders, cancellation of orders or changes in the priority of orders etc. The control of an AMS is expected to be flexible, open, scalable and re-configurable so as to tackle the more complex and uncertain information flows. The current challenge is to develop collaborative and reconfigurable manufacturing control systems that support efficiently small batches, product diversity, high quality and low costs, by introducing innovative characteristics of adaptation, agility and modularization. Information and communication technologies, and artificial intelligence techniques, have been used for more than two decades addressing this challenge.

Today, the market tends increasingly towards mass customization, with customers clients individually selecting from various product options. Customers require high responsiveness and the ability to cope with a multitude of conditions. They increasingly need agile robotic assembly systems, able to cope with dynamic production conditions dictated by frequent changes, low volumes and many variants. A robotic assembly system is an industrial installation that receives parts and joins them in a coherent way to form a final product. It consists of a set of equipment items (manufacturing resources or modules) such as conveyors, pallets, simple robotic axes for translation and rotation as well as more sophisticated industrial robots, grippers, sensors of various types, etc.

The current state-of-the-art industrial robots are capable of sub-millimeter movement accuracy [Briot 2009]. However, they are often programmed by an operator using crude positional controls from a teach pendent. Reprogramming these robots when their task is altered requires that the robot cell be taken off-line for a human-led teaching period. For small batch processors or other customers who must frequently change their line configuration, this frequent down time may be unacceptable. The robotic systems of tomorrow need to perform their duties at least as well as human counterparts, be quickly re-tasked to other operations, and cope with a wide variety of unexpected environmental and operational changes. Improvements in these areas are believed to: generate industrial systems that are quickly changeable, follow a Plug&Play approach, avoid time- and work-intensive re-programming, and maintain productivity also under perturbations. Much attention has been given to the requirement for assembly systems to be easily reconfigurable or to seamlessly integrate new components.

In this paper, we present a literature review of agility methods, use cases, and metrics that are attempting to enhance the agility of robots in manufacturing environments. This is in support of the Agility Performance of Robotic System project, part of the Robotics for Smart Manufacturing Program at the National Institute of Standards and Technology (NIST). The goal of this project is to deliver robot agility performance metrics, information models, test methods and protocols, validated using a combined virtual and real testing environment, that will enable manufacturers to easily and rapidly reconfigure and re-task robot systems in assembly operations.

The paper is organized as follows:

- In Chapter 2, we describe some approaches to enhance agility in manufacturing robotic systems. These are categorized into hardware abstraction, process adaptability, and human cooperation.
- In Chapter 3, we describe some approaches in the literature that have attempted to create use cases to test robot agility in manufacturing applications. Few use cases were found, but that ones that were are presented in this section.
- In Chapter 4, we describe a set of metrics that can be applied to the measurement of flexibility in agile manufacturing systems. These can be broken down into machine flexibility, product flexibility, material handling system flexibility, operation flexibility, routing flexibility, and volume flexibility.
- In Chapter 5, we conclude the paper and describe efforts that are planned in the future to collect use cases and metrics from industry directly.

CHAPTER 2

APPROACHES TO ENHANCE MANUFACTURING AGILITY

2.1 Manufacturing Environments and Systems

Daghestani [Daghestani 1998] made an attempt to clarify the difference between manufacturing environments and manufacturing systems since a literature a review on his part showed inconsistency in the definition of these two terms. According to Daghestani [Daghestani 1998], manufacturing environments are product-dependent. Attributes defining manufacturing environments include [Kingsman 1993, Brannon 1993, Donaldson 1995]: 1) Product characteristics. Features and functions of the product, 2) Product variety. Different types of products the company should produce, 3) Lead time. Period of time until the product enters the market, and 4) Product life cycle (PLC). Length (or number of periods) and quantity a product is in demand over its life-cycle.

The different ways the company selects to deal with these attributes in order to control the environment is referred to as a manufacturing system (equipment used, production techniques, etc). Therefore, a company can be operating under many systems at the same time.

2.2 Agile Manufacturing Environments

The term agile manufacturing has been used by many in academia and industry as the solution to dealing with the ever-increasing turbulent and dynamic market going into the 21st century [Cho 1996]. Most literature encountered assert that agile manufacturing refers to a dynamic manufacturing setting which allows rapid reconfiguration and is highly adaptive to quick market changes through widespread use of information technology [Graves 1995, Xiaoyuan 1996]. Sharifi & Zhang [Sharifi 2001] viewed agility as comprising of two main factors: responding to changes in proper ways and due time, and exploiting changes and taking advantage of changes as opportunities. The authors identified high rate of new product introductions as well as quick introduction of new products as key properties of an agile manufacturing system.

Agile manufacturing environments differ from traditional manufacturing environments in the fact that product life cycles are becoming shorter while the quest for higher qualities are becoming more consequential, and products are becoming increasingly diversified and global. Such product characteristics are becoming increasingly more prevalent and are being documented by many studies. For example, different authors report at least one of the following product characteristics [Sanderson 1990, Cordero 1991, Hisrich 1991, Millson 1992]:

- Decreasing concept-to-market and, thus, the introduction time between new products.
- Decreasing length of PLCs.
- Increasing product variety.
- Decreasing volumes for identical products.

2.3 Agile Manufacturing Systems

Goldman *et al.* [Goldman 1994] defined an agile manufacturing system as a system that is capable of operating profitably in a competitive environment of continually and unpredictably changing customer opportunities. Tsourveloudis & Valavanis [Tsourveloudis 2002] regarded the main capabilities of an agile production system as the ease with which the system can change between products, and the ability to introduce new products without investments. According to Elkins *et al.* [Elkins 2004], agile manufacturing systems for engine and transmission machining applications will permit fast cost-effective responses to unpredictable and ever-changing product demand, and support rapid product launches for previously unplanned products tailored to meet changing customer desires. Quinn *et al.* [Quinn 1997] has adopted a definition of agile manufacturing that applies to light mechanical assembly of products made from components in part families: *Agile manufacturing is the ability to accomplish changeover between the manufacture of different assemblies*. Rapid changeover is defined as the ability to move from the assembly of one product to the assembly of a similar product with a minimum of change in tooling and software.

2.3.1 Robotic Assembly Systems

In recent years there has been considerable interest in assembly planning and robotic systems for assembly manufacturing. Hu *et al.* [Hu 2011] define assembly as the capstone process for product realization where component parts and subassemblies are integrated together to form the final products. At the more abstract Assembly Planning level, an assembly plan is a sequence of assembly tasks that start in a state where all parts are unconnected and terminates in a state representing the final assembled product. At this level each task is specified in terms of assembly parts or sub-assemblies, with no reference to production line resources or tools. At the Control Planning level each assembly task is broken down into steps, each one corresponding to an assembly robot operation. A control plan is a sequence of control tasks that start in a state where all parts are unconnected and all resources are available for assembly and terminates in a final state with the product fully assembled. Each task at this level is specified in terms of assembly parts (or sub-assemblies) and production system resources, and therefore, control plans require knowledge about system resources.

A robot, according to the Robot Institute of America, is *A reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed* *motions for the performance of a variety of tasks*. Therefore, because of their re-programmability and adaptability aspects, robots are suited to many requirements or applications associated with industrial tasks [Kumar 2012].

As such, many efforts study how to efficiently integrate robotic solutions in assembly systems. Below is a classification of robots used in manufacturing robotic assembly systems.

Industrial Robots

A literature review on manufacturing assembly systems mainly shows efforts describing industrial robots. The different types of industrial robots used in manufacturing assembly can be categorized as follows (based on manipulator geometry) [Clapper 2013]:

- Cartesian robots/Gantry robots [Majors 1997] are used for pick and place work, application of sealant, assembly operations, handling machine tools and arc welding. Cartesian robots/Gantry robots consist of an arm with three prismatic joints and whose axes are coincident with a Cartesian coordinator.
- Cylindrical robots [Geering 1986] are used for assembly operations, handling at machine tools, spot welding, and handling at diecasting machines. Cylindrical robots consist of axes that form a cylindrical coordinate system.
- SCARA robots [Yao 1999] are used for pick and place work, application of sealant, assembly operations and handling machine tools. SCARA robots consist of two parallel rotary joints to provide compliance in a plane.
- Articulated robots [Puiu 2009] are mainly used for assembly operations, diecasting, fettling machines, gas welding, arc welding and spray painting. Articulated robots consist of an arm that has at least three rotary joints.
- Parallel robots [Khalil 2011] are mainly used for pick and place work and assembly operations. Parallel robots consist of arms that have concurrent prismatic or rotary joints.

Mobile Robots

Besides industrial robots, mobile robots have been introduced in modern manufacturing systems [Lazinica 2005b, Lazinica 2005a, Angerer 2012, Delrobaei 2009]. Such robots should be autonomous, adaptable, and function smoothly in order to cope with unstructured and highly complex manufacturing systems. Mobile robots are used for: 1) Transport: Mobile robots are used as carriers for assembling products. This function is performed with the use of autonomous mobile robots with exchangeable pallets. 2) Assembly: Mobile robots with manipulator and part storage for different assembly parts. 3) Supply: Delivering of assembly parts to assembly stations. This function is usually performed by autonomous mobile robots that adapt to transport assembly parts in quantities. 4) Load: Positioning of assembly pallet on transport robot. 5) Unload: Removing the assembly pallet of the finished product from the transport robot.

2.4 Use Cases

Robots have long held a pre-eminent place in high-volume, high-capital industries such as auto manufacturing, but recent advances in robots' brawn and brains have seen their use expand into many new industries. This section will look at recent applications for small and large part assembly, advances in 3D vision, and trajectory optimization. The citations in this section come from published whitepapers and use cases from robotics manufacturers ABB, Fanuc, Kuka, and Yaskawa.

A common yet challenging task for industrial robots is the assembly of systems and subsystems from smaller components, often selected from bins or kits. Automotive applications are still a staple of industrial robotics, but apart from heavy-lifting assembly operations such as vehicle axles [ABB c] or engine cylinder heads [ABB d], smaller systems such as brake assemblies [Yas a] or lighting fixtures [Yas b] are also being assembled by robotic workers. Similarly, small electromechanical systems can now be assembled with high-speed, high-precision systems, including televisions [ABB b], meters [Fan a], or key fobs [Fan d].

In addition to traditional realms of employment, assembly robots are carving out new niches in emerging fields demanding precision and reliability while still seeking to scale production economically. For example, fuel cell assembly can be accelerated with specialized robots [Kuk b], leading to cost and reliability improvements. Robots have even made their way into sewing carbon fiber cloth for use in aircraft [Kuk a].

Finally, new technologies are transforming the way even traditional robot tasks are performed. For instance, performance of already installed an running platforms can be improved with online trajectory characterization and learning [Fan b], or by re-optimizing in simulation without shutting down production for manual teaching [Fan c]. Similarly, advances in 3D perception are enabling robots to deal with more challenging pick-and-place environments by performing object recognition on the pieces to be assembled [ABB a].

All of these advances are beginning to see field deployment, and are ready for wider adoption. In the next sections, we will look instead at capabilities that are under active development, but are likely to drive the next wave of advanced robotic applications.

2.5 Hardware Abstraction

A principal characteristic of a mature technology industry is the ability to design a system at a relatively high level, then implement the abstract design using standard (sometimes parameterized) tools. However, too many current robotic installations are built with ad-hoc, non-transferable code. In order to be able to design systems at a higher level, engineers need a unified way of describing robots, tasks, and objects in such a way that the hardware implementation details need not be hard-coded into the design details. The following sections highlight various methods for designing general systems to run on specific platforms.

2.5.1 Robot Ontologies

A robot ontology defines the framework within which a robotic system can characterize its world. Having a shared and comprehensive vocabulary with which to describe itself, its tasks, and its environment is a prerequisite for robots that seek to collaborate with one another, and for engineers who wish to create extensible behaviors at a more abstract level. Thus, it is important for such frameworks achieve broad adoption in order to be useful to the robots and their programmers.

A number of attempts at defining these robot world frameworks have been made over the years, varying in scope and application. A major effort currently underway is described in [Schlenoff 2012], an IEEE-sponsored effort which lays out goals of describing a core robot world language and several specific use cases. Another ongoing project is the RoboEarth framework, described in [Tenorth 2013a], which outlines the creation of a "Wikipedia for robotics", encompassing robot and object descriptions as well as skill level descriptions intended to be shared on robot-to-robot via the Internet.

Often, ontology definitions may specialize into defining robot taxonomies, as seen in [Schlenoff 2005b] and [Schlenoff 2005a], where explicitly delineating the classes into which an agent can fall is a major focus that enables determining utility for various tasks. Other variations highlight the ability to execute a specific skill or behavior, whether for manipulator robots, as in [Huckaby 2013], or for additive manufacturing, such as [Liu 2010b]. Of course, some knowledge representations seek to model both of these aspects, as well as defining classes for environmental objects, as in [Tenorth 2013b].

2.5.2 Cloud Robotics

Another enabling technology for escaping the bonds of single-purpose robot installations is the emerging field of cloud robotics, introduced by James Kuffner from Google and CMU [Guizzo 2011]. In these systems, robots gain increased capabilities from being connected either to the Internet, or to a large intranet. A primary purpose of this connectivity is access to the knowledge databases defined in the previous section, with particular examples including the RoboEarth/KnowRob projects in [Tenorth 2013b] and [Tenorth 2013a].

In addition, connection to a network allows for the deployment of robots with lower onboard computational capability, as intensive calculations can be directed to a dedicated server. This can drive lower development and deployment costs, as computationally heavy tasks such as object recognition [Kehoe 2013] or motion planning in a cluttered environment [Hunziker 2013] can be performed on well-equipped machines, perhaps sporting multiple GPUs or other computation tools. This also centralizes design and maintenance work, allowing high-level software changes to be decoupled from the specifics of each robot installation.

Finally, traditional roles for cloud computing can be leveraged in a a robotics context. For instance, cloud-based data backup [Hookings 2013a] or operational data collection and reporting [Hookings 2013b] are common IT paradigms currently being applied to industrial robots by several manufacturers. These techniques enable easier management of fleets of robots for even smaller businesses.

2.5.3 ROS-Industrial

Finally, no discussion of hardware-agnostic robot development would be complete without highlighting the ongoing ROS-Industrial project [Edwards 2012]. ROS-I is a project that strives to adapt the Robot Operating System (ROS) popular for academic research to the industrial community. This allows for faster integration of research breakthroughs, as well as access to a broad spectrum of computer vision, motion planning, and robot control tools. For example, MoveIt!, the ROS-based motion planning framework, currently supports nearly 50 robot platforms [MoveIt User Community 2014].

2.6 Process Adaptability

An important concern for small-medium enterprises considering a robotic installation is their traditionally smaller batch size and greater process variability. In addition to the programming developments mentioned in Section 2.5, several research trends over the past decade have investigated methods for increasing this process-level flexibility. When these concerns are well managed, powerful new applications can be realized for challenging domains [Spencer 1996].

2.6.1 Managing Variability

Industrial robots tend to be known for their extreme precision, but this precision is wasted if the object to be operated on has far more variability than the operating robot. Fortunately, this variation can be modelled and handled by closing the loop on manufacturing processes.

Much of the research on managing variation focuses on modelling and propagating position errors at a given step, ex. [Mantripragada 1999], [Zhou 2003], [Liu 2010a]. The assembly process is usually modelled using a state-space formulation, with the process error being described by a (probabilistic) state transition model. Those familiar with Kalman filtering will recognise the roles of process and measurement noise models and their incorporation into the true state estimate. The final error is often represented by a differential motion vector.

However, simply modelling error propagation is insufficient to solve the problem. Knowing the expected error bounds enables closing the loop at a further step in the process. In [Balakirsky 2014], sensor feedback is combined with a system ontology to identify and correct errors. In general, machine vision provides loop closure for many robotic systems, and advances in 3D sensing hardware and algorithms are driving powerful 3D-reconstruction based adaptive systems.

2.6.2 Mass Customization

One of the major trends in agile manufacturing is the flexibility to handle small batches of a product, allowing for production of a greater variety of items, as well as better responsiveness to new product lines. In the extreme case this becomes known as mass customization, where each item is tailor-made for a customer's order [Piller 2004], [Fogliatto 2012].

The ROSETTA Project [Patel 2012] is one project seeking to improve robot flexibility in this sector. Major focuses of the project include boosting ease of programming (Section 2.5) and simplifying robot integration into human systems (Section 2.7.1).

2.7 Human Interaction

Most SME robotic installations cannot dedicate a massive warehouse to their mechanized workers, nor dominate their current workspace with extensive safety cages and barriers. Additionally, robots are not yet dexterous enough for certain tasks, so human involvement may be required at various stages in the pipeline. Thus, robots need to play nicely with their biological coworkers [Dong 2011].

2.7.1 Workspace Collaboration and Human Safety

At the forefront of considerations when integrating robots into a workflow is the issue of worker safety. Traditionally, industrial robots have been massive, rigid machines able to achieve high precision in the presence of disturbance forces, with little regard to whether the disturbance came from a process variation or from a coworker who had strayed too close. Two major focuses of work in this area are in risk analysis and mechanical compliance .

At one end of the safety spectrum is the concept of provably safe, in which a robot cannot cause harm to even an intentional human actor [Mitsch 2013] Other sources, such as [Kulić 2006]. prefer to compute a measure of the risk in the current system, termed a danger index. Similarly, [Lacevic 2013] incorporates a danger field, which defines operating regions where the robot must be afforded the most respect.

Manufacturers are also aware of the growing desire for closer human-robot interaction. A newer generation of robotic arms incorporates human safety into the mechanical design [Universal Robots 2013], enabling better worker collaboration [Will 2013] without requiring proofs of algorithm safety. Finally, work is underway to certify different classes of worker safety in the presence of industrial robots [Matthias 2011], [Fryman 2012].

Once issues of safety have been handled, discussion can proceed on how best to integrate human and mechanical workers. [Krüger 2009] and [Tan 2009] give case studies examining how to efficiently integrate the two sides of the manufacturing system to boost productivity while maintaining safety.

2.7.2 Learning from Demonstration

One of the more exciting developments in the field of human-robot collaboration is the possibility of teaching the robot with no programming from the operator. Such learning research has been underway for some time (see [Argall 2009] for a review), but the technology is finally maturing to the point of entering commercial products. Perhaps the most famous instance of this is the Baxter robot [Fitzgerald 2013], although other manufacturers are beginning to incorporate similar learning systems, such as the Kinetiq learning system being developed by Robotiq and Yaskawa [Kin 2013], [Robert 2013].

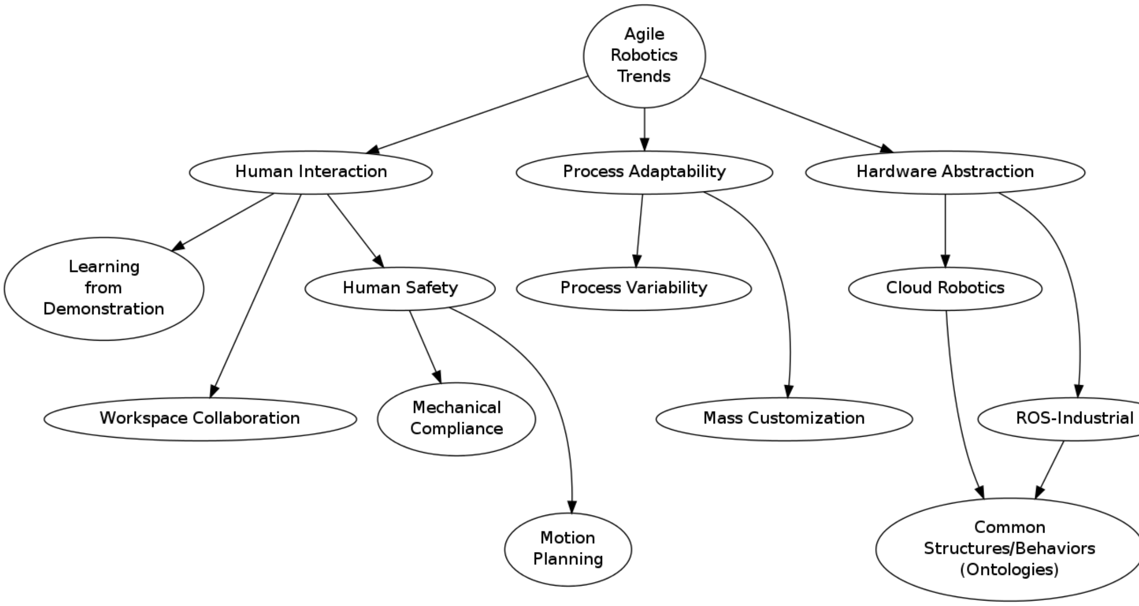

Figure 2.1: Topic Hierarchy with Associated References.

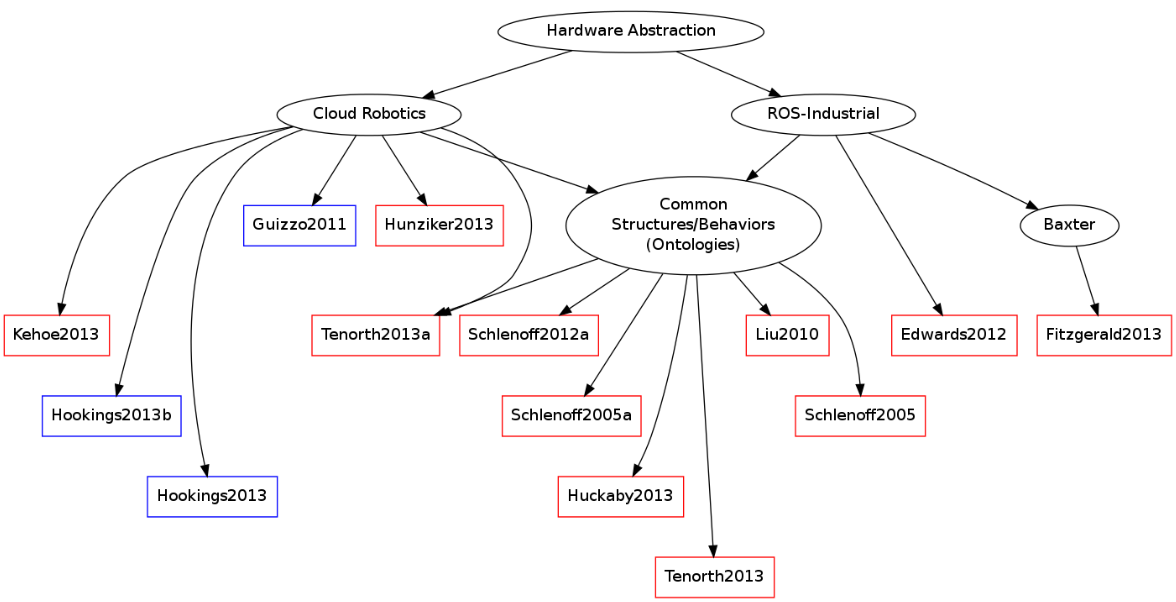

Figure 2.2: Topic Hierarchy with Associated References. (continued)

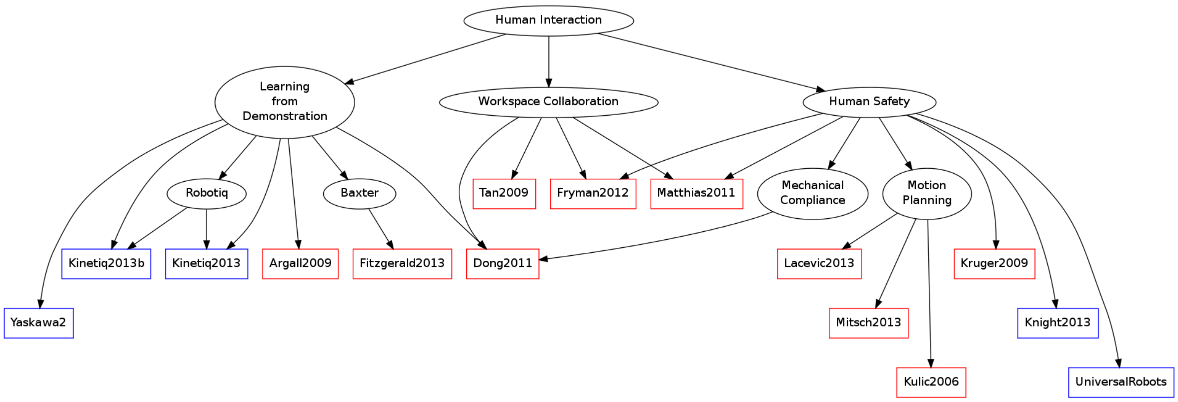

Figure 2.3: Topic Hierarchy with Associated References. (continued)

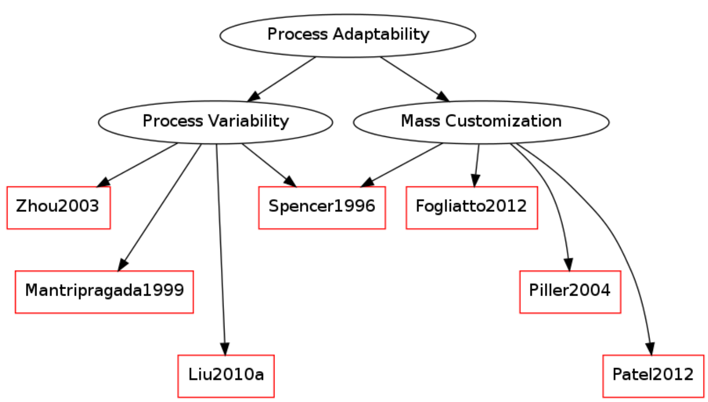

Figure 2.4: Topic Hierarchy with Associated References. (continued)

CHAPTER 3

ROBOT AGILITY USE CASES

As part of the Robotic Systems for Smart Manufacturing Program and specifically the Agility Performance of Robotic Systems Project, there is a need for use cases that are representative of the industry's needs. Thus there is a combined effort to determine these use cases through two different methods. One is by getting input from industry representatives, while the other is through a literature review, the results of which are described below.

3.1 Non-Assembly Use Cases

In this Chapter, we present use cases from non-assembly manufacturing operations.

3.1.1 Parts Sorting

Song *et al.* [Song 2000] used, as an example, a parts sorting task where a set of randomly placed bolts on a conveyor needed to be sorted into separate bins, as shown in Figure 3.1. The robotic workcell in this example consisted of a single robotic manipulator arm, a disc conveyor, and a number of sensors to determine the placement and orientations of the randomly placed bolts. The task requires the manipulator and conveyor's motion be synchronized and use the sensors to be able to pick and place the bolts.

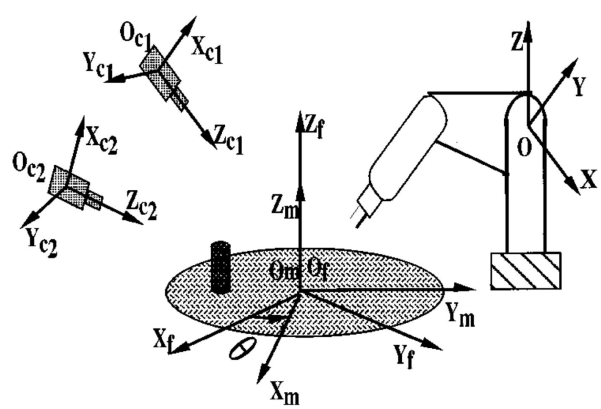

Figure 3.1: Parts Sorting Task with Robotic Manipulator and Disc Conveyor [Song 2000].

3.1.2 Milling

Figure 3.2: Robotic Milling Operation Use Case [Chen 2001].

Chen [Chen 2001] used, as a case study for the reconfigurable workcell, a light machining task involving multiple robots as shown in Figure 3.2. In this case study, the first robot starts by picking up an object and transfers it to the second robot which performs a complete milling operation on a dome-shaped top of a cylindrical workpiece. The first robot then takes the object back and places the milled object into a storage rack. This particular case study could be useful for future focus areas and/or as a use case more focused on collaborative robotics given the multi-robot nature of this example.

3.2 Assembly Use Cases

The following examples fall into the category of assembly-type manufacturing use cases.

3.2.1 Snap and Insert

Quinn *et al.* [Quinn 1997] used, as an example assembly task for testing their system, a small assembly with four plastic components as shown in Figure 3.3. Part A acts as a base to which parts B, C, and D are attached. Part B gets snapped on to the base, after which the subassembly is inverted. Parts C and D are then inserted into the bottom, with the help of a special guide. The paper describes this task as a typical light assembly task, perfect for their workcell. The paper describes three cases for division of labor for two robots. Case 1 consists of the two robots performing the complete assembly task in parallel, while Case 2 involves each robot performing part of the assembly task (Robot 1 attaches Part B to Part A, then hands off the sub assembly to Robot 2 to perform the insertion of Parts C and D). Case 3 would consist of Robot 1 feeding the parts to Robot 2, which would perform the assembly.

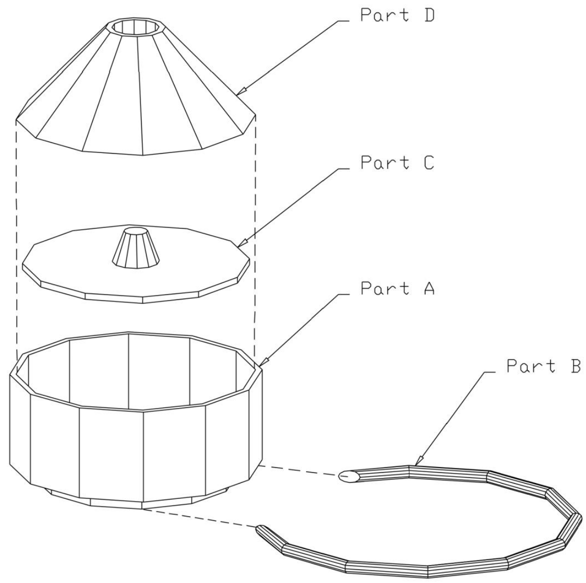

Figure 3.3: Small Snap and Insert Assembly Containing Four Plastic Parts [Quinn 1997].

3.2.2 Adhesive Tape Roll Dispenser

Frei and Di Marzo Serugendo [Frei 2008] used, as an example, an assembly system consisting of body parts (Parts 1 and 3), a tape roll (Part 2) and a screw (Part 4) for locking the body parts together, as shown in Figure 3.4. The case study used consisted of three robots to perform the assembly process. Robot 1 would assemble the Body Parts 1 and 3, while Robot 2 assembles Part 2 and Robot 3 assembles Part 4.

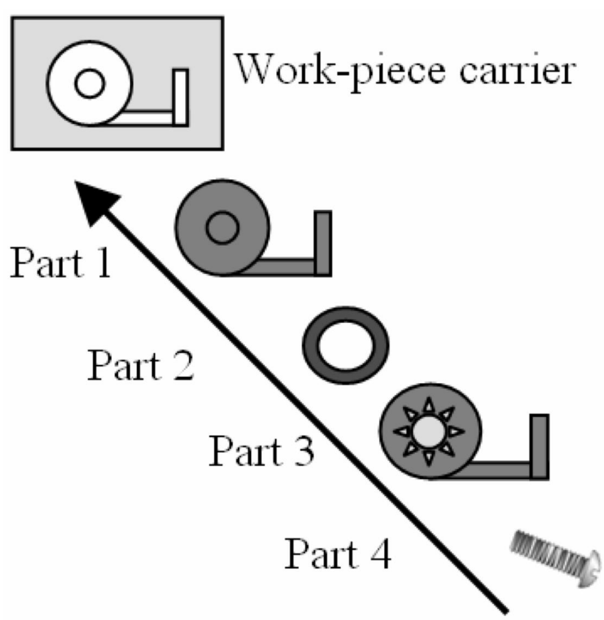

Figure 3.4: Adhesive Tape Roller Assembly and Kitting Process [Frei 2008].

3.3 Change Cases

Use cases for changes were also a focus of the literature review. A couple of examples are described below.

3.3.1 Adhesive Tape Roll Dispenser

Frei and Di Marzo Serugendo [Frei 2008] proposed a number of scenarios to trigger their self-organization process, as shown in Figure 3.5. The first scenario was to establish a new layout or product order consisting of new user preferences. This would also be the initialization scenario to begin the assembly process. The second scenario would be a change in the locking method from a screw-type to a snap-fit method. This would result in the removal of Part 4 and Robot 4, as well as the need for Robot 1 to be able to apply force to the snap-fit. The third scenario would be a change from a tube of tape rolls to a stick of tape rolls. This would result in Robot 2 needing to switch its method of grabbing the tape roll from expansion to compression.

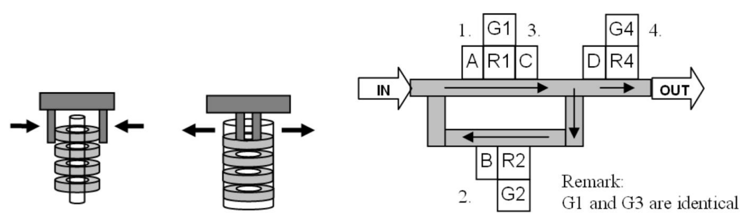

Figure 3.5: Tape Roll Change Case and Assembly Layout [Frei 2008].

3.3.2 Change Cases for Planning & Scheduling

Ling *et al.* [Ling 1994] used a set of three test cases (one normal situation and two situations where agility was needed to handle disruptions) as part of testing their Planning and Scheduling methodology. Case 1 was the normal situation and was used as the baseline to measure the changes caused by the other cases. Case 2 involved the introduction of a new high priority order into the system causing a re-prioritization of the existing robotic assembly testbed components. Case 3 involved a machine breakdown, which has a similar effect as Case 2 where a re-prioritization of the existing components must occur to absorb the impact of the broken machinery. Another re-prioritization would occur when the machine has been repaired and is ready to return to use in the assembly process.

Chapter 4

Robot Agility Metrics

Effectively measuring, analyzing, and improving manufacturing metrics is not a simple task. While there are certain metrics that work well for specific areas of a manufacturing system, multiple combinations of metric indicators are often required to ensure that a larger objective will be met. Therefore, the design and the tasks of the manufacturing system need to be carefully analyzed. It is often said that what gets measured gets done.

Evans and Messina [Evans 2001] analyzed the importance of defining universally accepted performance metrics for intelligent systems. The analysis outlines current efforts to develop standardized testing and evaluation strategies. The authors also discuss the need for industry accepted metrics for inter-comparison of results and to avoid duplication of work. Falco *et al.* [Falco 2013] held a workshop to address the application of dexterous robot technologies to meet the application needs of small batch production, and to promote the greater theme of applying dexterous robotics toward flexible manufacturing. The development of metrics to measure dexterity was one of the main topic of the workshop. The aforementioned authors extend a challenge to the research community to actively work towards the process of developing standard metrics. As new technologies emerge, performance metrics and associated test methodologies are needed to unify research efforts, characterize the state of technology, and to provide a means for end-users to evaluate the capabilities of robotic assembly systems.

This section discusses the metrics from a literature review that are used to assess the agility performance of manufacturing assembly systems. Our review shows that the only common terms found in the different versions for agile assembly consist of manufacturing facilities to possess a high degree of flexibility, enabling mass customization of production. Mass customization is the capability of a firm to offer high product variety, high overall volume and at the same time, low cost and fast delivery.

4.1 Metrics at the High Level of Manufacturing

In manufacturing, each major goal typically requires multiple metrics. The list of metrics that appear in this section are grouped together relating to specific higher-level goals and objectives.

4.1.1 Manufacturing Cycle Time

The time it takes to do one repetition of any particular task typically measured from "Start to Start" the starting point of one product's processing in a specified machine or operation until the start of another similar product's processing in the same machine or process.

Cycle time is commonly categorized into:

- Manual Cycle Time: The time loading, unloading, flipping/turning parts, adding components to parts while still in the same machine/process.
- Machine Cycle Time: The processing time of the machine working on a part.
- Auto Cycle Time: The time a machine runs un-aided (automatically) without manual intervention.
- Overall Cycle Time: The complete time it takes to produce a single unit. This term is generally used when speaking of a single machine or process.
- Total Cycle Time: This includes all machines, processes, and classes of cycle time through which a product must pass to become a finished product. This is not lead time, but it does help in determining it.

4.1.2 Time to Make Changeovers

Measures the speed or time it takes to switch a manufacturing line or plant from making one product over to making a different product.

> Reducing changeover time is like adding capacity, increasing profitability and can help most manufacturers gain a competitive edge. Image a pit crew changing the tires on a race car. Team members pride themselves on reducing changeover by even tenths of a second because it means that their driver is on the road faster and in a better position to win. The same philosophy applies to manufacturing the quicker you are producing the next scheduled product, the more competitive you are [cha 2014].

By reducing or eliminating part-specific tooling, changeover times are driven as close to zero as possible.

4.1.3 Efficiency

Efficiency is a measurement (usually measured as a percentage) of the actual output to the standard output expected. Efficiency for assembly systems measures how well productivity is performing relative to existing standards. Metrics to measure efficiency os assembly systems are described below.

Production System

Manufacturing companies use metrics to measure and manage their production systems. Later we will see how automation can be used to improve these metrics. Metrics may be developed and applied to the system, and upon feedback of metric data, various administrative decisions can be made to improve the system. In this section we look at some key measures that can, with relative ease, be captured from an operational production system.

Time to Assemble a Product Modelling, Implementation and Application of a Flexible Manufacturing Cell

Throughput Throughput characterizes the production volume and is an important measure of assembly system performance. Due to the randomness in production (machine breakdowns, random processing times, etc.), the number of parts produced by a production system is a random variable [Li 2009]. Often, this measure is normalised as the production rate (the average number of parts produced by the last machine in the production system per unit of time) or line efficiency.

Li *et al.* [Li 2009] presented reviews of recent advances and future research topics in manufacturing throughput analysis of production systems with unreliable machines and finite buffer capacities. Colledani & Tolio [Colledani 2005] presented a decomposition based methods for analyzing manufacturing system throughput in designing configuration and reconfiguration of producing drums for washing machines. The proposed method has been used to support the reconfiguration of a real system producing washing machines. In particular, the line producing drums for washing machines has been considered. Li & Huang [Li 2004] presented a throughput analysis methods for multiple product lines with split and merge.

Production Rate Production rate is defined as the number of work units completed per hour and is calculated as follows:

$$R_p = \frac{60}{T_p} \tag{4.1}$$

Where T_p is the average production time per unit (T_p) calculated using equation 4.2

$$T_p = \frac{T_b}{Q} \tag{4.2}$$

where T_b is the batch processing time and Q is the batch quantity. T_b is calculated as follows:

$$T_b = T_{su} + Q \times T_c \tag{4.3}$$

where T_{su} is the set-up time to prepare for the batch, T_c is the cycle time for each unit, and Q is as before. $T - c$ is calculated as follows:

$$T_c = T_o + T_h + T_{th} \tag{4.4}$$

where T_o is the time of the actual processing or assembly operation; T_h is the handling time; and T_{th} is the tool handling time.

Production Capacity Production capacity is defined as the maximum rate of output that a production facility is able to produce under a given set of assumed operating conditions. Production capacity (PC) is calculated using equation 4.5.

$$PC = n \times S_w \times H_{sh} \times R_p \tag{4.5}$$

where n is the number of machines or work centres in the facility; S_w is the number of work shifts per week; H_{sh} is the number of hours a work centre operates per shift; and R_p is the average production rate. When the number of operations required in the processing sequence is considered, the production capacity is computed as follows:

$$PC = \frac{n \times S_w \times H_{sh} \times R_p}{n_o} \tag{4.6}$$

where n_o is the number of processing operations that the work part undergoes.

Utilization Utilization (U) compares the actual plant production against its potential plant capacity. Utilization is computed as follows:

$$U = \frac{Q}{PC} \tag{4.7}$$

where Q is the total production quantity produced by the facility during a given time period and PC is the production capacity over the same period.

Availability Availability examines the machine time differences between failures and repairs. Availability (A) is computed as follows:

$$A = MTBF - \frac{MTTR}{MTBF} \tag{4.8}$$

where $MTBF$ is mean time between failures and $MTTR$ is mean time to repair.

Manufacturing Lead Time Manufacturing lead time (MLT) is the total time required to process a certain part or product through the plant. It includes all lost time (production equipment failures, delays, rework, storage time, etc). MLT is calculated as follows:

$$MLT_j = \sum_{i-1}^{n_{oj}} (T_{suji} + Q_j T_{cji} + T_{noji}) \tag{4.9}$$

where MLT_j is the manufacturing lead time for part or product j; T_{suji} is the set-up time for operation i; Q_j is the quantity of part or product j in the batch being processed; T_{cji} is the operation cycle time for operation i; T_{noji} is the non-operation time associated with operation i; n_o is the number of operations through which the work must pass; and j is the part or product.

Work-in-process Work-in-process (WIP) assesses the quantity of parts or products in the factory that are undergoing processes, or waiting to be processes. WIP is calculated as follows:

$$WIP = \frac{A \times U \times PC \times MLT}{S_w \times H_{sh}} \tag{4.10}$$

where A is availability; U is utilization; PC is the production capacity of the facility; MLT is the manufacturing lead time; S_w is the number of shifts per week; and H_{sh} is the hours per shift.

4.1.4 Overall Equipment Effectiveness (OEE)

Overall Equipment Effectiveness (OEE) is a multi-dimensional metric. OEE is a multiplier of Availability×Performance×Quality, and it can be used to indicate the overall effectiveness of a piece of production equipment, or an entire production line. The goals of OEE are threefold [Eckstrom].

1. Maximize production Availability by minimizing Down Time.
   - Down Time Loss is a function of breakdowns in equipment and tooling, setup time, adjustments, material shortages, operator shortages and warm-up time.
2. Maximize Performance by minimizing Speed Loss.
   - Speed Loss is due to slowing lines or complete stops caused by obstructed product flow, jams, misfeeds, blocked sensors, equipment wear and operator inefficiency.
3. Maximize Fully Productive Time by minimizing Quality Loss.
   - Quality Loss is a function of rejects, scrap and rework caused by factors such as incorrect assembly, in-process damage and in-process expiration. OEE defines Quality as the ratio of Fully Productive Time to Net Operating Time (Fully Productive Time is Net Operating Time less Quality Loss).

4.2 Metrics at the Assembly Level of Manufacturing

The increased number of new models and variants have forced manufacturing enterprises to meet the demands of a diversified customer base by producing products in a short development cycle, yielding low cost, high quality, and sufficient quantity. Modern manufacturing enterprises have two alternatives to face the aforementioned situation. The first one is to use manufacturing plants with excess capacity and stock of products in inventory to smooth fluctuations in demand. The second one is to use and increase the flexibility of their manufacturing plants to deal with the production volume and variety. While the use of flexibility generates the complexity of its implementation, it still is the preferred solution. Chryssolouris [Chryssolouris 2006] identified manufacturing flexibility as an important attribute to overcome the increased number of new models and variants from customized demands.

Flexibility, however needs to be defined in a quantified fashion before being considered in the decision making process.

4.2.1 Agility Vs. Flexibility

There is an extensive amount of research in the open literature discussing agile and flexible manufacturing philosophies. It is obvious that agile manufacturing is often confused with flexible manufacturing. This section attempts to describe the differences and relations between these two notions.

- Flexibility and Agility are Fundamentally Different: Shewchuk [Shewchuk 1998] indicates that flexibility and agility are fundamentally different. In his studies, the author describes flexibility as the ability to change a manufacturing system from within, whereas agility refers to the ability to change a manufacturing system from the outside, i.e., externally. This difference between these two notions was adopted in Daghestani's study [Daghestani 1998] in order to model an agile manufacturing environment. Daghestani points out that a flexible manufacturing system (FMS) is very flexible for what it was designed to do. This includes changes which can be made from within the system, such as changing between pallet and fixture types the system can accommodate, changing tools at magazines, etc. However, FMSs are rarely agile since they are extremely rigid systems which take a lot of time and effort to change (i.e., from the outside) once they are in place and running.

- Agility as a Combination of Speed and Flexibility: Agility is often perceived as combination of speed and flexibility. Gunasekaran [Gunasekaran 1998] defines agile manufacturing as the capability to survive and prosper in a competitive environment of continuous and unpredictable change by reacting quickly and effectively to changing markets, driven by customer-designed products and services. To be able to respond effectively to changing customer needs in a volatile marketplace means being able to handle variety and introduce new products quickly. Lindbergh [Lindbergh 1990] and Sharafi & Zhang [Sharafi 1999] mentioned that agility consists of flexibility and speed. Essentially, an organisation must be able to *respond flexibly* and *respond speedily* [Breu 2002]. Conboy & Fitzgerald [Conboy 2004] identified terms such as *speed* [Tan 1998], *quick* [Vor 1995, Kusak 1997, Upton 1994, Yusuf 1999], *rapid* [Hong 1996], and *fast* [Zain 2003] occur in most definitions of agility.

- Agility as an Extension of Flexibility: Several authors view agility as an extension of flexibility. Wadhwa & Rao [Wadhwa 2003] consider flexibility as an expedience to the efforts in dealing with change. They distinguish change into two types: stochastic (uncertainty related) and deterministic (certainty related). This finally leads to their conclusion of the difference between the concepts of flexibility and agility as the former responses to predictable changes, while the later responses to unpredictable changes, that is, *Flexible changes are responses to known situations where the procedures are already in place to manage the change. Agility extends the capability of flexibility by requiring the ability to respond to unpredictable changes to well defined conditions before it can extend its capabilities to responding to unforseen changes. From this perspective, flexibility is a prerequisite to become agile.*

A literature review shows that flexibility objectives at the assembly level have been reported to be material handling flexibility, routing flexibility, product flexibility, operation flexibility, and failure flexibility [Wiendahl 2007, Parker 1999, Diffner 2011]

4.2.2 Material Handling Flexibility

Flexibility of a material handling system is its ability to move different part types efficiently for proper positioning and processing through the manufacturing facility it serves [Sethi 1990].

Material handling flexibility is defined as the ability of a material handling system to move different part types effectively through the manufacturing facility. This includes: loading and unloading parts, inter-machine transportation and storage of parts under various conditions. Material handling flexibility might increase machine availability and reduce throughput times [Diffner 2011]. Efficient material handling is needed for less congestion, timely delivery and reduced idle time of machines due to non-availability or accumulation of materials at workstations. Safe handling of materials is important in a plant as it reduces wastage, breakage, loss and scrapes etc. Having a flexible material handling system increases availability of machines and thus their utilization and reduces throughput times. According to Tompkins *et al.* [Tompkins 2010], about 20 to 50 % of the total production cost is spent on material handling. In addition, all the complexity of manufacturing is passed on to the material handling system.

One material handling technology addressing the needs for robotic assembly systems is automated guided vehicles (AGVs). AGVs belong to a class of highly flexible, intelligent, and versatile material handling systems used to transport materials from various loading locations to various unloading locations throughout the facility. The different types of AGVs found in the literature are towing vehicles, unit load transporters, pallet trucks, forklift trucks, light-load transporters, and assembly line vehicles.

Metrics Assessment Material Handling Flexibility – Performance measurements of material handling in a manufacturing system can be classified based on the production performance and on the vehicle performance.

- Production performance:
  - Tsourveloudis & Phillis [Tsourveloudis 1998] used a fuzzy logic approach to measure material handling flexibility. The parameters used to assess the material handling flexibility of a manufacturing system are:
    * Rerouting factor which indicates the ability of a material handing system to change travel paths automatically or with small setup delay and cost. Rerouting ability is a necessary property for the establishment of routing flexibility.
    * Variety of loads which a material handling system carries such as workpieces, tools, jigs, fixtures etc. It is restricted by the volume, dimension, and weight requirements of the load.
    * Transfer speed which is associated with the weight and geometry of products, as well as the frequency of transportation.

    * Number of connected elements such as machines and buffers.

- Dai *et al.* [Dai 2009] did a performance comparison between a free-ranging flexible material handling system (FMHS) and a fixed-track system. The results showed free-ranging FMHS considerably improving the performance of a manufacturing system when compared to the free-track system. The different metrics used to demonstrate the superiority of the free-ranging FMHS are listed as follows:
    * Manufacturing cycle efficiency (`MCE`) is a traditional measure of the manufacturing process. `MCE` is defined as the ratio of the time in actual production and setup process over the total time in the production area [Fogarty 1992]. The higher the ratio, the higher the percentage of time spent in the workstations.
    * Value added efficiency (`VAE`) measures the percentage of time added to a product during the production process. `VAE` is defined as the ratio of total run time to the total manufacturing time [Fogarty 1992].
    * Work in process (`WIP`) is defined as the inventory between the start and end points of a product routing and is commonly used as a criteria to assess manufacturing systems [Fogarty 1992, Viswanadham 1993]. It has significant effect on the inventory cost and the capability of flexible and quickly responding to customers' requirements.
    * Average time in the system (`AVT`) [Saad 1998] is the long-term average time of a part spent in the system from entering the loading station to departing the unloading station. This can be used to measure the speed of the response to a new order.
    * Throughput quantity (`TH`), which is often simply referred to as throughput or production volume, is the number of jobs completed in a given period of time. This can also be called production rate [Beamon 1998, Egbelu 1984]. According to Little's Law, the relationship of `TH`, `WIP`, and the cycle time (`CT`) is defined as:
    * Workstation utilization is defined as the fraction of actual operating time to the total available time [Viswanadham 1993]. It reflects the average efficiency of the workstations being used in the production line. In the apparel industry, the order size is relatively small. Different products often require different sequence of production processes.
    * Total transportation distance is the most frequently used criteria for evaluating material handling systems [Kim 2005]. It is defined as the weighted sum of material flow distances between different workstations or departments. The minimum material flow distance is valuable for enhancing the utilization of the entire system, reducing the throughput time, and the `WIP`. The authors defined the total transportation distance for both the free-ranging FMHS and the fixed-track system.

- Vehicle performance:
    - Total average loaded travel distance: This is the average distance traveled by an AGV when it is loaded.
    - Total average empty travel distance: This is the average distance traveled by an AGV when it is empty.

– Number of deliveries required per hour.
– Loading and unloading time.
– The total time per delivery per vehicle.
– Number of deliveries per vehicle per hour.

Automated material handling can also reduce workplace injuries by limiting the number of potential incidents.

4.2.3 Routing Flexibility

Routing flexibility of a manufacturing system is its ability to produce a part by alternate routes through the system [Sethi 1990].

Alternate routes in this definition refers to the use of different machines, different operations, or different sequences of operations. Routing flexibility is different from the material handling flexibility, which is the property of a specific component of the system. Routing flexibility allows for efficient scheduling of parts by better balancing of machine loads. Furthermore, it allows the system to continue producing a given set of part types, perhaps at a reduced rate, when unanticipated events such as machine breakdowns, late receipt of tools, a preemptive order of parts, or the discovery of a defective part occur. Thus, it contributes toward the strategic need of meeting customer delivery times.

Metrics Assessment Routing Flexibility – For Tsourveloudis & Phillis [Tsourveloudis 1998], routing flexibility is an inherent property of the manufacturing system and it expresses its ability to respond to unanticipated internal changes and variations. The authors are mainly motivated by the fact that arises routing flexibility arises the existence of interchangeable machines, capable of performing similar operations. The ability to handle breakdowns, which is the main characteristic of routing flexibility, exists if each operation can be performed on more than one machines. to substitute for another. The authors designed a fuzzy approach to measure the routing flexibility of a system by using

- Operation commonality which expresses the number of common operations that a group of machines can perform in order to produce a set of parts.
- Substitutability which is defined as the ability of a system to reroute and reschedule jobs effectively under failure conditions. The substitution index may also be used to characterize some built-in capabilities of the system as for example, real-time scheduling or available transportation links. Substitutability is associated with the material handling system and the layout of the machines.

In their comparison between routing flexibility and machine flexibility, Tsubone & Horikawa [Tsubone 1999] used the following parameters to assess the performance of a manufacturing flexibility for routing flexibility and machine flexibility:

- Machine breakdown rate: The machine breakdown rate, MR, is defined as the ratio of the total time of machine breakdown to the available working time, as follows:

$$MR = \sum_{m=1}^{M} \frac{MBT_m}{M \times H_1} \tag{4.11}$$

where MBT_m is the actual total time of machine breakdown for machine m and H_1 is the available working time in the shop under the assumption that each machine has no flexibility.

- Duration of machine breakdown: Duration of machine breakdown, MC, is defined as the ratio of the mean machine breakdown time to the mean operation time, as follows:

$$MC = \frac{\beta}{\alpha} \tag{4.12}$$

where α is the mean operation time and β is the mean machine breakdown time.

Joseph & Sridharan [Joseph 2011] evaluated the routing flexibility for producing individual part types in terms of measures such as routing efficiency, routing versatility, routing variety and routing flexibility.

- Routing efficiency: Throughput time or flow time of a part can be considered as a comprehensive measure of routing efficiency. Determination of routing efficiency of a route involves comparing the flow time of the route with the minimum flow time in the set of routes.

- Routing versatility: Routing versatility implies that the more the number of routes available for producing a part, the more the flexibility of the system is. Furthermore, the greater the similarity of performance outcomes of the routes set, the more flexible is the system.

- Routing variety: Routing variety is defined as the difference among the routes of producing a specific part. Generally, the greater the differences among the routes, the higher the degree of variety and hence the higher the degree of flexibility. The difference between two routes can be calculated as the ratio of the number of different machines visited to the total number of machines visited in the two alternative routes.

- Routing flexibility of the system: The routing flexibility (RF) of the system in producing k part types is obtained as

$$RF = \frac{1}{k} \sum\nolimits_{j=1}^{k} E_j \times R_j \times D_j \tag{4.13}$$

where E_j is routing efficiency on producing part type j, R_j is routing versatility of the system in producing part type j, and D_j is the total difference of the routes set for part type j.

Hoshino *et al.* [Hoshino 2008] developed a flexible and agile multi-robot manufacturing system with AGVs and product-processing robots for fluctuating low-volume and high-mix demands. The system aimed at addressing the problem of workload balancing. Workload balancing is required when new orders are received from customer demands thus leading to unpredictable fluctuations. The authors used the system operation time (h) and the system utilization ($\frac{total\ operation\ time\ of\ each\ robot}{system\ operation\ time}$) as the performance metrics to show the efficiency and superiority of their system over a simple manufacturing system.

4.2.4 Product Flexibility

Product flexibility entails the ability to manufacture multiple products on the same capacity, and the ability to reallocate capacity between products in response to realized demand. [Goyal 2011].

In order to satisfy a wide range of customer demands, manufacturing facilities need to change their output to accommodate a variety of products by producing several different products simultaneously within a given period. The manufacturing system must have the capability of changing the production in two phases, that is in the short term and in the long term. In the short term, the manufacturing system must be able to integrate product mix flexibility response (quickly change among the current variety of product at low cost). In the long term, the manufacturing system must be able to integrate product mix flexibility range (ability to change the product range). The flexibility range indicates how much a system can change, and the flexibility response indicates how easily the system can change [Slack 1980]. Therefore, the product mix range flexibility can be measured by identifying the number of products that the manufacturing system can produce [Browne 1984, Muramatsu 1985, Sethi 1990]. The product mix flexibility response however can be expressed as the time to change from one product to another.

Robots that are equipped with dexterous manipulators are of paramount importance to address challenges in next-generation automation where high-mix, low-volume parts production needs fast changeover and reprogramming in order to stay efficient. Dexterous manipulation will allow for grasping a great variety of objects with different shapes in any number of orientations quickly, adeptly, and decisively [Falco 2013]. Bicchi [Bicchi 2000]suggested that dexterous manipulation is the capability of changing the position and orientation of the manipulated object from a given reference configuration to a different one within the hand workspace. Okamura *et al.* [Okamura 2000] generalizes the definition further, describing dexterity as a cooperative manipulation between multiple manipulators, or fingers, cooperate to grasp and manipulate objects, implying that manipulators with simple end effectors alone are not capable of dexterous manipulation. Ma & Dollar [Ma 2011] pointed out that dexterity needs to be differentiate from general manipulation. Dexterity in the literature is associated to anthropocentrism where precision manipulation tasks are performed between fingertips and other small finger-like appendages. The authors, however, discussed a more generalized task and object-centric definitions of dexterity by focusing on systems' kinematic and dynamic capabilities.

Metrics Assessment Product Mix Flexibility Response – The quickness of the changeover is a key issue in establishing the measure of product mix flexibility response. Some of the efforts measuring product mix flexibility response are described below.

- An effective measure of the product mix flexibility response must incorporate factors that indicate the difference between two products [Das 1993]. The authors used the degree of distinction between products, and the proportion of time required for changeover. Since their study focused on assembled products, the distinction between two products is measured as a function of the number of assembly components used in the two products.

- Tsourveloudis & Philis [Tsourveloudis 1998] developed a fuzzy framework to measure the product flexibility of a manufacturing plant. The different metrics involved in the proposed framework are:

  – Part variety is associated with the number of new products the manufacturing system is capable of producing in a time period without major investments in machinery and it takes into account all variations of the physical and technical characteristics of the products.
  – Changeover effort in time and cost that is required for preparations in order to produce a new product mix.
  – Part commonality refers to the number of common parts used in the assembly of a final product. It measures the ability of introducing new products fast and economically and also indicates the differences between two parts.

Metrics Assessment Dexterous Manipulation – Many efforts in the literature proposed analytical measures of dexterity index. The dexterity index is a measure of a manipulator to achieve different orientations for each point within the workspace. For instance, Pond & Carretero [Pond 2011] determined the dexterous workspace size of a particular manipulator and studied the influence of architectural parameters on the dexterous workspace volume. The authors used the constrained dimensionally homogeneous Jacobian matrices where the matrices are dimensionally consistent and are constrained. Other efforts used the condition number of manipulator's Jacobian matrix mapping actuator velocities to end effector velocities [Gosselin 2009, Badescu 2004]. More analytical measures for dexterity index can be found in [Elkady 2010].

The National Institute of Standards and Technology (NIST) produced a report based on an industry workshop [Falco 2013]. The workshop featured presentations from consumers of dexterous robotics, next-generation dexterous robot manufacturers, and dexterous robot hand technology. The goals of the workshop were to address the application of dexterous robot technologies to meet the application needs of small batch production, and to promote the greater theme of applying dexterous robotics toward flexible manufacturing. The different panelists articulated their idea on how to increase dexterity for assembly. Some of these ideas are:

- Reducing the weight of robotic hands to improve the robot's payload limitations.

- Increasing the modularity of robotic hands so that interchangeable hands can handle different classes of part geometry.

- Integrating force sensing technology directly into robot joints, as opposed to the use of force transducers attached to a tool flange.

- Adding sensors to grippers (in terms of pneumatic grippers) to achieve capabilities such as force control, thus leading the development of intelligent gripping for examination, flexibility, and adaptation.
- Developing reactive grasping or perception that will communicate to the robot the size and shape of an object.

The report showed that there is a gap between the demand for dexterity and the available solutions to provide mode dexterous arms and hands. Moreover, all the panelists noted the lack of metrics for current technologies to measure dexterity. A rudimentary set of metrics were identified during the workshop that can be used to measure dexterity. Performance requirements of robotic hands were described in terms of position and force control as well as actuation speed. A panelist defined the elements of dexterity as coordination and agility. To apply metrics to coordination, any test of dexterity should include cooperative tasks where both arms work together. The agility for a given robot is the ability to reach the greatest possible volume with the greatest number of orientations and configurations. Another panelist suggested the level of dexterity may also be evaluated according to the number and types of applications that a particular robot is capable of supporting or performing. The most meaningful unit to measure dexterity is the cost savings that it can provide.

Metrics Assessment Force Control – Marvel & Falco [Marvel 2012] described the current state of force-controlled mechanical assembly, and highlights key robot technologies and force control algorithms and presented the metrics for force control and force-based assembly.

- Force Control Metrics – Force control algorithms provide a means of physically interacting with the world while limiting the potential for damaging either the objects within it or to the robot itself. This goal cannot be achieved if the robot's actions are not tightly controlled. As such, one of the largest overlying themes of robot performance evaluation is that of stability.
  - Settle stability is the time taken by the system to settle. The time to settle is the time necessary for the robot to settle such as it maintains a consistent contact force with a surface.
  - Obstruction stability measures the stability of the robot when an immovable object keeps the robot tool from reaching the goal state.
  - Control switch stability measures the stability of a robot when switching between control structures. This metric indicates the system ability to handle force and position errors.
  - Surface cohesion (Force Profiles) measures the ability of a robot to maintain constant surface contact during an application (such as paint removal). Other metrics include the speed at which the robot moves along a surface while maintaining force stability.
  - Incurred force limitations measures the ability of a robot applying force that does not exceed defined limits.

- Force-based assembly metrics consist of metrics used for assembly optimization.
  - Assembly time measures the automation efficacy and describes the required time to complete assembly tasks.
  - Success rate represents the number of successful assemblies which is a useful metric for system throughput and stability.
  - Incurred (maximum/average) force measures the ability of a robot to sense and quickly react to forces (depending on the type of material being used).

4.2.5 Operation Flexibility

Operation flexibility of a part refers to its ability to be produced in different ways [Sethi 1990].

Operation flexibility is a property of the part, and means that the part can be produced with alternate process plans, where a process plan means a sequence of operations required to produce the part. An alternative process plan may be obtained by either an interchange or a substitution of certain operations by others. Thus, a part that permits operations to be performed in alternate orders or using different operations in an interchangeable fashion would possess operation flexibility.

Metrics Assessment Operation Flexibility – According to Sethi *et al.*, the operation flexibility of a part can be measured by the number of different processing plans for its fabrication [Sethi 1990].

Kumar [Kumar 1988] decomposed the operations entropy into entropies within and between operations and entropies within and between groups of operations. This measure has been used to determine the next operation to be performed on a part by using the principle of least reduction of flexibility.

Some theoretical measures have been explored to evaluate assembly sequences under different contexts. For example, Sanderson & Homem de Mello [Sanderson 1987] used the And/Or graph approach to represent feasible assembly/disassembly sequences and a function based on parts entropy measures as evaluation criteria for search in the And/Or graph space. Park *et al.* [Park 1991] described the evaluation criteria based on four evaluation functions to minimize the chances of assembly failures caused by spatial errors of parts and assembly equipment. Bonneville *et al.* [Bonneville 1995] presented a genetic algorithm that uses the assembly trees as models for the plans to encode them in chromosomes. The liaisons graph and the geometric constraints of the model are then used to evaluate the assembly operations. Suárez and Lee [Suárez 1997] proposed a statistical measure of an assembly cost index to evaluate the assembly sequences in order to determine the optimal one.

The quality of an assembly process plan impacts the quality of the product. Process quality is the ability of the assembly process to assemble products without defects [Park 1987]. Koren *et al.* [Koren 1998] define quality as the deviation of a dimension from design intent. In other words, quality is measured in terms of closeness to design specification of certain key product characteristics.

Kramer *et al.* [Kramer 2013] developed a configurable scoring system that uses five factors combined as specified by a scoring file to compute the score of the plan. The scoring system allows one to compare the quality of different plans. The scoring system uses the following five factors combined as specified by a scoring file to compute the score. The factors and the score are recomputed after each movable goal object is checked.

- Right Stuff – The Right Stuff value, R, is a measure of achieving goal positions. Let G be the number of objects in the goal file placed correctly so far, B be the number of objects in the goal file placed incorrectly so far, and N be the number of objects in the goal file checked so far. Then $R = (G - B)/N$. If R is less than zero, it is set to zero.
- Command Execution – The Command Execution value, C, is the fraction of all commands in the command file that were executed correctly. This factor does not change during the second phase of operation. Let K be the total number of commands executed successfully and E be the number of errors that are not location errors. Then $C = \frac{K}{(K+E)}$.
- Distance – The Distance value, D is a measure of efficiency of robot motion in terms of distance. Let J be the total distance moved from initial position to goal position by all basic goal objects that have been checked so far, L be the total distance moved by the robot, and F be the fraction of movable objects that have been checked so far. Then $D = \frac{(2 \times J)}{(L \times F)}$. If D is greater than 1, it is set to 1. The numerator, $(2 \times J)$ is a crude measure of a short distance to move the robot in order to move the objects that have been moved so far to their goal positions.
- Time – The Time value, T is a measure of efficiency of robot motion in terms of time. The teleport time, P, is a crude measure of a fast time for moving the objects that have been moved so far to their goal positions. Let J and F be as in the preceding item, and let Q be the maximum speed of the robot. Then $P = \frac{(2 \times J)}{Q}$. Let H be the total execution time. Then $T = \frac{P}{(H \times F)}$. If T is greater than 1, it is set to 1.
- Useless Commands – The Useless Command factor is the value of the useless commands metric. This factor does not change during the second phase of Kitting Viewer operation.

The scoring file, as prepared by a user, designates each of the five factors as being either multiplicative or additive. For additive factors, a weight may be assigned in the file. For each factor, a valuation function may be assigned. A valuation function takes a raw factor with an arbitrary range and produces a number between 0 and 1. The final stage of producing a score combines numbers between 0 and 1. If a raw factor (useless commands, for example) is not necessarily between 0 and 1, a valuation function must be assigned to that factor. If a raw factor is always between 0 and 1 (right stuff, for example), a valuation function may be assigned, but is not required.

The scoring system is designed so that the score it produces is always between 0 and 100.

Each factor is designated as additive or multiplicative. A factor value V_i between 0 and 1 is found for each additive factor and a factor value U_i between 0 and 1 is found for each multiplicative factor. Each additive factor is assigned a non-negative weight W_i. An additive score S_a is produced by multiplying each additive value by its weight, adding the products together, and dividing by the sum of the weights. If there are no additive factors or their weights are all zero, $S_a = 1$.

$$S_a = \frac{(V_1 \times W_1) + (V_2 \times W_2) + \cdots + (V_n \times W_n)}{W_1 + W_2 + \cdots + W_n}$$

The value of S_a will be between 0 and 1 since all the components of the equation are positive and the largest the numerator can be is the size of the denominator.

Then the total score S is found by finding the product of S_a, 100, and all the multiplicative factors.

$S = (100 \times S_a \times U_1 \times U_2 \times \cdots \times U_m)$

4.2.6 Failure Flexibility

A failure occurs when an error affects the service delivered from a system in any way. An error is the difference between what is specified and what is actually there and occurs when the observed behavior conflicts with the desired behavior of the system [Odrey 1995]. Kokkinaki & Valavani [Kokkinaki 1996] define errors as manifestations of faults. A fault is the original source of an error, such as a broken air pressure valve or assembly part out of tolerances, which may led to an error directly or indirectly. An example of failure is a gripper not functioning properly that will prevent a part from being accurately positioned during production. Because of this, the part could not be properly positioned and results in a bad assembly. The gripper is the fault that generated the errors and failures. The error is a positional error (the undesired state) and the failure is the wrong assembly (a service that could not be delivered). Other instances of error during production can be split in two groups. The first group of errors deals with physical faults such as breakdowns, misalignements, incorrect parts and tooling. The second group of errors deals with non-physical faults such as shortage of parts or missing tool.

Failures can directly lead to production quality deterioration in automated manufacturing assembly systems and failure flexibility aims for a fast reaction in the assembly system. Bad quality of a manufactured product directly affects the function of the product and can increase the cost of the manufacturing system. When detected earlier, a failure that is addressed before the defective product gets out of the door can increase the cost of producing the same product by between 4 and 6 times the original cost. These costs include the cost of scrapping or reworking materials. If the product is being delivered or in the possession of the customer, the cost can easily run up to 150 times or more of the original cost. These additional costs are incurred due to recalls, warranty claims, liability, fines, sanctions, and loss of customers.

Failure recovery consists of the execution of a sequence of operations in order to recover from a failure situation. *A failure recovery is successful when the planned recovery operations are completely executed, allowing to resume execution of the nominal plan* [Lopes 1999]. *Unsuccessful recovery may happen due either to the application of an incorrect recovery strategy, given the initial failure diagnosis, or to errors in the initial diagnosis itself* [Lopes 1999].

Metrics Assessment Failure Flexibility – Fox *et al.* [Fox 2006] discussed plan replanning and plan repair when differences are detected between the expected and actual context of execution during plan execution in real environments. The authors define plan repair as the work of adapting an existing plan to a new context while perturbing the original plan as little as possible. Replanning is defined as the work of generating a new plan from scratch. Plan repair and replanning are compared using three different metrics: the speed of plan production (CPU time), the plan quality, and the plan stability (relative distances between the original plan and the new plan produced by repair and by replanning). Seabra Lopes [Lopes 1999] introduced learning at the task planning and failure recovery level to enable an assembly system to make decisions in the time scale of the normal execution of the task. The author showed that if some unexpected problem arises and records exist about problems of the same kind, the problem can be solved with no significant increase of the total time to complete the task. Leighton *et al.* [Leighton 2011] used a Petri Net Model to assemble geometric figure. The authors used the percentage of faults to assembly a product as one of the metrics to measure the performance of their assembly flexible cell.

Kannan & Parker [Kannan 2006] developed metrics to measure fault-tolerance within the context of system performance in multi-robot teams. Although not particularly applied to manufacturing systems, the metrics discussed by the authors may be used to measure the performance of multi-robot teams on manufacturing shop floors. The authors pointed out that traditional engineering methods addressing fault tolerance deal with reliability and availability. Reliability is defined as the probability that a device will perform its required function under stated conditions for a specific period of time. Reliability metrics mainly consist of the mean time between failure (MTBF). Other metrics used for evaluation include the mean time to repair (MTTR) and availability. These metrics are defined below.

- The mean time between failure (MTBF) provides a rough estimate of how long one can expect to use a robot without encountering failures. MTBF is computed as follows:

$$MTBF = \frac{T}{R} \tag{4.14}$$

  where T is the total time a robot was in use and R is the number of failures. If 10 devices are tested for 500 hours. During the test 2 failures occur. The estimate of the MTBF is: $MTBF = \frac{10\times 500}{2}$ =2,500 hours / failure.

- The mean time to repair ($MTTR$) represents the average time required to repair a failed component or device. In an operational system, repair generally means replacing a failed hardware part. $MTTR$ is computed as follows:

$$MTTR = \frac{TR}{NR} \tag{4.15}$$

  where TR is the total time spent repairing and NR is the number of repairs.

- Availability measures the impact of failure on an application or project and is computed as follows:

$$Availability = \frac{MTBF}{MTTR + MTBF} \times 100\% \tag{4.16}$$

Robustness can be used to assess the failure flexibility of a system. Kannan & Parker [Kannan 2006] described robustness as the ability of the system to identify and recover from faults. The authors measured the robustness of individual tasks assigned to multi-robot teams. Robustness of a control system was described by Pinto-Leitão & Restivo [Pinto-Leitao 2004] as the capability to remain working correctly and relatively stable, even in presence of disturbances. The degree of robustness is measured by introducing possible errors (as many as possible) in the system and then verifying if the control system could still work properly. The degree of robustness is given by $\frac{nP}{nT} \times 100\%$, where nP is the number of tests passed and nT is the total number of tests.

CHAPTER 5

CONCLUSION

In this report, we present a literature review of agility methods, metrics, and use cases that are attempting to enhance the agility of robots in manufacturing environments. While not comprehensive, this literature review provides a nice overview of the approaches that have been applied in the field.

In addition to the literature review, a series of industry interactions have recently occurred to hear firsthand from industry about the challenges they are facing in the area of robot agility. In addition, interactions are also focusing on identifying relevant use case scenarios that can help to scope the effort. This interaction is still in its early stage so details are not reported in this document; future documents will focus on this area.

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