Recent Advances and Future Challenges in Automated Manufacturing Planning

The effective planning of a product's manufacture is critical to both its cost and delivery time. Recognition of this importance has motivated over 30 years of research into automated planning systems and generated a large literature covering many different manufacturing technologies. But complete automation has proved difficult in most manufacturing domains. However, as manufacturing hardware has evolved to become more automated and computer aided design software has been developed to support the creation of complex geometries; planning the physical fabrication of a virtual model is still a task that occupies thousands of engineers around the world, every day. We intend for this paper to be useful to newcomers in this field, who are interested in placing the current state-of-the-art in context and identifying open research problems across a range of manufacturing processes. This paper discusses the capabilities, limitations and challenges of automated planning for four manufacturing technologies: machining, sheet metal bending, injection molding, and mechanical assembly. Rather than presenting an exhaustive survey of research in these areas, we focus on identifying the characteristics of the planning task in different domains, current research directions, and open problems in each area. Our key observations are as following. First, the incorporation of AI techniques, geometric modeling, computational geometry, optimization, and physics-based modeling has led to significant advances in the automated planning area. Second, commercial tools are available to aid the manufacturing planning process in most manufacturing domains. Third, manufacturing planning is computationally challenging and still requires significant human input in most manufacturing domains. Fourth, advancement in several emerging areas has the potential to create, in the near future, a step-change in the capabilities of automated planning systems. Finally, we believe that deploying fully automated planning systems can lead to significant productivity benefits. [DOI: 10.1115/1.3593411]

1 Introduction

Manufacturing is one of the most exciting human endeavors. It's the process of turning designs into concrete physical objects, cost effectively (i.e., the efficient production of artifacts). After the advent of computers, automated manufacturing planning became an active research area. The manufacturing planning problem has been studied from many different perspectives, and thousands of papers have been written about the subject. The first perspective is the role of computing technologies in manufacturing planning, where the following technologies have played a critical role:

- **AI Techniques**: Many first generation manufacturing planners were developed using the planning and search techniques developed by the artificial intelligence (AI) community. Parts were described in terms of their attributes, and manufacturing knowledge was coded to relate the part attributes to the planning decision variables. The main emphasis was on the process and the tool selection while determining the operation sequences.

- **Geometric Modeling**: The advent of geometric modeling enabled the use of detailed 3D part models and geometric simulations to assess the feasibility of the selected tools and setups. Geometric modeling also offered the possibility to eliminate the need to manually describe parts in terms of their attributes and instead automatically extract relevant features and attributes directly from computer aided design (CAD) models.

- **Computational Geometry**: The development of computational geometry led to rigorous examination of the algorithmic complexity of the underlying planning steps. This in turn led to identification of computationally hard problems and the subsequent development of approximate algorithms to provide workable solutions for these types of problems.

- **Optimization**: Most manufacturing planning problems involve optimization. So the advanced optimization techniques have been incorporated into the planning process. Currently, the manufacturing planning community uses techniques ranging from mathematical programming to evolutionary optimization.

- **Physics-Based Modeling**: Process physics plays a major role in selection and optimization of process parameters. Increasingly, the planning community is using physics-based modeling techniques to select and optimize process parameters.

The involvement of such diverse computing technologies means that the manufacturing planning field is highly interdisciplinary in nature, with active participation from manufacturing engineers, computer scientists, and mathematicians.

Another perspective from which the manufacturing planning problem can be studied is to examine how it varies with different manufacturing domains (e.g., machining, sheet metal bending, injection molding, and assembly). Different manufacturing domains have different requirements and approaches to decompositions of the planning problem. Although the history of planning system development varies with each manufacturing domain, all have been influenced by the computing technologies described above. While details of the planning steps differ with the technology, the following generic problems are characteristic of the field:

- **Transformation of Material**: Manufacturing processes enable solid, or liquid, or materials to be solidified, deformed, and
cut or assembled to create a component. Typically, the material moves through a series of intermediate shapes or configurations that result in the final shape. Therefore, the planning problem has to model and reason about the material transformations during virtual processing.

- **Choice:** The act of planning is synonymous with choice so usually several different planning solutions are viable. Indeed, a characteristic of manufacturing planning systems is that they deal with solution spaces that are combinatorially very large.

- **Tooling:** Manufacturing planning must also include the tooling required to perform the operations. This ranges from mechanisms to hold the work (e.g., robot grippers, jigs, and fixtures) to complex components designed to form specific shapes (e.g., molds).

In this paper, we have selected four application domains: machining, injection molding, sheet metal bending, and mechanical assembly to investigate the manufacturing planning problem. These domains collectively represent a significant cross-section of the manufacturing industry. In Secs. 2–5, we describe how computational technologies have led to advances in these application domains. We also describe the main planning steps and identify open problems in each of these application domains.

Many commercial tools are available to support manufacturing planning. However, there are few, if any, comparative studies of their functionality reported in the academic literature. Consequently, we make no reference to any commercial software and simply note that in most cases these tools only provide automation for specific subtasks of the overall planning problem. The status of planning automation is different in different application domains. Currently, the commercial tools offer the highest level of planning automation for sheet metal bending and limited automation for mechanical assembly. Overall, manufacturing planning still requires significant human input and we are far away from one-click automated planning systems in most domains.

Section 6 describes the main reasons why complete automation has turned out to be challenging in the manufacturing planning area. This section also describes emerging technologies that are expected to further enhance the level of automation in the manufacturing planning area. Finally, we conclude this section by describing productivity enhancements that can be realized by the development and deployment of fully automated manufacturing planners.

## 2 Planning for Computer Numerically Control (CNC) Machining

The steady advance of automation technologies and geometric modeling has slowly reduced the time required to transform virtual representations into physical components. But while the execution of low level machining instructions has been entirely automated for many years, the generation of the overall strategy (i.e., plan) to transform material from raw stock to final product still requires significant human input. This is because although many individual steps have been mechanized (e.g., tool path generation and collision detection) the design of an overall manufacturing plan still requires engineering judgments and manual inputs. This section reflects on some of the inherent difficulties in manufacturing planning for machining and then identifies the main planning approaches.

### 2.1 Background and Initial Developments

The planning of CNC machining processes is a long established but analytically difficult research problem [1]. At first glance, the task appears quite tractable: machining has a number of easily identifiable subtasks (i.e., setup-fixture planning, tool selection, and cutter path planning) each with clear objectives.

However, 30 years of research has made it apparent that each of these steps requires sophisticated geometric reasoning. Indeed, the magnitude of the computational challenge has not always been apparent because humans infer the properties of shapes (e.g., stability, access, stiffness, etc.) so easily that the assessment often appears trivial until researchers attempt to replicate these processes algorithmically. For example, consider the 3D symmetry; most people could tell at a glance if even a complex component is symmetrical yet computational methods are only now being developed that can match this level of performance [2].

Difficulties also arise because of the strong cross-coupling between the individual subtasks (e.g., tool selection, set-up planning, etc.) that allow every step of the planning process to place constraints on every other. Indeed, almost every planning decision has the potential to require changes in all of the other elements. Consider, for example, the component shown in Fig. 1; the orientation of the pockets dictates the fixture design, which will determine the effective stiffness of the component during machining and limit the length and speed of the cutting tools available to form the “thin-walled” features, whose surface finish tolerance may demand a particular machining path (e.g., taking shallow cuts to avoid tool chatter) [3].

Furthermore, the difficulties of dealing with such a highly non-linear planning task have been exacerbated by the fact that the individual steps of the CNC machining process are each rich in novel computational and reasoning problems. Often machining subtasks (e.g., feature recognition and automated fixture design), because of their inherent complexity, are investigated in relative isolation from the context of the overall planning problems. Although impressive bodies of work are associated with topics such as cutter path generation [4,5], tool selection [6–8], feature recognition [9,10], and fixture design [11–13], the sheer complexity of the challenges inherent in these subtasks has until recently limited the study of the whole.

This is a key observation because the approach taken to designing the subtask changes with the nature of the interface envisaged...
to the wider planning process. Frequently, the stronger the constraints placed on the planning process by the physical context of the available machines, fixtures, systems, tooling, and stock material, the more tractable the planning process is.

When the fully automated (or at least tightly integrated) design to CNC manufacturing systems has been reported in the literature [14–16], their functionality has invariably been achieved by constraining the planning problem. For example, parts can be produced on a specific three axis mill and using a fixed selection of tooling, rather than attempting to solve the generic problems inherent in the subtasks.

This pragmatic approach has allowed a high degree of automation to be achieved going from “model to metal” by propagating the limitations of machine tools up the planning pipeline. The significance of this approach is clear when one considers how it changes the nature of the feature recognition task.

Early recognition systems were designed to simply output a largely symbolic description of a shape to AI planning systems. On simple components, where individual features are isolated from each other, this is a realistic aim and generation of a canonical shape description based on a library of features like “slots” and “pockets” have been frequently reported [17,18].

However, on parts with complex geometry, where features interact the descriptions are frequently ambiguous with many possible interpretations [19] that can easily lead to combinatorial explosions (i.e., as the number of features increases, the combinations that are critical to planning grow exponentially). But a plan requires only one particular interpretation of a shape’s feature content [20] and although researchers have investigated various methods of selecting the best sub-set, it has been demonstrated that the geometric constraints associated with machine tools are a particularly powerful way of constraining the number of choices.

2.2 Current Research. While the development of systems capable of the generative planning of arbitrary shapes is still an active research topic, the linking of planning to specific machines (what we call here Machine-Driven Planning) has proved to be a highly effective method for pruning the number of possible feature interpretations and fixture designs [2]. In essence, this approach changes the feature recognition question: from “where are the pocket features” to “what feature volumes can be associated with this diameter of cutter” [20] or “what feature volumes can be accessed from this direction?” [21] or “how can the raw material be held by this machine’s chuck?” The approach is illustrated by the complex component shown in Fig. 2, where knowledge that the part is being produced on a mill-turn component is used to identify separate milling and turning features. The use of a tool’s kinematics to aid the identification of features has been generalized to notions of a configuration space that support the machining of freeform surfaces [22].

Although Machine Driven Planning appears to have emerged as the most common paradigm in the high precision engineering applications associated with B-rep models, no review of this area can ignore the trend to treat CNC planning simply as a volume clearance problem. This approach (which we refer to as Volume-Driven Planning) attempts to apply a single universal plan to the production of all components regardless of their shape. The method “uses layer-based removal from a plurality of orientations in order to create geometry in a highly automated manner” [23]. However, the price paid for this degree of automation is efficiency and accuracy. Machining is usually carried out by small cutters (to ensure access) that follow something akin to a scanning pattern (i.e., raster pattern) to ensure that all material is removed [24]. Furthermore to enable the use of graphics hardware in calculating access and collisions, the geometry is often represented by faceted models (rather than B- reps with analytical surfaces). This representation inevitably impacts the accuracy with which surfaces can be produced.

The emergence of “machine-driven” planning has been enabled in large part by the dramatic advances in both shop floor communications and the processing power embedded in modern machine tool controllers. Early process planning was frequently conducted in almost complete isolation from the machine tools expected to ultimately “run” the plans generated. Communication was a one-way download of G-codes over RS232 serial lines. In contrast today’s broadband communications allow the capabilities of individual machine tools to be queried, instructions downloaded and executions monitored. The arrival of serious computing power at the machine tool has not gone unnoticed by the industry and efforts like the emerging STEP-NC [20] standard seek to provide a uniform platform for wide spread adoption and development of machine-driven process planning.

In contrast, volume-driven rapid prototyping has been enabled by advances in both computing and machine tool hardware. For example, the use of mesh representations (e.g., STL) allows volume systems to take advantage of dedicated graphics hardware (i.e., GPU) to solve previously difficult to compute questions about access and tooling patterns [25,26].

However, no amount of fast computation would make the approach feasible if multi-axis machining centers had not transformed the planning problem by frequently removing the need for multiple setups. On mill-turn machines, for example, the issues of work holding become secondary to collision avoidance between the tool and workpiece.

2.3 Emerging Directions. Process planning is almost synonymous with the use of simulation to provide offline validation of setups, geometry, and cutter paths. Because of this crucial role, process, visualization has moved from crude wire-frame images to photorealistic renderings of the entire manufacturing process.

Today’s machining simulations reflect a world of rigid solids, which neither deflect nor vibrate under the loads imposed by the cutting tools. Yet in determination of fixture design and surface finish, the stiffness of components is a crucial factor in maintaining control of the process dynamics. Indeed, until physically based simulations of cutting processes are included in planning systems (including swarf, dwell marks, tooth engagement, and cutting fluids, etc), the results of any process plan will only be an approximation that needs to be verified by physical trials [27]. Although the introduction of physical simulation will benefit both volume and machine-driven planning in the long term, there can be immediate benefits. Improved feedback between the machining process

![Fig. 2 Feature interactions on a mill / turn component [10]](http://computingengineering.asmedigitalcollection.asme.org/doi/abs/10.1115/1.4006578)
and planning systems will enable sophisticated error compensation schemes that allow accuracy beyond the nominal capabilities of the machine tool [28,29].

3 Planning for Injection Molding

Injection molding is the most popular process for making thermoplastic polymer parts. It is a near-net-shape manufacturing process that can produce parts with good surface finish and accuracy. The process is suitable for high volume production due to its fast cycle time. Recent advancements also allow injection molding of metals and ceramic parts.

The injection molding community is interested in a high level of planning automation to cut down on lead times. Ideally, one would like to have a one-click mold design tool. Such a tool would automatically design molds after the CAD model of the part has been created, but like CNC machining, this would require a large number of decisions to be made by considering many different options. And again like CNC machining many of these decisions require solving sophisticated computational geometry and optimization problems. Given these considerable challenges it is not surprising that the automation of mold design has received significant attention from the research community.

3.1 Background and Initial Developments. The initial focus in this field was on the automated design of two piece molds consisting of cores and cavity. In order to solve this problem, one had to find a suitable parting direction and parting surface. Advantages in computational geometry and the geometric reasoning area led to early progress in this field. Chen et al. [30,31] related demoldability (i.e., the problem of separating mold pieces from the mold assembly such that they do not collide with each other and with the molded part) to a problem of visibility. Ravi and Srinivasan [32] presented sectioning and silhouette methods for parting line generation. Wong et al. [33] presented a slicing strategy for generating the parting line. Hui and Tan [34] heuristically generated a set of candidate parting directions. Majhi et al. [35] described a method for finding the flattest parting line.

Most of the initial methods were incomplete in the sense that they selected some heuristic directions from which demoldability needed to be verified using some form of geometric simulation. Ahn et al. [36] have given theoretically sound algorithms to test whether a part is castable (and the same conditions apply for moldability) along a given direction and compute all such possible directions by traversing all the vertices, edges, and faces in a spatial arrangement of great circles and arcs of great circles that denote the critical events on a unit sphere. Elber et al. [37] have developed an algorithm based on aspect graphs to solve the two-piece mold separability problem for general free-form shapes. McMains and Chen [38] have determined moldability and parting directions for polygons with curved edges. Recently, researchers [39,40] have also presented new algorithms that utilize programmable graphics hardware to test the moldability of parts.

Often complex injection molded parts include undercuts, patches on the part boundaries that are not accessible along the main mold opening directions [41–47]. Undercuts are molded by incorporating additional components in the molds. These components are called side actions and are removed from parts using translation directions different than the main mold opening direction (also referred as parting direction). In order to design side action, one first needs to recognize undercuts. Therefore, injection mold design automation for complex parts requires solving: (1) the recognition of undercuts and (2) the design of side actions.

Injection molds contribute to mold cost by resulting in an additional manufacturing and assembly cost as well as by increasing the molding cycle time. Therefore, generating shapes of side actions requires solving a complex geometric optimization problem. Different objective functions may be needed depending upon different molding scenarios (e.g., prototyping versus large production runs). Manually designing side actions is a challenging task and requires considerable expertise. Banerjee and Gupta [45] presented an algorithm for generating shapes of side actions to minimize a customizable injection molding cost function.

3.2 Current Research. In order to gain competitive advantages, many companies are utilizing specialized molds that offer new benefits. Therefore, the current work in this field is focused on automated mold design problems for specialized molds.

Multipiece molds can be used to make complex parts that cannot be made by traditional molds. For example, multipiece molding technology overcomes the restrictions imposed by traditional molds by having many parting directions. These molds have more than one primary parting surface and consist of more than two mold pieces or subassemblies. Each mold piece has a different parting direction. A multipiece mold can be visualized as a 3D jigsaw puzzle, where all the mold pieces fit together to form a cavity and then can be disassembled to eject the molded part.

Chen et al. [48] presented an algorithm to solve multipiece mold design problem. They divide multipiece mold design process into two steps. In the first step, the object boundary is subdivided into smaller regions that will be realized by different mold pieces. The parting direction is found for each mold piece region by solving a linear optimization problem. During the second step, all mold pieces are created.

Priyadarshi and Gupta presented geometric algorithms for automated design of multipiece molds [49]. Their algorithm automates several important mold-design steps: finding parting directions, locating parting lines, creating parting surfaces, and constructing mold pieces. This algorithm constructs mold pieces based on global accessibility analysis results of the part and therefore guarantees the disassembly of the mold pieces [50].

In some situations, mold pieces can be sacrificed after the molding process to extract the part. Huang et al. [51] described an algorithm based on accessibility-driven partitioning approach to design multipiece sacrificial molds.

Multipiece mold design problems are computationally very challenging. Existing techniques work well if the number of mold pieces in the final solution is relatively small. These problems have close resemblance to the set cover problem and hence finding the optimum solution appears to be challenging due to the underlying combinatorics. However, a formal complexity analysis has not been published for these problems.

Multistage molding (also called multishot molding) has several advantages over traditional techniques that involve molding the components separately and then assembling them to create products. It allows integration of functional elements, thereby reducing the number of components and additional assembly steps. Multistage molding process involves sequential injection of multiple different materials in the mold. During this process, the mold cavity shape is altered after each injection stage.

Kumar and Gupta [52] presented the first algorithm to design multistage molds for producing multimaterial objects. Li and Gupta [53] extended this work. They presented a geometric algorithm for automated design of multistage mold designs for rotary-platen process. Yin et al. [54] proposed an algorithm to automatically generate a sequence of mold stages to produce a multimaterial object. None of these algorithms considered the molding of articulated assemblies. Priyadarshi and Gupta have presented an algorithm for generating a molding plan for an articulated assembly to be produced by multistage molding [55].

3.3 Emerging Directions. Previous sections mainly focused on the mold design problems that are purely geometric in nature. Another important area in injection mold design has been cooling channel design and runner system design. Both of these areas benefited significantly from the incorporation of physics-based simulations during the mold design.

The runner system is an important component of injection molds. The main function of the runner system is to supply mold
cavities with a molten polymer from the injection nozzle. Multiple cavity molds are used for injection molding of (1) many parts from a single shot to increase productivity and/or (2) parts with cavities separated by preloaded inserts for in-mold assembly applications. The main design consideration for the runner system is to achieve balanced flow. A balanced flow results in reduced variations in pressure and temperature in all cavities at the end of filling phase. Recent work in the runner system design is focused on combining flow simulations with optimization.

In many approaches, a parametric model of the runner system is used and often evolutionary optimization techniques (e.g., genetic algorithms) are used to identify the parameters of the runner system (e.g., diameters and lengths). Advances in the flow simulation area have significantly advanced this field. Recent representative work in this area includes [56–57]. However, current work in this field tends to be specialized to handle only certain types of constraints and criteria. Significant progress needs to be made in this area to handle complex runner systems used in industry and a wide variety of constraints encountered in the industry.

Typical polymers used during the injection molding have poor thermal conductivities and hence time to solidify is an important factor in the overall cycle time. In order to reduce the cycle time, cooling channels are used in the molds. These channels provide active cooling to ensure that the molten material in the molds solidifies quickly to prepare the parts for ejection. The design of cooling channel is an important aspect of the mold design. The design decisions include the number of channels, the size of channels, and how these channels are routed through the mold. Significant advances have been made in this field due to the use of detailed heat transfer simulations. Recent representative works in this field include [58–60]. Current approaches impose significant restrictions on the runner configurations. Current simulation methods also make a number of simplifying assumptions. Hence, this area has a significant room for making further progress.

4 Planning for Sheet Metal Bending

Sheet metal products are often hidden under plastic covers, and they provide rigid support for attaching and shaping complex products, such as the internal frame of a computer workstation. The production of sheet metal parts begins with a flat sheet where many parts are nested into something that looks like a jigsaw puzzle. Laser cutters or automated punching machines then cut out the individual pieces out of the flat sheet, which then is the flat pattern for sheet metal bending. Rapid progress was made on the layout of these flat parts (e.g., automated nesting) and the automated cutter paths to extract the patterns from the flat sheets. It was a 2D problem and many academics were attracted by the problem of optimizing material utilization in the flat parts (e.g., nesting as many parts as possible in as few sheets as possible). For example, researchers attempted to optimize the nesting of rectangular shapes into given bounded blanks [61]. This work continued to evolve into systems that allowed the nesting of more and more irregular shapes [62].

Researchers also began to investigate planning problems in the production of sheet metal parts. Planning problems in sheet metal area can be classified into two categories. The first category deals with general sheet metal operations, including punching, stamping, drawing, and bending [63–65]. The second category deals with only bending sequences and the details of their operation [66–68], which is our focus in this paper.

4.1 Background and Initial Developments. The sheet metal bending problem deals with transforming a flat sheet into a 3D shape by performing a sequence of bending operations. Research progress on planning and automatically producing the final 3D bent parts has proved to be a much harder problem than 2D nesting, because of the radical differences in intermediate geometries that can be produced.

4.2 Current Research and Emerging Directions. The state of planning automation is relatively high in the sheet metal bending area, but the recent research activity has been confined to a few groups. However, this area does have potential for improvements.

So far, we have discussed problems in sheet metal bending that are simply based on intermediate geometries of a part and the relative geometries of the tools and the bending machine itself. However, “real” sheet metal bending is characterized by many difficult process dynamics. While there has been significant research progress in each area, effective solutions (i.e., time, money, and shop floor practicality) remain open concerns. These process considerations include the following topics:

- **Parts droop during handling:** Large sheet metal parts elastically bend during handling. This is a relatively easy problem...
when a human is handling the parts, but is extremely difficult when a robot is handling the same part, because the part is “flopping” around during very precise handling maneuvers. Understanding the effect of drooping is further complicated when parts have narrow “necks” of material, which can plastically bend during handling, which can destroy the part.

- Parts slip during handling: During automated production of parts there is a huge emphasis on making the parts as quickly as possible. When a robot gripper is handling a large flat part and twisting it high speeds, it is quite easy for the part to slip in the robot gripper. This issue is exacerbated because sheet metal is typically coated with a thin layer of graphite lubricant, which is intended to prevent parts from sticking together in a stack.

- Bends spring-back after the bend operation: After a bending machine has made a particular bend some component of the bend is elastic (springs-back) and some component is plastic (permanent bend). In order, to produce the correct bend angle the spring back must be anticipated and purposefully over bent or alternatively the spring back must be measured and re-bent to produce the correct angle.

- Bends cause the material to stretch: This issue causes great confusion between the flat part design (e.g., dimensions) and the final 3D design (e.g., total dimensions) because the process is also changing the size of the original part. This has many ramifications in even simple designs, for example, consider an open box shape with four bends and where the corners are bent up into a tight configuration (e.g., almost water tight at the corners). Unless the bends are inset with relief holes at the corners, the flanges will not meet after the part stretches during bending.

In addition to the above mentioned problems that occur during bending, product designers introduce their own problems. Common sense suggests that the part should not collide with the tool or the bending machine. But in fact this is not the case. Often designs (e.g., flange heights) are pushed to an extreme so that a flange may actually hit the tool and elastically bend during the collision (not plastically bent). In other words, designers know that they can get away with certain kinds of collisions without damaging the part and/or tools and they often push their designs to these limits.

Figure 4 illustrates this point with a part has 7 bends and most notably requires two radically different shaped tools to complete the part. Figure 4(a) illustrates how an extreme “goose-neck” tool is required to access the featured bends (red circles). Often these flanges actually touch the tool, which can render the part “unbendable” for a simplistic planner. Figure 4(b) shows the necessity to use radically different tool geometries to access bends with very different surrounding geometries. Automatic planning systems face the paradox of having to choose tools before the final bend sequence is selected and choose the bend sequence before the best tools can be selected. Thus, the systems must solve the effective geometric constraints of both tools and bend sequences simultaneously.

In some instances, there are no tools available in a facility to make particular bends that accommodate complex geometrical constraints and therefore they must be purchased from a tooling supplier or changes in the design must be made to accommodate tools that are available. Surprisingly, even simple parts have some production challenges that must be carefully designed away or purchased away. The goal of an automated planning system is to automatically configure the machine tool’s setup including all the tools for making the part. In addition, the system must also determine the production steps that are necessary and their necessary sequence. In the recent past, most (or all) of these steps were carried out manually.

5. Planning for Mechanical Assembly

Mechanical assembly planning, like the manufacturing technologies discussed in previous sections, covers a range of topics linked by common subtasks. So regardless of whether the automation is implemented by dedicated machinery, reconfigurable robotic arms or manually by workers carrying out computer generated instructions the same issues of tooling (i.e., gripper/feeder/jig design), gripping, sequencing, and collision free path planning are present. Once again each of the tasks places constraints on the others so, for example in robotic assembly, the choice of gripping features is strongly linked to the design of the gripper used, as is the clearance required to insert the component in the path planning phase.

There are also similarities with the other planning tasks in that reported work has focused on geometric aspects of the problem (e.g., clash detection, automatic identification of assembly sequence constraints in the geometry), there are other physical phenomena involved in the process which have been investigated largely in isolation (i.e., stiffness, dynamic forces, and dimensional tolerances).

5.1 Background and Initial Developments. Automatic assembly sequence planning has been a research topic since the early 1980’s. The assembly process starts from a configuration where all the components are completely disassembled and the last assembly operation leads to the final product. An assembly sequence plan specifies the order in which parts and subassemblies are to be inserted into each subassembly. The overall goal of research in this area is the automatic generation of an efficient and feasible assembly sequence plan rather than an optimum one.

The early assembly sequence planners were mainly interactive in nature. Geometric constraints were supplied by a human, interactively, by answering a series of questions asked by the computer. One such system was described by Fazio and Whitney [75]. Automated geometric reasoning was later used to answer these questions automatically. These approaches generated several candidate assembly sequences and tested their feasibility by applying...
geometric reasoning. But these approaches tend to generate a large number of candidate assembly sequences and repeat the same geometric reasoning process many times. Attempts were also made to store and reuse previous computations and in some cases new assembly representations were used that implicitly reduced the number of geometric computations.

The work by Wilson and Latombe [76] used nondirectional blocking graph (NDBG) representation, which implicitly contained the geometric constraints. A NDBG was automatically generated from the input geometry of the product by applying geometric reasoning. Woo and Dutta [77] generated disassembly sequences by modeling disassembly as an “onion peeling” procedure where one starts from the boundary components and works inward using the disassembly tree. An algorithm for component disassembly was developed and used to perform disassemblability analysis of a component from an assembly or subassembly. This algorithm only considers disassembly of 1-disassemblable subassemblies. Beasley and Martin [78] developed an algorithm for 2-disassemblable subassemblies. Milner et al. [79] presented an algorithm for finding the optimal assembly sequence.

Homem de Mello and Sanderson’s [80] model of assemblies include attachments, which describe fastening methods. Four types of attachment are considered: clip, pressure, screw, and glue. Even though the attachments can be used to generate disassembly sequences, the detailed tool movements required to carry out these attachment are not modeled. The first detailed work on tool selection was reported by Wilson [81]. Wilson developed a tool representation that includes the tools use volume, i.e., the minimum space that must be free in an assembly to apply the tool. Gupta et al. [82] presented a detailed approach for modeling tools, selecting tools, and generating tool movements. Their work allowed tools to be modeled as articulated devices.

5.2 Current Research and Emerging Directions. Assembly planning requires geometric analysis to ensure collision free movements and the identification of gripping points that allow robust pickup and insertion. At a high level, these tasks might be considered analogous to the cutter path planning and feature recognition systems used by CNC machining systems, but the differences are significant.

While gross motion planning (navigating in the environment) shares some similarities with the need to provide collision free movement of cutting tools the fine motion planning (where parts are near or in contact with other parts) need to be handled in fundamentally different ways. Indeed, gross motion planning in automated assembly is no different than any other kind of free space robotic navigation [83], while fine motion planning is often tightly coupled with sensor based control.

Similarly while the recognition of assembly features share several philosophical similarities with machining, the details mean a distinctly different approach is required. The common aspect is that the features seek to identify the reflection of tooling geometry on a component, in machining this is the size and form of a cutter, while in assembly this is the shape of the gripper’s contact points (e.g., fingers) or mating geometries. However, while machining features are located on a single physical object, assembly features are frequently associated with the relative position of two of more separate components (e.g., a key and keyway). So, identification requires the analysis of assembly models rather than individual geometric models [84].

Driven by the commercial importance of assembly work and the advent of industrial robotics in the 1980s (despite the limited computing power available when a single collision check could take 30 minutes) produced a large body of academic work on issues of CAD/CAM for assembly. However, the assembly planning area is commercially not as mature as the other three areas described in this paper (e.g., lack of commercially available tools). The contributing factors for this observation are as following. First, most low volume assembly is done manually. So most planning steps are performed by human operators (perhaps with the exception of assembly sequence generation). In this case, there is no value in generating detailed motion plans for parts being assembled by human operators. Design for assembly usually ensures that only one standard tool (e.g., screw driver) can be used to perform an assembly operation. So, the tool selection problem is not that complex in practice. On the other hand, most high volume assembly is done on specialized equipment. Therefore, performing assembly planning without a detailed equipment model is not feasible. Also, the assembly planning cost is relatively low compared to the cost of designing and constructing the specialized assembly cell. In this case, the equipment designers often perform the assembly planning themselves.

Assembly process planning is an area which is being reinvigorated by changes in the computational resources, industrial environment, and commercial need. Recent research motivation comes from high value products (e.g., aerospace, medical, and automotive) where automation in clean room environments or high volume lines continues to provide motivation. The results are also finding new application in the growing industrial interest in the prospects of automated disassembly for recycling and remanufacture [85]. This coupled with the availability of dedicated graphics hardware that support near real time collision detection [86] are providing continuing impetus for this important subject.

Trends in industry are changing and interest in automated assembly appears to be gaining momentum. High volume products have shorter and shorter product life cycles and increased business opportunities. Consider the current war over dominance in the smart cell phone market. Each version and style of cell phone only lasts 3 to 6 months before it is pushed aside by the next version. The result is that assembly lines have to rapidly designed, programmed and deployed before the competition moves their products to market first. The exterior styles change as well so that the latest versions can be easily spotted and seen as the latest in a “cool gadget.” While there may be only a few software additions to a phone, the change in the body can cause havoc in assembly lines.

Assembly planning area has many open problems. Currently, the assembly planning community uses the following representation: (1) B-Rep, (2) facetted representation, and (3) voxel-based representations. Each of these representations has its strengths and weaknesses. Simpler representations (e.g., facetted and voxel-based) enable simple geometric test. But the large number of elements in these representations leads to a very large number of geometric tests. On the other hand, exact geometric representations (e.g., B-Reps) leads to very complex tests. We believe model simplification can be a very useful preprocessing step to eliminate the unnecessary details from the model to facilitate efficient assembly planning.

Once parts are modeled appropriately for automated planning, we must again turn to the physical characteristics of parts. These characteristics determine what robot motions are required during assembly and what the most appropriate sensor feedback is to control (e.g., force, vision, acoustic, or absolute position). Many parts are very soft and very small (e.g., rubber buttons and joystick covers), while other parts are relatively large and rigid (e.g., metal internal PC frames and exterior plastic covers). A part’s rigidity and size strongly determines the method of assembly as well as the necessary tools. Hence, assembly planning systems needs to look beyond pure geometric reasoning to generate correct assembly plans.

A fine motion plan or the “the last inch” of motion is also a key and open step in automated assembly. Two parts need to be brought together and attached and these two key steps are often dependent. For example, some parts are simply screwed together. In this case, the parts must be held rigidly relative to each other. A different pair of parts may be snapped together with specially designed snapping features. In this case, one or both of the parts is expected to elastically deform during and initial motions and then with one or both parts snapping back to original position (final
assembly state). Humans use force feedback in the initial phases of assembly and then depend on acoustic information to hear when the assembly step is complete. Hence, future assembly planning systems need to be integrated with a wide range of sensors.

Once attachments have been made it is critical to determine whether an attachment step has been successfully completed. Some researchers have used support-vector-machines to automatically learn the differences between success and failure [87] in an assembly step. Once trained these decision rules can be used to quickly determine whether a successful attachment between parts has been made. The inability to make a rapid success-or-failure determination can lead to adding valuable parts to a “junk assembly,” which wastes both time and money.

6. Conclusions

Our analysis shows that significant progress has been made in the automated manufacturing planning area over the last 30 years. All of the manufacturing domains reported in this area have benefited from the use of AI techniques, geometric modeling, computational geometry, optimization, and physics-based modeling. Although commercial software tools are available to support specific aspects of the planning task in all the manufacturing domains discussed the process still requires human input for all but for most of the planning problems.

The manufacturing planning problem has turned out to be harder than envisioned in the early days of this field. The reasons for this are as following: (1) Decomposition of the planning problem into a number of simpler independent steps is difficult because decisions made in one step significantly influence decisions made in all other steps. So, one is confronted with a challenging planning problem that cannot be easily decomposed. (2) The combinatorial nature of the decisions makes the overall computational complexity of manufacturing planning problem extremely high. So in many cases, solving hard problems automatically appears to be computationally intractable. (3) Most manufacturing domains lack computationally fast, accurate physical simulations that can be used during the solution search process. This means that solutions identified by the planning process may not be feasible and hence human input becomes inevitable. (4) To make the planning problem tractable requires bounding the search space. Human planners often think out-of-the-box on hard planning problems. They effectively transform a planning problem into a design problem. And unfortunately, automated design problems are even harder than automated planning problems.

However despite these difficulties, we believe that following emerging technologies will be useful across all the manufacturing planning applications:

- **Physics-Based Modeling**: In every one of the production technologies discussed, research into automated planning is in the process of moving beyond rigid geometric models to consider other physical effects that impact on the viability of plans. For example in CNC machining, cutting forces and component stiffness are currently ignored; in mold design, the thermal efficiency of the cooling channels was overlooked; in sheet metal bending, the elasticity of components will determine the feasibility of tool design and in assembly planning the friction between a gripper and parts must be considered. The next decade is almost certain to see the integration of physics-based modeling into manufacturing planning for many processes [88].

- **Exploitation of Dedicated Hardware**: Collision detection and accessibility assessments have been seen as fundamental to every manufacturing planning application discussed. In the near future, we expect GPU utilities to play a bigger role in mainstream planning systems. In a similar way, it is likely that the slow, standalone FEA and CFD simulation of manufacturing processes will eventually be run directly on the physics hardware emerging to support computer games (e.g. Nvidia PhysX™ processor). Consequently, we believe that both physical and geometric reasoning will be available to manufacturing planning systems via dedicated hardware.

- **Feedback**: The idealized geometry of the virtual world does not have to be separate from the physical reality of the factory floor. Networked machines will enable digital feedback on the accuracy of cutters, the distortion of molded parts, the spring back of sheet metal, and the insertion forces of assembly components. This data will allow real time error correction of the perfect (or nominal) geometry used to generate the plan. In this way, manufacturing plans of the future may no longer be read-only instruction sets but rather intelligent applications able to adapt and modify themselves to account for local conditions.

- **Tolerances**: In all the processes studied, the dimensional tolerances of a component are key considerations that implicitly define the engineering functionality of that component. Yet, there is little formal support for the geometric representation or reasoning of geometric uncertainty beyond the nominal dimensions of the geometric models. While much of the recent technical momentum in manufacturing planning appears to be heading away from B-rep modeling toward mesh based representations, we believe B-reps might continue to occupy a central role in precision manufacture because of their ability to support dimensional and surface tolerance information.

It is interesting to note that all the above are specific examples of general issues discussed in the recent WTEC review of engineering simulation [89] which drew the following conclusions:

- **Interoperability of software and data are major hurdles.**
- **In most engineering applications, algorithms, software, and data are primary bottlenecks.**
- **Visualization of simulation outputs remains a challenge.**
- **Experimental validation of models remains difficult and costly.**
- **Uncertainty is not being addressed adequately in many of the applications.**
- **Links between physical and system level simulations are weak.**

We believe that the availability of fully automated planners will increase manufacturing productivity through:

- **Short Product Life Cycles**: Removal of the planning bottleneck will make it economic for more commercial products to have shorter life cycles due to reduced production lead-time and costs.

- **Small Batch Sizes**: Automated planning systems would make it feasible to produce small batches of parts at unit costs comparable to large batch runs. Thus, the technology would help facilitate the just-in-time manufacturing objectives being demanded in virtually every industry that produces potentially customizable products.

- **Improved Process Scheduling**: When the basic parameters of a component’s manufacturing process (e.g., materials, time, and cost) can be rapidly determined, these can be used to develop more efficient factory schedules.

- **Enhanced Sales and Marketing**: Lastly, a significant competitive advantage is enabled by being able to offer a customer an accurate and timely price/delivery quote that in the end depend on all the above details. At the same time, this helps to guard against quotes that are under cost (i.e., loss instead of profit).

Acknowledgment

S.K. Gupta’s participation in this paper was enabled by NSF Grants CMMI-0727380, DMI-0457058, and OCI-0636164. Opinion expressed in this paper are those of the authors and do not necessarily reflect the opinions of the sponsors.
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