Putting the Turing into Manufacturing: Recent Developments in Algorithmic Automation

[Invited Keynote: Extended Abstract]

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ABSTRACT

As global labor costs increase and product life cycles decrease, there is renewed interest in research in automated manufacturing systems that can be reliably and rapidly configured. Inspired by Turing's abstractions for computing, *Algorithmic Automation* explores mathematical abstractions and algorithms that allow the functionality of assembly lines and manufacturing automation systems to be designed independent of their underlying implementations. Abstractions based on minimal sets of geometric primitives can provide the foundation for formal specification, analysis, design, optimization, and verification. Algorithmic Automation is characterized by: (1) formal specification of sets of admissible inputs (eg, polyhedra) and operations (eg, parallel-jaw grasps), (2) complete algorithms that compute all solutions or terminate with a report that no solution exists, and (3) bounds on complexity as a function of input size. This extended abstract summarizes selected results and open problems.

Categories and Subject Descriptors

I.2.9 [**Computing Methodologies**]: Artificial Intelligence—*Robotics*

General Terms

Algorithms,Performance,Reliability

Keywords

Automation; Manufacturing; Feeding; Fixturing; Grasping; Caging; Probing

1. INTRODUCTION

Manufacturing automation today is where computer technology was in the early 1960's: a patchwork of ad-hoc solutions lacking a rigorous scientific methodology. Computer-Aided Design (CAD) provides detailed models of part geometry but what is missing is a framework for the systematic design of automated assembly systems that handle parts (e.g. feed, sort, fixture, assemble, and inspect them).

Assembly lines employ a finite set of deterministic elements that perform specific physical actions (pushing, squeezing, turning, grasping, etc). This suggests that assembly automation may be amenable to composition by a set of minimal primitives for formal specification, analysis, and synthesis [6]. Algorithmic results in robotics and automation often apply results from computational geometry are presented at symposia such as the biannual Workshop on Algorithmic Foundations of Robotics (WAFR) [22, 23] and in publications such as the IEEE Transactions on Automation Science and Engineering (T-ASE) [13].

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2. ALGORITHMIC PART FEEDING

In manufacturing, parts often arrive in bags or boxes; an important function is *part feeding*, where such parts are precisely oriented prior to assembly or packing. A variety of clever mechanical techniques such as vibratory bowl feeders have been used for over a century, but these are designed ad-hoc by a rapidly diminishing cadre of specialists. A challenge is to develop algorithmic approaches that can take as input a CAD model of the part and generate as output a sequence of operations from a specified set that will feed the part (or a report that no such sequence exists). This problem was studied by Natarajan [26] and Eppstein [12], who reduced a version of the problem to that of finding reset sequences for monotonic deterministic finite automata.

In [15], I proposed a mechanical approach to orienting polygonal parts using sequences of open-loop grasp operations with a modified parallel-jaw gripper [16]. I presented an algorithm for computing an optimal sequence of grasp operations and showed that there always exists a sequence of operations that is guaranteed to orient any part (up to symmetry). I conjectured that $O(n)$ operations are sufficient for an n-sided polygon; Chen and Ierardi proved this conjecture in [8]. It was later shown that the complexity can be bounded by a constant that is a function of the geometric eccentricity of the part's bounding box [43]. The algorithm was generalized to algebraic parts [31], and applied to designing of an optimal sequence of mechanical fences on conveyor belts [45] and design of vibrational sequences for orienting micro-scale parts in parallel [4]. There is also work on algorithmic approaches to vibratory bowl feeder design [2, 1, 14] but a complete algorithm for feeding 3D parts, even polyhedra, is still an open problem.

3. ALGORITHMIC PART FIXTURING

Similar to robot grasping [25], *fixturing* is the problem of immobilizing a part with a set of contact points, often subject to higher forces and not restricted to points reachable by a hand. It has been known since the nineteenth-century that 4 contacts are necessary in the plane, (7 for 3D) and a variety of models and metrics have been studied for immobilizing [35, 39, 3] and caging (finding sets of points that don't necessarily immobilize but restrict an object from escaping) [34, 42, 41, 37].

Bud Mishra first considered the problem of fixturing with modular components [24]. Randy Brost and I developed a complete algorithm for finding sets of fixtures for a given polygonal part using three circular locators and a clamp on a regular lattice [5] and the negative result that an infinite set of polygonal parts cannot be fixtured in this manner [46]. Variations and extensions have been explored including fixturing with edge locators [44], with unilaterial contacts [18], fixturing deformable parts [19], fixturing a set of hinged polygons [9, 36] and fixturing with redundant contacts as a submodular coverage problem [38].

4. OPEN PROBLEMS IN ALGORITHMIC AUTOMATION

Many open problems arise when sensors are considered (eg, shape from probing) [6, 11] and when operations are treated as nondeterministic [40, 10, 29]. Tolerance modeling remains a fundamental open issue. The most common tolerance model specifies that part geometry must fit within a geometric zone between two bounds: the least and greatest "material conditions" [32, 33], This model permits arbitrary shape complexity within this zone and hence is extremely difficult to analyze; researchers have assumed instead linear edges between vertices that are restricted to individual tolerance zones [27, 7]. A variant on the latter approach is to use statistical sampling of shape [20], which is facilitated by parallel-computing but is not complete. A rigorous tolerance model based on computational geometry would be extremely valuable.

Widespread access to the Internet and "Cloud Computing" can provide access to parallel computation, large data sets [21, 17] and to open-source software and benchmarks for [28, 30]. The data structures and algorithms being contributed to the open-source Computational Geometry Algorithms Library (CGAL) implement Minkowski sums, offset polygons, Voronoi diagrams, and Delaunay triangulations that are valuable tools to guarantee correctness of algorithmic automation implementations [13].

5. SUMMARY

Algorithmic Automation explores mathematical abstractions and algorithms that allow the functionality of assembly lines and manufacturing automation systems to be designed independent of their underlying implementations. Abstractions based on minimal sets of geometric primitives can provide the foundation for formal specification, analysis, design, optimization, and verification. Algorithmic Automation is characterized by: (1) formal specification of sets of admissible inputs (eg, polyhedra) and operations (eg, parallel-jaw grasps), (2) complete algorithms that compute all solutions or terminate with a report that no solution exists, and (3) bounds on complexity as a function of input size. Much remains to be done.

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http://goldberg.berkeley.edu/algorithmic-automation/.

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