2nd Year Summary Report to
Howard Moraff, Program Director,
National Science Foundation,[1]
on Award IRI-9123747:

Reduced Complexity Manipulation with the Parallel-Jaw Gripper

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Although parallel-jaw grippers are widely used in industry, conventional wisdom holds that they lack versatility. We propose to develop geometric algorithms for orienting and recognizing parts using these grippers and to demonstrate the results with a practical system for handling industrial parts. - from the proposal for Award IRI-9123747.

During the second year of this project, we have published extensively and initiated a collaboration with two Silicon Valley companies that will apply past and future research results to a commercial parts feeding system. In this report we summarize teaching and research accomplishments during Year 2 and list publications that were written with the support of the National Science Foundation.

1 Summary of Student and Teaching Accomplishments

Two continuing PhD students, Duk Kang and Jeff Wiegley, are making good progress. Duk's thesis proposal on empirically-based grasp strategies was accepted in December 1993 and Jeff was screened into the PhD program. We are pleased that another continuing PhD student, Kyeonah Yu, has rejoined us after a one-semester maternity leave. Three new PhD students have joined the group: Yan Zhuang was a Mathematics student who transferred into CS, and Hadi Moradi and Xioa Huang are EE students. In addition, Ed Rowe, an undergraduate, and Chong Nguyen, a high-school student, did research in our lab.

The major teaching development this year was a Technology Reinvestment Project Award of $4,000,000 to a consortium of five L.A.-Area univerisities to develop new curricula for undergraduate education in Manufacturing. I am part of the USC team, and am developing a new course entitled "Robotics and Sensing For Automated Assembly", which will introduce several of the algorithms developed under Award IRI-9123747 into the undergraduate classroom.

2 Summary of Research Accomplishments

The work that established a basis for this project was published in August 1993 [1]. Since then, research groups at Cornell and Stanford have initiated independent projects based on the results in that paper.

At the SPIE conference on in September 1993, I presented a paper on using a parallel-jaw gripper to *position* parts (past work used the gripper to orient parts) [6], and gave an invited tutorial on "New Developments in Feeding, Fixturing, and Grasping". In October 1993, I was fortunate to be invited to attend the 6th International Symposium on Robotics Research where I presented a summary of work funded under this Award [7].

Working via the Internet with Dr. Anil Rao, who is now a postdoc at University of Utrecht, we extended the planar part feeding algorithm to the large class of *algebraic parts*, those whose convex hull can be described by algebraic curves. In December 1993, we submitted an article on this result to the IEEE Transactions. Two of our earlier articles appeared in journals this February. One described an $O(n^2 \log n)$ algorithm for finding plans to discriminate between a set of given polygonal parts with an instrumented parallel-jaw gripper [8]. The other described an $O(n \log^2 k + k^4 \log k \log^* k)$ algorithm optimally locate a "registration mark" on an n-sided part subject to k planar transformations [9]. In January 1994 I attended the NSF Grantees Conference at MIT where I presented a poster [10] describing progress during Year 1 to members of the Engineering Directorate.

During the Fall, I worked with Jean-Claude Latombe, Randy Wilson, and Dan Halperin to organize the 1st Workshop on the Algorithmic Foundations of Robotics (WAFR) which was held in San Francisco in February 1994. The workshop brought together 52 leading researchers from Robotics and Computational Geometry. I presented a paper on "Completeness in Robot Motion Planning" which will appear in an edited volume later this year [11]. In March 1994, I co-chaired a AAAI Workshop on Manipulation at Stanford and presented a paper on Reduced Intricacy and Sensing and Control (RISC).

A major development this year was a partnership with Brian Carlisle, President and CEO of Adept Technology, to develop a commercial part feeding system based on a SCARA arm with integrated vision system. In a series of discussions, we designed a modification to the parallel-jaw gripper that would permit efficient operation of a programmable parts feeder. In this approach, parts are initially singulated on a conveyor belt by random scattering. They are then identified by machine vision and reoriented by the modified gripper into a desired final pose. In June of 1993, Adept and USC filed a joint patent application for the modified gripper. We presented the design to a group of 130 experts at an RIA workshop on Flexible Part Feeding in October [12]. Since then, several companies have expressed interest in this work, including General Motors, AT&T, Motorola, Eastman Kodak, and McDonnel Douglas.

To rapidly configure such a system, we are exploring algorithms to predict the distribution of stable poses under the influence of gravity. and to plan reorientation strategies for the gripper. This will an important subject of research in the coming years. We have also initiated collaborations with John Craig at Silma and David Kriegman at Yale.

In the past year I visited UCLA, the Technical University of Berlin, Sandia National Labs, Lehigh's Iaccoca Institute, and NASA to give research talks on the work supported by Award IRI-9123747.

We have now dubbed our lab the "Automation Design Laboratory". The bulk of our equipment budget was expended during Year 1 for the purchase of an Adept 604-S robot system. This year we purchased a 486 PC to support research on interface of commercial CAD models (AutoCAD) to robot motion planning algorithms. With the remaining equipment budget, we plan to purchase memory for Prof. Ram Nevatia's IRIS Indigo, which he has graciously agreed to let us use as a platform for Silma's CIMstation as part of the collaboration with Adept.

Next month, at the IEEE International Conference on Robotics and Automation, our group will present 4 papers [2, 3, 4, 5]. Based on a suggestion by Howard Moraff, I also organized a workshop on "Design of Parts and Devices for Automation" which will be held in conjunction with the Conference (see enclosed).

During the third year of the Award, we expect to make progress toward the goal of of "developing a practical system for handling industrial parts." In Fall 1994, I will take a "mini-Sabbatical" in the the Bay Area to work closely with Adept and Silma, as well as with colleagues at Stanford and UC Berkeley. NSF Award IRI-9123747 continues to be a primary source of funding for the Automation Design Lab.

We are now planning for the 1994/95 fiscal year and beyond so as to maintain our momentum in this highly productive research area.

(K.Y.G. – Los Angeles, CA – 21 April 1994)

Many of the papers published in the past year with support from Award IRI-9123747 are collected in [13].

References

[1] Ken Goldberg. Orienting polygonal parts without sensors. *Algorithmica*, 10(2):201–225, August 1993. Special Issue on Computational Robotics.

[2] Brian Carlisle, Ken Goldberg, Anil Rao, and Jeff Wiegley. A pivoting gripper for feeding industrial parts. In *International Conference on Robotics and Automation*. IEEE, May 1994. Also available as USC Techreport IRIS-93-316.

[3] John Canny and Ken Goldberg. “RISC” for industrial robotics: Recent results and open problems. In *International Conference on Robotics and Automation*. IEEE, May 1994. Also available as USC Techreport IRIS-93-315 and via anonymous ftp from 128.125.51.19 under pub/Tech_Rept/Iris/1993/IRIS_93_315.ps.Z.

[4] Randy Brost and Ken Goldberg. A complete algorithm for synthesizing modular fixtures for polygonal parts. In *International Conference on Robotics and Automation*. IEEE, May 1994.

[5] Yan Zhuang, Yin-Chung Wong, and Ken Goldberg. On the existence of modular fixtures. In *International Conference on Robotics and Automation*. IEEE, May 1994. Also available as USC Techreport IRIS-93-314.

[6] Amir Mottaez, Murilo Coutinho, and Ken Goldberg. Positioning polygonal parts without sensors. In *Sensors and Controls for Automated Manufacturing Systems*. SPIE, September 1993.

[7] Ken Goldberg. Feeding and sorting algorithms for the parallel-jaw gripper. In Takeo Kanade and Richard Paul, editors, *Robotics Research: The Sixth International Symposium*, 1993.

[8] Anil Rao and Ken Goldberg. Shape from diameter: Recognizing polygonal parts with a parallel-jaw gripper. *International Journal of Robotics Research*, 13(1), February 1994.

[9] Anil Rao and Ken Goldberg. Placing registration marks. *IEEE Transactions on Industrial Electronics, Special Issue on Industrial Robotics*, 41(1), February 1994.

[10] Ken Goldberg. Dextrous manipulation with the parallel-jaw gripper. In *Design and Manufacturing Grantees Conference*, January 1994. (Proceedings published by the Society of Manufacturing Engineers).

[11] Ken Goldberg. Completeness in robot motion planning. In *Workshop on the Algorithmic Foundations of Robotics*. A. K. Peters, 1994. San Francisco, California.

[12] Ken Goldberg. Removing the ‘black art’ from part feeder design. In *Robotic Industries Association (RIA) Workshop on Flexible Part Feeding*, October 1993.

[13] The parallel-jaw gripper. A bound collection of papers that appeared in 1992/93 and were supported in part by NSF under Award IRI-9123747, November 1993.