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Heuristic algorithms to guide assembly of jet engine rotors to reduce static unbalance have been devised and analyzed.

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GEORGIA INSTITUTE OF TECHNOLOGY

ATLANTA, GA.

FINAL REPORT

February 28, 1998

AFOSR GRANT F49620-95-1-0121

John J. Bartholdi, III and John H. Vande Vate
Co-principal investigators

Georgia Institute of Technology
School of Industrial and Systems Engineering
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2. Objectives

Our primary task was to improve the balance of jet engines by intelligent assembly.

During the final two years we broadened our objectives to include exploration of "self-balancing assembly lines". This was an opportunistic decision to exploit some immediately applicable ideas that emerged tangentially from the current project. We pursued this new topic on two fronts: manufacturing and warehousing.

3. Project status

This is the final report at the conclusion of the project.

4. Accomplishments

We have developed algorithms for building a turbine shaft that is either

- straight (minimizes maximum distance from true); or
- best fits the bearings on which it will rotate.

We studied the deformation of machined, elastic surfaces when bolted together. As is familiar to anyone who has changed a tire, torquing sequence will affect how precisely the surfaces mate. We are identifying what makes a torquing sequence "good" and analyzing heuristics to produce good torquing sequences. In this case, the cost of the heuristic is in the worst-case performance, which must meet certain standards, and in the time to execute the torquing sequence, which determines labor time. When a highly skilled mechanic is torquing hundreds of bolts, the difference in execution cost between an $O(n^2)$ and $O(n^3)$ algorithm can be considerable.

These results will appear in a technical report soon.

We are finishing the evaluation of how our balancing heuristics affect inventory policy and have analyzed several models that predict what levels of blade inventory are required. However, we cannot as yet authoritatively interpret these results for actual practice, as the major manufacturer of blades has been reluctant to share production data with us.

Our main accomplishment has been to devise and analyze heuristic algorithms to guide assembly of jet engine rotors to reduce static unbalance.

Jet engines are assembled by welding or bolting together smaller discs. As a first step in investigating methods for reducing vibration, we focused on the problem of reducing the static unbalance in each disc. One source of unbalance in a disc is differences in the weights of the fan blades sequenced around it. Consequently we began by considering the problem of sequencing the blades around the disc so that their center of gravity coincides with the center of the disc. Unfortunately, this is NP-hard even in its simplest idealization. Nevertheless, we have devised several fast heuristics that have two valuable properties that distinguish them from current practice:

- They come with worst-case guarantees of accuracy that are superior to those possible for current practice.
- They run more quickly than the algorithms of current practice.

In fact, when the number of blades is even, but not a multiple of four, our heuristic provides the strongest possible worst case performance guarantee. In other words, no other procedure can provide a better performance guarantee — not even the hopelessly impractical procedure of trying all possible ways of sequencing the blades.

The performance guarantee of our procedure is expressed in terms of the magnitude of the difference between successive weights of fans. This kind of bound allows us to set the manufacturing tolerances for the blades at exactly the level required to guarantee a specified quality of balance in the final assembly. For example, the sixth stage turbine disc of the Pratt & Whitney PW 2000 jet engine must be statically balanced at a minimum of 900 rpm to within 1.0 ounce-inch without adding counterweights. Our procedure guarantees this quality of balance if the difference between successive weights is no more than 0.08 ounces. To provide the same guarantee when the blades are sequenced according to current practice, the difference between successive weights must not exceed 0.008 ounces, a manufacturing tolerance that is an order of magnitude more demanding. Thus, intelligent assembly allows the manufacturing tolerances to be relaxed significantly while guaranteeing the same performance specifications.

This illustrates the theme of our research: Intelligent assembly can reduce manufacturing costs without sacrificing performance.

Our work produced an interesting insight that may have practical implications: Our procedure has a better guarantee of performance when the turbine disc has an even number of blades---but not a multiple of four. Intuition supports this, at least in retrospect: When there are an even number of blades, we can place opposing pairs so that the resultant unbalances counteract each other...except when the number of blades is a multiple of four, when orthogonal pairs are independent of one another. Of course this effect is less pronounced with more blades; but it suggests that, where possible, turbine discs should be designed to have

5. Personnel supported

• John J. Bartholdi, III	Professor
• John H. Vande Vate	Associate Professor
• Vijay Nori	Graduate Student
• Paul Goldsman	Graduate Student

6. Publications

6.1 Submitted but not yet accepted

J. J. Bartholdi, III and K. R. Gue, "Balancing travel cost and congestion in an LTL freight terminal" (1997).

J. J. Bartholdi, III and D. D. Eisenstein. "Bucket brigades: A self-organizing order-picking system for a warehouse" (1996).

Dai, J., Hasenbein, J. and Vande Vate, J. H., "On The Monotone Global Stability Region of a Three-Station Fluid Network" (1996).

Dai, J., and Vande Vate, J. H., "On the Stability of Two-Station Queuing Networks" (1997).

6.2 Accepted but not yet published

S. V. Amiouny, J. J. Bartholdi, III and J. H. Vande Vate. "Heuristics for balancing turbine fans" (1996).

J. J. Bartholdi, III, L. A. Bunimovich, and D. D. Eisenstein. "Dynamics of 2- and 3-worker `bucket brigade' production lines", to appear in *Operations Research.*

S. Chang, D. Llewellyn, and J. H. Vande Vate. "Two-lattice polyhedra: duality", to appear in *Mathematics of Operations Research.*

S. Chang, D. Llewellyn, and J. H. Vande Vate. "Two-lattice polyhedra: extreme points", to appear in *Mathematics of Operations Research.*

S. Chang, D. Llewellyn, and J. H. Vande Vate. "Two-lattice polyhedra: finding a maximum vector", to appear in *Mathematics of Operations Research.*

6.3 Published

J. J. Bartholdi, III and D. D. Eisenstein. "A production line that balances itself", *Operations Research* 44(1):21–34 (1996), Special Issue on New Directions in Operations Management.

A. Ramudhin, J. J. Bartholdi, III, J. M. Calvin, J. H. Vande Vate, G. Weiss. "A probabilistic analysis of 2-machine flowshops", *Operations Research* 44(6):899–908 (1997).

Dai, J. and Vande Vate, J. H., "Global Stability of Two-station Queuing Networks" *in Stochastic Networks: Stability and Rare Events*, pages 1–26, (P. Glasserman, K. Sigman and D. Yao, Eds.), New York:Springer Verlag (1996).

7. Interactions/Transitions

7.1 Participation/presentations at meetings, conferences, seminars

Ernst & Young Center for Business Innovation, Conference on "Embracing Complexity: A colloquium on the application of complex adaptive systems to business", Cambridge, MA (August 1997), "Bucket brigades: A self-organizing way to share work".

SIAM National Conference, Orem, UT (May 1997). Plenary session: "Bucket brigades in the apparel industry and warehouses".

AU-UAB Miniconference in Dynamics, "Bucket brigades in the apparel industry and warehouses".

INFORMS-San Diego (May 1997), Tutorial on "Self-organizing logistics systems".

The Warehousing Educational and Research Council, Atlanta Chapter (March 1997); "Bucket brigades: A self-organizing scheme for order-picking in a warehouse".

Council of Logistics Management, Chicago Roundtable (March 1997). "Bucket brigades: A self-organizing scheme for order-picking in a warehouse".

"The Stability of Two-station Queuing Networks" with J. Dai. Presented at the 14th Triennial IFORS Conference in Vancouver, B.C., July 1996.

"Tutorial: Global Stability of Re-Entrant Queuing Networks" with J. Dai at the Atlanta INFORMS meeting. November 1996.

"On the Monotone Global Stability Region of Fluid Networks" with Jim G. Dai and John J. Hasenbein at the San Diego INFORMS meeting May 1997.

"Virtual Bottlenecks" with J. Dai and L. F. McGinnis at the SRC Workshop on Process Modeling February, 1997. This meeting included representatives from Intel, National Semiconductor, Texas Instruments and other major semiconductor manufacturers.

7.2 Consultative and advisory functions to other agencies

Results from this research are now a regular part of the following Georgia Tech "short courses" for industry, which are taught to hundreds of practitioners annually:

- "Best practices in logistics", Mexico City
- "Transportation, Distribution, and Warehousing", Atlanta, GA.
- "Advanced Order-picking", Atlanta, GA
- "Best practices in order-picking", Mexico City
- "The Warehousing Short Course", Atlanta, GA.
- "How to design and layout a warehouse or distribution center", Atlanta, GA

7.3 Transitions

Delta Airlines, Technical Operations Center, Atlanta, GA: We have continued to work with Delta Power Plant Engineer Michael Wilson and others responsible for the renovation of Delta's most common jet engines. We are planning how our heuristics for balancing turbine fans can help them achieve better balanced engines and we are exploring how our balancing procedures might affect Delta's strategies for pre-positioning inventory.

United Technologies/Pratt & Whitney. We continue to work with Dr. Leon Seitelman, Senior Research Mathematician at Pratt & Whitney, to integrate our theoretical results into Pratt's production process. We have been in contact almost weekly.

Advanced Design, Inc.: Dr. Kevin Kauth is a turbine design consultant with much experience in design of jet engines. We have talked with him several times about our results. His reactions were very gratifying: He was particularly interested in our idea to avoid designs with a number of turbine blades that is a multiple of four (because of consequent difficulty balancing). He said this idea was new to him and was convincing. He also mentioned that top designers (such as he) frequently based designs on a collection of rules, of which our suggestion should be part.

Tug Manufacturing Corporation of Kennesaw, Georgia (manufacturers of tow tractors and related equipment for the aviation industry). We continue to work with them to implement manufacturing by bucket brigades. This is important to them because, incredibly, they do not have documented production standards but must increase production rate to meet a booming market. Bucket brigades are perfect here because they are self-balancing, even without knowing work standards. Our contact is Tod Rankin, Vice President for Operations.

Revco Drugstores, Inc. We supervised implementation of our ideas on self-balancing order-picking systems at all of their six distribution centers in the US; and we documented a 34% increase in pick rates. Our contact has been Victor Lee, Director of Distribution Services of Revco Drugstores, Inc. (He recently left Revco to assume a similar position at WalMart.) (Many visits during last year.)

Eileen Heisler Director of Distribution, Fel-Pro, Inc., Skokie, IL

David P. McClellan, Manager of Distribution Center, Siemens Energy & Automation, Inc., Columbus, OH

Bill Hayes, Control System Group, The Kingston-Warren Corporation, Phoenix, AZ

Edwin N. Pierson, Director of Physical Distribution, Converse, Charlotte, NC

Stephen T. Hopper, Systems Manager, W&H Systems, Inc., Atlanta, GA

Doug Jones, Warehouse Manager, McMaster-Carr, Elmhurst, NJ

Tim Martin, Ryder Integrated Logistics, Atlanta, GA

John A. White, III, Andersen Consulting, Atlanta, GA
Steve Kibort, Operations Manager, Denver Management Group, Denver, CO

Curtis L. Stowers, Logistics Research, Caterpillar, Inc., Morton, IL

Viking Freight, Charlotte, NC

Jeffrey Blain, Manager R&D – America, Schindler Elevator, Morristown, NJ

Ken Critchlow, Plant Manager, The Coach Factory, Carlstadt, NJ

Tom Bauer, President and CEO, C&K, Cleveland, OH

John Battles, Senior Industrial Engineer, Hallmark, Liberty, MO;

Jerome Beyesolow, Director of Manufacturing, Allied Foods, Atlanta, GA

Glenda Underwood, Champion Products, Clayton, NC

Finally, we have had so many inquiries from industry into our ideas of self-balancing production lines that we have set up a web page to facilitate the spread of our ideas:
http://www.isye.gatech.edu/People/Faculty/John_Bartholdi/bucket-brigades.html

8 New discoveries, inventions, or patent disclosures

We have verified, through discussions with turbine designers such as Dr. Kevin Kauth of Advanced Design, Inc. and Dr. Leon Seitelman, Senior Research Mathematician of Pratt&Whitney, that our insight is new and helpful: Avoid designs in which the number of blades on a fan is a multiple of 4 because that makes the turbine unnecessarily difficult to balance. In addition, Dr. Seitelman has functioned as the conduit to introduce our turbine-balancing heuristics to the shop floor of Pratt & Whitney, primary contractor for the jet engine that will power the USAF's F-22.

9. Honors/Awards

J. Bartholdi: Presidential Young Investigator Award, 1984–