Engineering Research Centers Program

Summative Review of the Engineering Research Center for Reconfigurable Manufacturing Systems (RMS)
University of Michigan
Morgan State University

May 22-23, 2007

Summative Review and Site Visit Report for

Performance Years One through Eleven

A short version of the NSF original report

Site Visit Team:

Charles Carter
Consultant
Winchester, VA

David Dornfeld
Professor, Department of Mechanical Engineering
University of California at Berkeley
Berkeley, CA

Warren DeVries
Dean, College of Engineering & Information Techn.
University of Maryland, Baltimore County
Baltimore, MD

Anthony C. Okafor
Professor, Mechanical and Aerospace Engineering
University of Missouri-Rolla
Rolla, MO

NSF Staff: **Bruce M. Kramer**
Program Director, ERC Program

(1) Executive Summary

Vision and Intellectual Merit

The [1995] original vision statement of the ERC was: "Reconfiguration science will form the basis for a vital production technology in the coming era of global market demands that will evolve into an entirely new manufacturing field with enduring benefits to the U.S. economy. The proposed Center for Reconfigurable Machining Systems will lead in developing the knowledge and science base for this field, including mathematical tools to optimize the system as a whole, new real-time networking software, new design methodologies for systems and for machine hardware, new controller architectures, and innovative system integration tools and technologies."

This was distilled into:

"Exactly the functionality and capacity needed, exactly when needed."

The critical elements of the vision statement are that the Center's activities will evolve an "entirely new manufacturing field" and "lead in developing the knowledge and science base for this field."

The vision laid out in the initial proposal has been achieved to a great extent. Changes in the culture of manufacturing typically occur every few decades, and the work of the center has substantially increased awareness of the importance of reconfigurability as an enabling technology for realizing flexible quality production and created a number of tools for executing these systems. Examples of successful implementation of these tools are evident in the work at the center and in the feedback from the Industrial Advisory Board. The vision of the RMS has been accepted by the industrial partners of the center and is driving the next few years' activities.

The test bed developed by RMS has proven to be a valuable "laboratory" for testing elements of reconfigurability, probably has the most comprehensive capabilities of any such facility in the US, rivals similar facilities in Europe, and is a valuable resource for other academic and industrial researchers (in Michigan and elsewhere in the US) to validate research.

The center's focus on a systems level view and integration of distinct thrusts to achieve a "whole is greater than the sum of the parts" impact is notable.

There is strong evidence of the effectiveness of both the vision of the center director and the ability of the director to execute that vision with respect to building teams of researchers, each pursuing their part of the vision, orchestrating an integration of these parts at a systems level and, through prototyping and validation, identifying the key intellectual and technical roadblocks and defining a research agenda to overcome them.

The enthusiastic feedback of the Industrial Advisory Board indicates the RMS' efforts have been both successful and valuable.

One of the unique features of this center is the composition of the team. From faculty investigators, to research scientists, to graduate and undergraduate students, a carefully assembled group with diverse, but complementary, expertise has been assembled. This "community of research" is evident and has been as critical to the success of the RMS as their technical accomplishments, since a large number of researchers schooled in both the methodology of research and the benefit of interdisciplinary work, as well as the core technical areas, has received a quality of education that could not have been achieved elsewhere. Overall, the center and its director are to be complimented on the makeup and competence of the team.

In summary, the vision laid out in the initial proposal has been achieved to a great extent. The organization apparent over this period of 11 years is impressive and reflects a serious effort of the management to insure effective use of resources (financial, personnel, and experimental). This careful management appears to have laid the foundation for another 4 years of center operation from extramural and retained funds.

The University of Michigan has been a supportive host to the center and it is hoped that the RMS will continue to have access to the resources made available by the university for the past 11 years. This is particularly important in the educational components of the center, which have been very effective in addressing the educational awareness of the 'pipeline' of potential students in manufacturing.

The impact measured by the usual metrics (industry support, technical publications, patents, visibility) is significant. Reconfigurable manufacturing is "on the map" and, importantly, should continue to be after the center's graduation.

Broader Impact

The ERC/RMS's core partners, particularly the major automobile manufacturers, have been active participants in advising the center, moving research results from the test beds to pilot demonstrations in their facilities, and recruiting graduates from the center to both transfer the technology and provide technical leadership in the future.

… the industrial partnership remains very strong, particularly with the automobile manufactures. They will be a key part of sustaining this ERC after NSF support ends. The "Big Three" each have committed to $200,000 in membership fees next year, with contingent commitments of the same amount through the following 3 years. These contributions, plus other partners' membership fees, will provide up 40-50% of the graduated center's research budget. This is a very strong commitment from an industry that is not in a strong financial position, and must be seen as an endorsement of the value of the research, people and tools coming out of the ERC/RMS.

The RMS has worked with its partners to move research and innovation from the test beds to adoption by industry, starting with their industrial partners. This includes both hardware and software tools. Evidence of this focus includes twelve patents, ranging from reconfigurable machine tools and inspection machines to software for designing and planning reconfigurable manufacturing systems. Working with their partners, they built a reconfigurable machine tool (RMT) that was displayed at the 2002 International Manufacturing Technology Show. They are completing the design of a Reconfigurable Inspection Machine (RIM) with ERC/RMS optical metrology and software systems, which is slated for pilot operation in 2007.

Their industrial partners appear to be adopting and deploying the software design and analysis tools more rapidly than the hardware tools. Examples include the software for performance analysis, emulation of network communication performance, and stream of variation theory.

Manufacturing is being transformed: it is global and changing very quickly, enabled by both the knowledge developed in the ERC/RMS, and the "flatness" of the world. The ERC/RMS is a high profile focus for the knowledge and innovation needed to be globally competitive.

The interdisciplinary research culture is a strength of this center.

A textbook by Dr. Shi has just come out, and one by Dr. Koren is nearing publication. Their adoption rates will give a clearer view of the broader educational impact.

… adding Morgan State as a partner was a great benefit, both in terms of creating a more diverse research team, which was clearly a benefit, and the very positive synergy in integrating them into the educational and research missions of the center.

The physical manufacturing research infrastructure developed by the ERC/RMS is unique in the US. No other university has as extensive space, experimental equipment and technical support, and it is one of the best in the world.

The leaders of the RMS are extremely well connected globally. This network has been expanded and, more importantly, the faculty, staff and students of the ERC/RMS have drawn great benefit from and have contributed greatly to expanding the international network of scholars in manufacturing research.

(2) Summary Analysis of Performance in the ERC's Key Features over Ten Years and the Strength of its Future Plans for Self Sufficiency

We can attest to the fact that the ERC has successfully applied mathematical science to problems previously solved manually thus introducing the possibility of powerful computer-based solutions. The quality of the research can be measured by two parameters. One is the ready acceptance of the industrial members and the other is the number of citations the published papers by staff have received. On both counts, the ERC has performed well.

The ERC is becoming recognized as an important center for manufacturing research in general.

Thrust Area #1 - Enterprise and System Design

In this area, the ERC has focused mainly on the development of methods and tools related to system performance. The solutions provided can be applied to a broad range of manufacturers.

All of the tools developed in this thrust area have been well received by the ERC industrial members, in part because they are based on analytical models, rather than discrete event simulation, that provide answers much more quickly. In a meeting with industrial members, the site review team heard positive comments from companies, such as Ford, GM, Chrysler, and Cummins.

Thrust Area #2 – Control: Systems and Machines

This thrust area, led by Professor Dawn Tilbury and Research Scientist James Moyne, appears to have been exceptionally successful in number of key accomplishments. These include methodologies for: control, diagnostics and safety networking, enterprise consolidated control, process control simulation and optimization. Many of these contributions were validated on the center's reconfigurable factory test bed (RFT), which played a key role in both defining the extent of the problems being addressed and validating the solutions developed.

The large impact of this thrust area's work is evident outside the community of industrial collaborators. A substantial publication list in leading technical journals of *the appropriate field* (emphasis added – the publications are reviewed by those knowledgeable in the research area) has been cited extensively and awarded a number of best paper awards.

One of the Industry Advisory Board members indicated that his company's global benchmarking indicated that the RMS's research in this Thrust Area was first rank.

Thrust Area 3 – In Process Metrology

The greatest impact of this thrust has been in the area of metrology software and infrastructure development for use by the automotive industry in the inspection of transfer lines.

The ERC has performed high quality research in this thrust area. The site visit team is very impressed by the excellent cross-institutional collaboration in this thrust area between faculty, undergraduate and graduate students from the University of Michigan and Morgan State University. This is a model outreach program to a minority institution.

According to the report presented at this 2007 site visit, RIM technology has been transferred to the factory floor of ERC member companies at GM Flint Plant and GEMA –Dundee MI. During the 2005 site visit we understood that this implementation was imminent and we were concerned that it had not happened, since the project is one of the most successful in the ERC. This is one of the most significant accomplishments in technology transfer.

Thrust Area 4 – Operations and Ramp up

One of the more significant solutions of RMS is being called Stream of Variations (SoV). This is a method of tracing the variabilities resulting in manufacturing defect from their sources to the final assembly point. In a complex system, a problem first noticed at final assembly is difficult to trace to its source. The SoV technique provides a tool for identifying the source of error.

One of the Associate Directors and Leader of one of the thrust areas, Professor Ju Ni, is currently the Dean of the University of Michigan at Shanghai, China.

Education/Educational Outreach

There have been excellent achievements in this focus area through recruitment of a good set of graduate and undergraduate students of diverse background. Some of the accomplishments include the development of an undergraduate manufacturing systems concentration, the development of two required core courses and two elective courses in reconfigurable manufacturing systems at the University of Michigan, and development of three courses at ERC partner Morgan State University.

The outreach programs and initiatives of the ERC are very well-intended with potential good impact. One of the examples of the impact of the outreach program is the transfer of some students from tribal colleges to the University of Michigan for graduate studies, which would not have happened without the educational outreach program.

Dr. Kannatey-Asibu, who is the Associate Director for Education and Outreach, has done a marvelous job.

The collaboration with Morgan State University in Baltimore, Maryland continues to be a significant and key contribution of this ERC. This collaboration has potential for long-term benefit in terms of developing a core of minority engineers, as well as expanding the manufacturing research initiatives to the Baltimore area.

The ERC has organized several CIRP conferences in the past years, leading to dissemination of the concept and vision of the RMS to many countries and their researchers. The papers and presentations by the ERC researchers also help to advance this cause.

Industrial/Practitioner Collaboration and Technology Transfer

Collaboration and technology transfer go hand-in-hand, and can best be documented by citing examples of the participation of the partners.

Daimler Chrysler

- Application of PAMS at Indiana transmission plant
- Line balancing at assembly plant
- Life cycle economic modeling
- Factory-wide control architecture to reduce down time
- Porosity inspection at GEMA plant
- Cylinder bore surface finish inspection
- Optimization of measurement intervals to reduce measurements

Ford

- Application of PAMS at Cleveland engine plant
- Simulation and validation of complex manufacturing systems
- Evaluation and comparison logic control approaches
- Stream of Variations application and measurement reduction

GM

- Integration of PAMS and line balancing software
- Process planning for powertrain
- Analysis of performance of serial and parallel machining lines
- Evaluation of Ethernet and ProfiNET
- Integration of control systems and networks
- Porosity inspection at Flint engine plant
- Non-contact cylinder bore surface inspection
- Data-driven measurement reduction

Infrastructure

The Center Director remains committed to the center and its vision, and the leadership team has grown in experience and responsibility as the center moves toward self sufficiency. It should be noted that while members of the original leadership team have changed, two have moved on to be deans at other top research universities, others to leadership positions at the University of Michigan as associate deans or department chairs in the Colleges of Engineering and Business, and two were elected to the National Academy of Engineering. This speaks very highly of the quality and ability of leadership of this Center.

The vision and goals of the ERC/RMS' plan have been effectively employed to make decisions, set the research agenda, and allocate resources to accomplish the center's goals. However, they have also taken advice from their external advisory group and NSF site visit teams in reviewing and revising their strategic plan. This team will need to continue this approach moving to self-sufficiency.

The diversity of the center's leadership has improved over time to the point where it is typical for many other ERCs. We learned at this site visit that one of the women faculty members, who is now a TA leader, but joined the ERC as an Assistant Professor, has been promoted to Professor of Mechanical Engineering.

We believe that the student body, both undergraduate and graduate, now exceeds the national average in diversity, particularly in fields like mechanical engineering, computer engineering and computer science. With the addition of Morgan State in 2005, there is a large jump in the number of women and underrepresented minority graduate students, although the change is not as dramatic with undergraduates.

The ERC/RMS faculty and staff, their advisory board and the center's leadership team have planned for self-sufficiency by revising their structure and moving from four thrust areas to three: Systems Design and Operations, Manufacturing Information and Control, and In Process Metrology. In this process, they have decided to focus on the automotive sector, where their major industrial support comes from. Three of the automotive partners have committed $200,000 each, the amount of their membership during the period of the ERC's NSF support, that will be reviewed annually for the next four years. This, plus other partners' memberships will make up 40-50% of the graduated center's research budget. We believe that the RMS leadership and core faculty are committed to advancing the frontiers of manufacturing research after NSF support ends.

The physical manufacturing research infrastructure developed by the ERC/RMS is unique in the US. No other university in the US has space, experimental equipment and technical support like it and it is one of the best in the world. Being able to maintain the financial support to justify this wonderful facility is a goal that the group is committed to achieving.

We believe that the research plan and resources are sufficient to carry on the research of the center. The risk aspect is that while they are building on their area of greatest experience in research, innovation and collaboration – the automotive industry – this industry's leadership position is being challenged globally. In light of the financial positions of these firms and their markets their financial commitment should be seen as a strong endorsement of the value of the research, people and tools coming out of the ERC/RMS.