Final Report
Workshop on Research Needs in Machining and Machine Tools

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Introduction

The NSF-sponsored Workshop on Research Needs in Machining and Machine Tools was held on March 5-6, 2018 at the National Science Foundation, 2415 Eisenhower Ave, Alexandria, VA. The purpose of the workshop was to identify fundamental research needs for a resurgent US machine tool and machining industry. The workshop brought together key thought leaders from academia, industry, government agencies, trade organizations, and national labs to identify and prioritize research needs in machining and machine tools. The participants are listed in Appendix A. The participant demographics are provided in Table 1.

Table 1: Participant demographics.

Sector	Number	Percent
Government	13	18%
Industry	21	28%
Academia	40	54%
	64	100%

The objectives of the two-day workshop were to:

- review the state-of-the-art in fundamental research in machining and machine tools
- identify priorities, needs, gaps, and challenges facing machine tool builders and users across a broad range of market segments
- identify key current and key missing resources for machine tool and machining fundamental research and development
- benchmark US machine tool and machining research investments against those from other nations
- formulate recommendations for new initiatives, new policies, and further actions necessary to create a robust US machining and machine tool industry.

Agenda

Day 1

8:00 am

Scott Smith, Welcome, purpose, and introductions

8:15 am

Keynote session: Framing the issues in technology capacity, and national security

- 8:15 Adele Ratcliff, Program Director, DOD Industrial Base Analysis and Sustainment
- 8:45 Tim Shinbara, Vice President, Association for Manufacturing Technology
- 9:15 Mike Molnar, Director, Advanced Manufacturing National Program Office (AMNPO)
- 9:45 Karthik Ramani, Donald W. Feddersen Professor, Purdue University

10:15-10:30 am
Break

10:30 am
Session 1: Fundamental research opportunities in machine tools and machining

- 10:30 Scott Smith, UNC Charlotte
- 10:50 Yujie Chen, Caterpillar
- 11:10 Greg Vogl, NIST

11:30 am
Session 2: Translational research opportunities in machine tools and machining

- 11:30 Dan Frayssinet, DP Technology
- 11:50 Jerry Halley, Tech Manufacturing
- 12:10 Chris Tyler, Boeing

12:30 pm
Working lunch: rapid fire perspectives from participants

1:30 pm
Panel 1: What are current technological, economic, and policy barriers faced by the US machine tool industry?

- Mark Rubeo, Moore Nanotechnology
- Mark Larson, Makino
- Axel Henning, OMAX
- David Mohring, OptiPro

2:30 pm
Panel 2: What can the federal government do to incentivize research activity and growth in the US machine tool and machining industry?

- Rob Ivester, DOE
- Tracy Frost, DOD
- Steve Schmid, NSF

3:30-3:45 pm
Break

3:45 pm
Session 3: Fundamental research opportunities in machine tools and machining

- 3:45 Noel Greis, UNC Chapel Hill
- 4:05 Bill Barkman, Y-12
- 4:25 Steven Stahley, Cummins
- 4:45 Jaydeep Karandikar, GE GRC

5:05 pm
Continue rapid fire perspectives from participants

Day 2
8:00 am
Scott Smith, Welcome and summary of day 1

8:30 am
Panel 3: Open swim
Rapid perspectives from participants

9:30 am
Panel 4: How can current and new research efforts be leveraged by the machine tool and machining industry?

- Alex Slocum, MIT
- Laine Mears, Clemson University
- Bruce Kramer, NSF
- Brigid Mullany, NSF

10:30 am
Panel 5: How can US industry incentivize research activity and growth in the US machine tool industry?

- Jaime Camelio, CCAM
- Steve Stahley, Cummins
- Dean Bartles, UNH
- ZJ Pei, TAMU

11:30 am
Wrap-up, Scott Smith

12:00 pm
Working lunch to discuss National Strategic Plan for Advanced Manufacturing

2:00 pm
Adjourn

Themes
There were four consistent themes that emerged during the workshop discussions.

1. There is consensus that machining and machine tools is valued across a broad range of sectors, including national security, energy, automotive, aerospace, and national economic health.
2. Self-aware machining is an enabling technology for next-generation manufacturing.
3. Economic pressure on the machining and machine tool industry handicaps its ability to be forward thinking (beyond 1-2 years) and, therefore, constrains R&D funding. A related issue is that the role of system integrator (i.e., a focus on assembly of components to produce a system)

tends to limit R&D efforts. The outcome is that it is difficult to transition basic research, even if funded by another source, into the industry.

4. Workforce needs span training to engineering education, but these perceived needs vary across industry.

Although existing challenges were readily identified, a unifying vision for the next steps required to re-energize and grow the US machining and machine tool industry was not articulated by the participants.

Recommendations

Based on the workshop presentations, panels, and discussions, the following recommendations are provided to realize a robust US machining and machine tool industry.

Funding should be directed to address the following:

1. national machining and machine tool needs in both innovation and capacity
2. self-aware machining and machine tools
3. spatial and temporal convergence of machining process data and model predictions
4. persistent machining modeling challenges, including cutting force, tool wear, and structural damping.

By a renewed focus on these research topics, it will be possible to invigorate machine tool design and process capability innovation and knowledge generation.

Because a unified vision for the research that is required to support a national agenda for increasing machining and machine tools capability and capacity was not agreed upon by the participants, it is recommended that the workshop be held annually. At subsequent workshops, it is suggested that:

- industry participation is increased by early invitation
- grants funded in the previous year are summarized for industrial attendees
- PIs are available to interact with industry
- feedback on funded projects is requested and recorded
- industry identifies research questions that augment the ongoing projects and then partners with relevant projects (as appropriate)
- project supplements are made available to support the new research.

The outcome will be that industry is more directly supported by NSF-sponsored research. This will lead to tighter collaboration between NSF, industry, and academic researchers. Workforce training will naturally be improved by this collaboration and the national economy and manufacturing capabilities will be enhanced.

Big idea candidates

As noted, a recurrent theme throughout the workshop discussions was self-aware machining. The natural extension of this idea is self-aware manufacturing that spans the machine tool to the factory to the enterprise. To enable this innovation in US manufacturing, new knowledge is required in:

- manufacturing science
- computer science (advanced computations and data)

- business analytics
- IIOT/big data.

The challenge is inherently multi-disciplinary and beyond the scope of the MME program alone. While MME research efforts will play a critical role, additional program involvement and significant, multi-year funding will be required to transform the state-of-the-art.

A second large scale framework was suggested in “Machine Tools and Machining for High-Wage Countries”. The basic idea is that competitive machining and machine tool industries in high wage countries must look different than those in low-wage countries. In high-wage countries, the machines have to be more highly automated, more productive, more precise, and more capable. They have to be used more efficiently, and require less maintenance and manual intervention. The supporting workers need more information, and the information needs to be aggregated in a quickly comprehensible way.

Website

A workshop website was programmed and launched. This web site has multiple purposes:

1. share information with participants and other interested parties from government, industry, and academia
2. collect ideas from participants (a web form was provided; the responses are included verbatim in Appendix B)
3. assess the workshop activities.

https://coefs.uncc.edu/tschmit4/machining-workshop/

Evaluation summary

Six questions were presented in an online post-workshop evaluation.

1. How do you feel about what information you gained from this workshop?
Five responses (1-5) were possible ranging from “very unsatisfactory” (1) to “very satisfactory” (5).

2. Would you recommend this workshop (if repeated) to future participants?
Five responses (1-5) were possible ranging from “definitely no” (1) to “definitely yes” (5).

3. What is your overall rating for this workshop?
Five responses (1-5) were possible ranging from “poor” (1) to “excellent” (5).

4. What activities in the workshop are the most helpful?

5. What activities in the workshop are not helpful?

6. Research needs you'd like included in the report.

Table 2: Question 1-3 results (17 respondents).

Question number		1	2	3	4	5	Average score
1	Responses	0	1	0	6	10	4.44
	Percent	0	5.9	0	35.3	58.8	
2	Responses	1	0	1	3	12	4.44
	Percent	5.9	0	5.9	17.6	70.6	
3	Responses	0	1	0	4	12	4.56
	Percent	0	5.9	0	23.5	70.6	
						Average of three questions	**4.48**

For all three numerical evaluations from the completed forms:

- 92.2% were rated at a performance level of 4 or 5 (out of 5)

Table 3: Question 4 responses.

Networking
The panels were most helpful.
Participation of Industry and funding agencies was impressing.
- Networking with those with whom synergistic research collaborations can be formed. - Getting the views of those from various federal agencies (NSF, DOD, NIST, Nat'l offices) - Helps to understand the challenges & opportunities in industry & ac
The government leaders in manufacturing all get together. It is a miracle to have Tracy Frost (DOD), Rob Ivester (DOE), Mike Molnar (DOC) all come to NSF to listen to us. Great job!
Different perspectives and group consideration of them.
Networking with colleges from various stake holders. Presentation materials especially related to current and future research activities.
The whole workshop contained a lot of good information. It was interesting to hear the perspectives of machine tool builders, users, researchers, and government customers. I found a lot of the "open swim" or rapid fire sessions brought out some of the more interesting and useful discussion.
The keynote session provided considerable insight into the current state of the industry. All panel discussions were worthwhile for sharing ideas.
Interaction with the personnel of government agencies and industry folks
Presentations and panel discussions
Participant presentations
1. Learning about the Manufacturing and Education relationship for teaching and R&D. 2. Current NIST and NSF activities and requirements relating to Machine Tools. 3. Good Panel discussions for different perceptions, goals and insights. 4. DOD and DOE involvement and comments 5. Industry Machine tool perceptions and Governmental perceptions of R&D needs and funding needs.

I only attended day 1. I enjoyed networking with everyone. Adele from DOD was good

Table 4: Question 5 responses.

none
Open swim was used by academia to pitch their research activities some of which were completely unrelated to machine tools and machining. It was somewhat disappointing.
Actually, I wanted to see the funding trends of machining and machine tool research, but I couldn't see. What are the next generation machining and machine tool research topics? Bio, CPS, CAD/CAM...? I am confused.
Maybe have a session focused on highly innovative opportunities that would likely be seen as no do-able in present practice, but inspirational for risky research - a kind of "wouldn't it be nice if..." e.g. "wouldn't it be nice if Machine A could tell
Shotgun approach. I expected a grand map to guide us in what meta-themes we were considering at each step. The panel topics sort of did that, but I like a 1-slide big picture view.
The rapid fire presentations seem to be more of sales pitch for various organizations or individuates. It would have been better if these would have focused more on current needs. More users of machining/tools to get the customers perspective.
While the panels had some interesting perspectives and information, sometimes the conversation shifted a little from the focus of the workshop.
None
Not as such. All sessions were quite informative and useful.
None
Product presentations were very interesting, but not coherent with the theme of the meeting.

Table 5: Question 6 responses.

Advanced machining technologies
How to create funding sources for machine tool and machining which requires federal help.
Glad to see that the needs from industries are very similar. However, I think there is one topic - flexible manufacturing, that has NOT been discussed, though Caterpillar and other industries partners all show the needs of this.
1. On-machine measurement sensors and instrumentation 2. In-process machining process monitoring 3. Machine tool development education and training programs for undergraduate and graduate students

Already communicated, I believe.

Biomedical machining is a personal journey as a result of struggles to acquire advanced machine tools for research and education

Albert Shih, University of Michigan

As a professor at University of Michigan and NC State University, I tried hard and failed to acquire machine tools for my research in machining. This is the main reason that I am working on biomedical machining. I hope to share my personal struggles. I am not unique. Many manufacturing researchers in the US share my struggle. We need to provide manufacturing researchers a better research environment and opportunities to access to machine tools and resources.

I was a grinding engineer in Cummins for 7 years. I exceled and had several key inventions in ceramic and CBN grinding because of I could use state-of-the-art grinding machines. After joined NC State University in 1998, I did not have a grinding machine for research. My students and I travelled to the Oak Ridge National Lab frequently and stayed there during summer to use their grinding machines. Thanks to the NSF CAREER grant, I was able to acquire a basic $45,000 Chevalier surface grinder. This remains as the only machine that I was able to acquire in my 20-year academic career.

I joined the University of Michigan (UM) in 2003 and was blessed to have access to a few good but not great machines build in the 1980s and 1990s. In the past 15 years at UM, we failed to acquire any new machine after numerous attempts with HAAS, DMG Mori, LIFT, and other sources. We get the best out of our existing machines and partner with Timken and Ford to use their machines for research. But it is hard, very hard. Most of my visiting scholars from China has a DMG Mori in their lab. I dream to have a DMG Mori for my research and undergraduate and graduate teaching. It is a pipedream.

I changed my research to biomedical manufacturing and exceled in biomedical machining mainly because I could not get advanced machines for research. When I talked to Barbara Linke, Bruce Tai, and many other young manufacturing faculty who struggled to acquire their first research machine, I have great sympathy because I was one of them.

I suggest to the National Strategic Plan for Advanced Manufacturing that, at the time when we have a great new cohort of young manufacturing assistant professors in the US, the federal government can create programs to provide them with advanced machines and resources for them to excel. A major national program for manufacturing equipment and graduate fellowship is an option. We want to see this new generation to stay in manufacturing and be successful. They will be the future leaders in manufacturing.

Human integration.
Integrated education (research to workforce development together rather than simply co-located)
Estimation from first principles; how do we depart from solely empirical approaches?
Control in the context of SMALL DATA. Everyone wants to eat big data sets offline, but there was little discussed on rapid analysis within the loop.

While this may not directly fall into research:
Work force development through community colleges and apprenticeship programs.
Under research:
Part Cleanliness measurement, we need to find alternative way of measuring the cleanliness of a part beyond scrubbing it with a solvent and capturing the debris in a filter.
Alternative to X-Ray CT scanning for internal features of large test articles

As an end-user of machine tools, the research needs on the process side of machining outweigh the means to get to the final product. Therefore, basic research in cutting tools/substrates/coatings, cutting fluids, rapid process implementation (e.g., process simulation, auto/rapid NC...), and machine tool 'health monitoring' is of interest to our industry.
As part of any RFQ for an aerospace government contract, include a deliverable for a R&D project related to machining or machine tools that can then be shared with industry since the government will have ownership.
Cybersecurity of machines and machining tools
Fundamental research in machining associated with new process and cutting tool development.
Develop the capability for CNC controls to operate "safely" in a compromised mfg. environment.
Summary below, details will be e-mailed. 1. SMART / Adaptive Manufacturing - definitions and goals. 2. DOD and DOE specific requirements 3. Job / Apprenticeship training for state of the art manufacturing is vital to the US economy. 4. Advanced manufacturing cells require extensive use of sensory feedback and data. Therefore the Service, Support and Data Analytics for these systems will be paramount for component manufacturing. 5. New Manufacturing Institutes for the General Machine tool and Metrology industry must unite with existing niche manufacturing institutes.

Appendix A: Participants

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Appendix B: Web form thoughts submitted by participants

Comment
1. Predictive performance models for machining processes 2. Process-induced product performance studies 3. Advanced cutting tools for machining process improvement 4. Sustainable machining for improved process/product quality and performance
How do we create a stronger business case to drive collaboration between industry and R&D? It has to have a clear effect on a company's bottom line. Academically it all makes sense but companies need short term ROI.
The recent ISO 14955 standard on environmental evaluation of machine tools introduces design methodology for energy efficient machine tools. This is the 1st part of the series and the effort is being led by EU researchers and industry. Efforts are also on going in China to develop energy efficient machine tools. There may be a need for US counterparts to engage in similar activities.
In a "high wage country" model: Do the workers really need to be these super-intelligent knowledge workers who analyze data and understand PLM or do we need intelligent systems that substitute for that knowledge and expertise? Or both? Which is more realistic?
Only from technology development perspective, I personally think differentiating US machine tool builders from other countries can be done from two ways. One is how can the machine tool builders take more advantages of their EXISTING built machine tools to maximize the customer's productivity (we had a very good discussion on this today), like compensate measured errors to increase accuracy of existing machine, monitoring the health of the existing machine tool, dynamic changes (tap test) of the machine tool, data interpretation of machine tool, etc. If machine tool builders is able to address the above issues that user are facing, definitely they will differentiate themselves from other competitors. Also, some of these issues should be able to solve in a short time period. The other one, which we did not talk about much, is how we can make a more reliable, more accurate, more repeatable machine tool AT FIRST PLACE, which is a multidisciplinary efforts, which

requires efforts in design, numerical control system, servo-motors, linear-motor, materials, assembly technologies, etc.
Caterpillar's interest in Large Part Machining with Small Machines present an interesting challenge that could help enhance US Machine Tool cost and availability... Large machine tools have long lead times, high cost, and require lots of infrastructure preparation. A novel small system that doesn't require giant castings and massive foundations would affect industrial flexibility and responsiveness.
Vogl (NIST) presentation on IMU approach should be evaluated for standards and commercialization. It ought to consider being coupled/augmented with inherent Servo data stream which could be acquired continuously. Servo data can be an element of Process Digital Twin with traceable reference.
So the purpose is to identify the fundamental research needs around machine tools and machining. Adele pointed out a shortcoming of the approach by throwing out topics without structure. What is the big picture? We know that there is digitization of machining systems, and that numerous sensors are being added, and that there is a need to upgrade control and language (a workshop is not needed for that). I would like to see an initial framework of machining strategy that everyone can look at and pick apart, add to etc., in order to guide the conversation. It can have a technical layer, organizational layer, and funding layer.
Lots of talk yesterday about big data offline analysis, but nothing about small data, rapid characterization and closed-loop control. Explore this topic.
Manufacturing Data streams that inform Primes and Users about process are needed to provide information about process, operations, and product pedigree. Tools like MTConnect focus primarily on Ops and Machine. There is value in attaching machining process data to Machine, Factory, and Product histories for a variety of value. There needs to be common standards and security that protect each ownership but enable specific transactions. For example, a machine or vendor has ways to pass forward process performance and dimensional data that informs subsequent operations. Tools need to be developed that act on it.
Establish a grand challenge project solicitation that drives researchers to create new machine designs in order to build an artifact that can't be made through traditional machining. Get the need for the artifact from industry, and have it be so that 3D printing is not a viable option (time- or surface-constrained). We need to break out of the incremental improvement bubble!
Something missing in Machine Tool education is the blending of curricula between technical training, undergraduate engineering, and graduate research. What if all those things happened in the same place at the same time? Can technicians better understand emerging technologies directly from engineers? Can researchers get more rapid and practical feedback on their ideas? This is how we work in the industrial organization; why are we not educating that way?
We have termed using optimal part designs to drive changes to machining (and other manufacturing) processes rather than degrading designs to fit infrastructure (i.e. DFM) as Manufacturing for Design - allow part or artifact designs to drive creative thinking about the process and system designs. If one is not allowed to change the design, how must the process change? (If you want to reach the moon, pulling it closer is not an option)

The main objectives persist: throughput, quality, cost. I'm a bit surprised that after a brief foray into linear motors that this technology hasn't become ubiquitous in the industry. We have data that shows they are superior to ball screws for uptime, quality, and cycle time. We also have data that confirms that they do not consume more energy than ball-screw machines. Perhaps we can view the ball-screw as in the "internal combustion engine"□ of machine tools, and linear motors as "electrification." What's the (perceived) barrier: cost. Some builders state that linear motors are cost neutral. Our builders charge a premium and, in fact, a couple don't even offer linear motors any more. Where is all the waste in machine tools: tool changes, positioning moves, etc? What does it take to further reduce that waste? Tool change times on many machine tools seem to be slow and stagnant but I suppose that's a cost of robustness? What is inhibiting wide-spread implementation of MQL machining? Where is the quality control for machine tools under load? I don't have data to back this up, but I have the perception that there is variation in critical elements of machines (spindle stiffness, clamping forces, fixture stiffness). How else can we explain that we occasionally have unique CNC programs (with tweaks in cutting parameters) for "identical" machines to achieve quality?
Is there an ability to develop more "platforms" to bridge the gaps in machine tool technology? Like MT Connect. Uber is a platform. Could we develop a platform to error-proof, driver assist, BoM estimator, topology optimization for near net shape, etc. then it can sit on top of the various machines and systems without having to be proprietary machine control related.
SMEs (critical supply chain to Tier 1 and defense people) must be not be forgotten in any future manufacturing stimulus/programs. The costs associated with mandated requirements (i.e. cyber security compatible) should be considered wrt to scale of company...Tax breaks in return for cyber certification? Direct assistance from MEP offices to offset costs and reduce the learning curve? Maybe the MEP does this, but how about a one stop Gov Policy Certification resource for SMEs support by federal govt; Consulting and company specific implementation plans for SMEs to achieve the needed certifications to do business/ stay in business with major suppliers. ... Same structure as a fraunhofer (govt and industry funded) but just for policy implementation/Tier 1 compliance etc. :-) .. too much coffee
I just wanted to thank you for all your efforts to pull together the NSF workshop. I thought it was excellent. Only you can say whether you got what you wanted from the two days. However, for me the value was a 360-view of the state of machine tools and its industry—both current constraints and future directions. If there is one overwhelming feeling at the end of the two days it is that, while small and large machine tool companies struggle to address many challenges day-to-day, the up side is that we are all committed to working toward the shared future that everyone talked about at the workshop. We have to work both ends. We have to continue to push the industry to be where it needs to be in the future to compete globally (better processes, Industrie 4.0, AI, etc.). Yet we have major infrastructure challenges in the national ecosystem that have to be addressed. Here's where the roadmap comes in, right? Not sure there is a single silver bullet.