Title: Manufacturing and Metrology

Participating Units:

Academic Departments: Mechanical Engineering and Engineering Science
Physics & Optical Science

Research Centers: Center for Precision Metrology (CPM)
Center for Freeform Optics (CeFO)

Leadership: Edward Morse
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Target category: Existing and Emerging Excellence

Keywords: Manufacturing, Metrology, Optics, Precision, Standards

1. Executive summary – Manufacturing and Metrology

Manufacturing is a dominant force in the American economy, employing over 12 million people and contributing over $2 trillion of value-added output yearly [1]. The manufacturing of aircraft, automobiles, medical devices, semiconductors, construction and agricultural equipment, advanced materials, defense equipment, and other technologically advanced products is sustainable only through continued advancement of science and engineering. Metrology, the science of measurement, is an essential aspect in advanced manufacturing and design, i.e. measurement of freeform surfaces associated with advanced energy needs (turbine blades) and defense related components (optical systems). Metrology is also critical in understanding the fundamental mechanisms of the processes used to make the aforementioned components, i.e. quantify the tool-workpiece interaction in machining, or the laser-powder interactions in additive manufacturing, etc. High levels of synergy between these two complementary, but different technical fields are required to accelerate the Nation's ability to generate the next generation of advanced products. UNC Charlotte is unique among US institutes in four distinct aspects; 1) recognized expertise in both manufacturing and metrology exist among our faculty, 2) two recognized, industry-funded research centers are co-located on campus, the Center for Precision Metrology (CPM), and the Center for Freeform Optics (CeFO), both providing a rich ecosystem for industry-academic collaborations, 3) the identified faculty have a long track record of combining their manufacturing and metrology expertise on federal and industry funded collaborative projects, and 4) strong undergraduate and graduate programs prepare our students for this increasingly high tech future workforce environment. Figure 1. provides a high level overview of UNC Charlotte's 'Manufacturing and Metrology' area of research excellence.

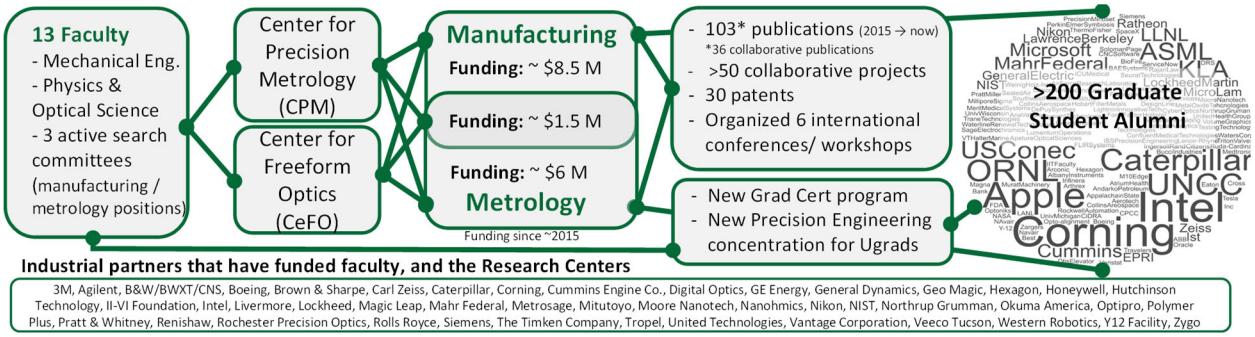

Figure 1: Overview of the Manufacturing and Metrology Area of Research Excellence.

Sustaining and further growing this area of excellence is essential to the Nation's welfare for reasons of economics, security, and workforce development. The Presidential *Executive Order on America's Supply Chains* [2] states that "Resilient American supply chains will revitalize and rebuild domestic manufacturing capacity, maintain America's competitive edge in research and development, and create well-paying jobs." The importance of domestic manufacturing could not be more clear. Meeting the future manufacturing workforce requirements is an additional challenge; although the total manufacturing workforce decreased from 2000-2018, the fractional change for workers with college degrees increased by 35% for those holding an MS, and nearly 50% for those with a PhD [3]. Because of a long term commitment to manufacturing facilities and research, UNC Charlotte is well positioned to lead in this area.

2. Evidence of Strength and Excellence

Faculty reputation: Thirteen faculty across two UNC Charlotte colleges are active in the Manufacturing and Metrology domain space (full list in supplemental material). In addition, there are three open positions (searches active) earmarked to make up for recent retirement and faculty departures. A high level summary of this group's strengths includes leadership roles in international-level organizations and honors: *SME's NAMRI*: Schmid, Fellow and Past president; Mullany, President-Elect; *International Academy for Production Engineers (CIRP)*: Davies, Fellow and past Chair; Mullany, Fellow and Chair, Goch, Fellow and past Chair; *NSF's Advanced Manufacturing program:* Schmid and Mullany, Program Directors; *ASME Standards Committee (B89) on Dimensional Metrology*: Morse, Chair; *NSF Career Awardees*: Schmid, Morse, Allen, Mullany, Porras-Aguilar; *Department of Commerce Federal Fellow*: Schmid; *ASME Gold Medal*: Schmid.

Funding and Awards: Manufacturing and Metrology research at UNC Charlotte exemplifies a broad range of funding from traditional National Science Foundation grants to collaborative research with the National Institute of Standards and Technology, proprietary research with industrial partners (see Fig. 1), and Plant-directed Research and Development (PDRD) grants from national manufacturing facilities in Oak Ridge and Kansas City. Additional funding comes through the research support by industrial affiliates of CPM and CeFO. From 2015 onward, the $16.4M in awards granted to the core faculty in this proposal can be classified as approximately 52% in support of manufacturing research (which typically heavily utilizes CPM metrology equipment), 36% in support of metrology research, with about 9% of the funds supporting projects that are explicitly examining the intersection of metrology and manufacturing. The remaining 3% were educational support such as workshops, faculty rotations at federal agencies, student travel support, etc. Additional support from CPM's affiliates program, not included in the above total, provides approximately $240K per year for graduate student stipends for research.

Collaborative track record: Examples of how manufacturing and metrology complement each other are evident in successful collaborative projects, which include extensive work in high-speed milling, tool tuning and tool-path modulation for machining, thermal modeling of manufacturing processes, error correction for free-form machining, and in-process monitoring of additive manufacturing processes. These examples all rely on either novel measurement processes or the novel application of existing measurement tools in order to achieve the goals of producing quality products in less time, using less energy. The funding secured over the past five years to support these collaborative projects was approximately 62% of the $16.4M total. Two examples of active collaborative awards and their potential future impact include:

- DURIP: Ultra-Precision Freeform Optics Generator for Space Situational Awareness and Surveillance, DOD (AFOSR), $ 947 K Pi: Davies, Co-PI: Suleski, Owens. This award expands the precision machining capabilities at UNC Charlotte, enabling future research projects.
- FMNet: A Network for Cybermanufacturing in Machining, NSF funded, $500 K, Pi: Schmid, Co-Pi: Mullany et al. Leading the establishment of this network will strongly position UNC Charlotte in responding to future manufacturing centric proposal calls.

This high level collaboration is also reflected in the number of joint publications, patents (30), and startups (at least 5). Approximately 35% of the 103 publications in the past 5 years having two or more authors from our team. Of course, most of the papers have our graduate students as co-authors, preparing them for future contribution to research in the field. The co-authors also reveal partnerships with universities, national laboratories and institutes around the world.

International reach and visibility: UNC Charlotte's visibility in the manufacturing and metrology space is evidenced by the organizations who have chosen us to host their meetings. These include annual conferences for the American Society for Precision Engineering in 2017, the North American Manufacturing Research Conference (SME) & Manufacturing Science and Engineering Conference (ASME) in 2015. More focused conferences include the International Conference on Metrology and Properties of Engineering Surfaces (2105), the 3rd CIRP Conference on Surface Integrity (CSI) 2016, the Computer-Aided Tolerancing (2020 – last-minute virtual), and a workshop on Additive Manufacturing of Advanced Ceramics was held by Mullany and Schmid in 2021. Technical Committee TC213 of the International Standards Organization (ISO) convened their meetings in Charlotte (hosted by CPM) in July 2006 and February 2012.

Broader Impact: In the arena of education, Charlotte is the only graduate program in the Americas that offers an array of graduate classes in Metrology and a graduate certificate program in Precision Metrology. Also, an undergraduate course (Metrology and Precision Engineering) has been taught five times, and has "guest lectures" by many of our team (Morse, Falaggis, Mullany, Tarbutton, Goch, Davies) in a lecture series format. Over 200 students have earned MS and PhD degrees while working on research enabled through CPM and CeFO and are employed in a wide variety of industries, academic institutions, and national laboratories, see Fig. 1. Many of these alumni have now reached sufficiently advanced positions that they are selected to represent their companies as affiliate members to CPM, or collaborators on other research projects.

Unique Infrastructure: UNC Charlotte's Center for Precision Metrology (CPM) maintains a capital investment of over $16M in advanced manufacturing and measuring equipment in 3000 square feet of precision temperature controlled laboratories (20 ± 0.1 °C). No other university in the United States – or the Americas – has this combined level of manufacturing and metrology capability. CPM's additional laboratory and office space covers approximately 30,000 square feet on the first floor of Duke Centennial Hall. In addition, CPM maintains laboratory space in the EPIC building for a very large measuring machine, and collaborates with the department of Physics and Optical Science in utilizing additional measurement resources in Grigg Hall.

Future vision and needs: To meet the demand for robust, sustainable manufacturing supply chains of the future, the manufacturing and metrology ecosystem requires a high degree of secure, digital interconnectivity, while also leveraging recent advances in data science. Conituned growth in Manufacturing and Metrology requires not only bringing new talent in core competencies but in complementary digital science fields too. While faculty are incorporating more advanced data science algorithms and forming new collaborations with the data science community, the addition of research scientists (or post docs) in the core competencies and advanced analytics would to accelerate more integrative research approaches targeting future needs.

3. Alignment with Regional and National Priorities

For many decades, American investment in manufacturing research fell behind other nations, as described in a 2015 study [4] from the North American Manufacturing Research Institute of the Society of Manufacturing Engineers (the same trends hold today, as manufacturing research investment has been stagnant since 2016). It is interesting to note that the entire American investment in public-private partnerships in advanced manufacturing research has historically been around the level of Singapore – a nation slightly smaller than Charlotte, but around ten times the population. The Made in China 2025 program is undoubtedly larger than is shared publicly, as the Chinese government stopped advertising their investment when other nations expressed concern. However, it has been noted that the Chinese investment in artificial intelligence alone is $1.5 trillion over ten years. The German Fraunhofer program invests $2 billion *annually* in applied manufacturing research and demonstration, with an industry commitment of another $1 billion. By comparison, the United States has invested around $1 billion in the Manufacturing USA and Manufacturing Engineering Partnerships program *since 2013*. In the same vein, EURAMET is supporting the European Metrology Research Programme (EMRP) at a rate of €400 million over a 7 year timeline, which is significantly more than dedicated metrology research in the United States.

The latest National Defense Strategy, published in 2018 [5], noted that advanced technologies derive from the commercial sector, which enables competitor nations and non-state actors to potentially gain access to them. Engineering designs can and have been offshored and manufactured in low-wage countries, unless the embedded manufacturing knowledge is too difficult to transfer. The only path forward for both economic welfare and national security is to continually innovate and translate basic science into products that are produced at scale and brought to market. It is not surprising that the Biden administration has suggested investing $300 billion in manufacturing infrastructure and research over the next four years. The Endless Frontiers act calls for $100 billion in new funding to be directed to the National Science Foundation, forming the new National Science and Technology Foundation. Central to this expansion of basic research will be the formation of a new Technology directorate with a heavy focus on manufacturing. Further, manufacturing is seen as essential to national security by the Dept. of Defense; key to energy policy by the Dept. Energy; and central to economic welfare by the Dept. Commerce. All of these organization will increase their manufacturing funding in 2021.

UNC Charlotte is ideally situated to take advantage of these initiatives. The faculty from the departments of Mechanical Engineering & Engineering Science and Physics & Optical Science have the expertise in manufacturing and metrology research, coupled with the infrastructure offered by the Centers for Precision Metrology and Freeform Optics, to continue to produce both graduates and research that meets the needs of the region and the nation.

References:

[1] U.S. Bureau of Economic Analysis (BEA)

[2] Presidential Actions: *Executive Order on America's Supply Chains* February 24, 2021

[3] *Manufacturing Trends for an Innovative, Sustainable Future*, presentation by Mike Molnar of the Advanced Manufacturing Program Office in September 2020.

[4] A NAMRI/SME Position Paper – *Advanced Manufacturing Initiatives: A National Imperative*

[5] *Summary of the 2018 National Defense Strategy* – Department of Defense

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