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Report on the

First Cybermanufacturing Workshop on

Enabling Composable & Modular Manufacturing through Abstractions:
Where Computer Science Meets Manufacturing

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International Computer Science Institute (ICSI)
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I.   Introduction

The *First Cybermanufacturing Workshop on Enabling Composable and Modular Manufacturing through Abstractions* was hosted by the International Computer Science Institute (ICSI) in Berkeley, CA on June 2nd and 3rd , 2016. It was supported by the National Science Foundation under award CMMI-1550603.

The workshop was organized to identify research opportunities and priorities at the intersection of computing and manufacturing, and engaged research leaders in the computing and manufacturing communities.

II.   Context

Over the last 200+ years, a number of highly disruptive innovations have transformed the way in which goods and services are produced. Beginning in the 18th century, assemblies of interchangeable mechanical components and mechanization replaced manual artisan production methods, eventually leading to the industrial revolution in the 19th century and mass production methods using machine tools and assembly line techniques in the 20th century. Electrification powered a broad variety of manufacturing tools and methods and introduced electronic control systems that permitted the instrumentation of manufacturing equipment and processes. In the second part of the 20th century, the introduction of information technology permitted realization of unprecedented automation, optimization, and productivity gains in manufacturing methods and systems.

In the early 21st century, a new wave of innovation is sweeping the manufacturing world including large and medium-sized enterprises as well as small businesses and even individual "makers". Enabled by increasingly powerful and cost-effective computing and information technologies, the manufacturing environments of the future are fast becoming complex networked cyber-physical systems that can be instantiated in one physical location or distributed across many. The physical, e.g., mechanical, chemical, electronic, etc., components of such systems will become, over time, fully integrated and virtualized by services, driven by computer interpretable models of product data, systems, and processes at the request of users representing a wide variety of corporate, professional, and personal interests. The manufacturing environments of the future will increasingly be viewed as *open*, *large-scale networked data and information systems* whose complexity will be compounded by the heterogeneity of physical models and processes, a vast variety of abstractions and representations, uncertainty, and scale.

As manufacturing environments become increasingly complex, distributed, accessible, and open, the identification of suitable abstractions that refactor the manufacturing enterprise into computationally tractable components that then lead to well-defined interfaces, and subsequently, modular and composable systems, is increasingly important. In the 1980's, the identification of new abstractions drove a paradigm shift in

the computer industry, when the introduction of the ubiquitous microprocessor and the development of a number of both proprietary and open-source operating systems drove unprecedented innovations in computer applications. Originally defined by vertical integration, closed proprietary hardware and software systems, and reasonably slow product and service innovation cycles, the computer industry rapidly became horizontally integrated, offering modular systems approaches with open interfaces that accelerated innovation in astonishing new ways. A similar transformation is currently underway in the networking industry. By re-conceptualizing network systems using techniques fundamental to computer science, the networking industry is transitioning to the paradigm of software defined networking (SDN). SDN leverages merchant silicon technologies, as the networking analog to the microprocessor, and both open-source and proprietary network operating systems in the network control plane, and is enabling new innovations in network features and applications. We believe that the identification of new abstractions in manufacturing has potential to lead to similarly disruptive innovations.

III.   Opportunity

As manufacturing environments increasingly act as *complex, large-scale networked data and information systems*, it is timely to consider re-conceptualizing their abstractions – models representations, languages, and architectures. In so doing, we seek to reduce, or even eliminate, the barriers created by proprietary hardware-software systems used in today's manufacturing enterprises that remain hampered by ad hoc interfaces, incompatible standards, and limited interoperability between systems and software needed to efficiently and seamlessly link operations throughout the enterprise – large or small. In fact, the current state of technology impedes innovation by focusing on solutions dominated by syntactic translations in circumstances in which semantics are not yet known or use cases for data are driven (and limited) by the existing functional breakdown of software tools.

Instead, we seek to identify new abstractions in manufacturing that will enable and support the development of a wide range of value-added manufacturing services that, for example:
- plug into an expansible architecture and may reside in the cloud;
- are intelligent, precise, predictable, affordable, and reliable;
- enable secure and distributed design and manufacturing;
- are transparently virtualized for a wide variety of users with a range of interests;
- provide methods for safeguarding the security and trustworthiness of cybermanufacturing system elements and integrate them to support end-to-end assurances;
- provide means by which to establish and maintain evidence-based certification and controlled visibility of explicit and implicit assumptions;

- promote and accommodate user-developed, interoperating manufacturing applications, including hardware computing platforms, operating systems, and middleware;
- generate and verify machine instructions and provide guidance in design for manufacturability;
- enable the development of product- and domain-focused parametric design applications that connect to manufacturing resources and incorporate process constraints to reduce or eliminate the need for process knowledge; and,
- provide methods for selecting and efficiently allocating networked manufacturing resources, including the decomposition of designs that optimize allocation based on multiple criteria.

IV.   Workshop Design

The workshop agenda is described in detail in Appendix 1. Workshop participants included thought leaders from the computing and manufacturing research communities, with representatives from academic institutions, industry and government. A list of the workshop participants, with organizing committee members identified, can be found in Appendix 2.

The agenda was divided into three main sessions:
- Modular, Composable, and Open Manufacturing;
- Data, Models, and Representations; and
- Cybermanufacturing Ecosystem and Infrastructure.

A summary of the discussions and recommendations derived from these sessions is provided below.

V.   Summary and Recommendations

Cybermanufacturing has emerged as a transformational change in human activities related to design and production of goods, spanning numerous economic, social, scientific, and technological advances. The workshop attempted to elucidate the central ideas and fundamental principles of cybermanufacturing by focusing on the three broad themes: (1) essential conceptual characteristics of cybermanufacturing, and specifically, modularity, composability, and openness; (2) role of data, abstractions, and computer representations; and (3) architectural, infrastructure, and systems issues in developing cybermanufacturing ecosystems. For each theme, the workshop participants identified objectives, challenges, and open issues that are discussed below. Each section is followed by a list of recommendations that are based on these discussions.

1. Modular, Composable, and Open Manufacturing

Modularity, composability, and openness in cybermanufacturing are not the end goals but the means to achieve unprecedented levels of agility, sustainability, scalability, verifiability, customization, and associated increases in productivity and reductions in costs. The workshop focused on fleshing out technical nature of these concepts and the role they play in developing next generation of cybermanufacturing systems.

1.1. Objectives

The concepts of modularity and composability have been a topic of research and practice in software development for quite some time and are integral part of the service oriented architecture (SOA).[5] It is critical to reexamine these concepts and how they are practiced in the context of cybermanufacturing. In particular, there is a major opportunity to rethink this workflow in terms of composable services, similar to how software services are systematically composed, which has contributed to the democratization of software application development. This workflow spans all design and manufacturing activities, including production planning in business enterprise. Software service composition relies on interoperable interfaces, and the standardization of such interfaces. However, there are substantial challenges (and therefore opportunities) to apply and scale up this paradigm to manufacturing.

Informally, *modularity* is based on well-defined interfaces and no interactions between, or assumptions about, the internal structures of the modules with well-defined functions. [6] Modularity and openness of such interfaces enable *composability*. A fundamental challenge is to identify and formalize abstractions for modularity and composability and to develop a practical framework that will support the rich diversity of applications in manufacturing, from continuous to discrete and from logical to physical. It is important that any such framework be extensible and accommodate future formats and standards. The state-of-the-art seems to be limited to individual industrial research attempts (e.g., MTConnect[7]), scattered academic attempts across diverse disciplines, and a number of activities at the National Institute of Standards and Technology. The latter is notable for developing open integrated architecture for different layers, including SaaS, PaaS/middleware, and IaaS/OS and initial attempts at manufacturing services composability analysis.[8]

Composability and interoperability in cybermanufacturing are particularly challenging because they imply the ability to compose not only computational models and software for manufacturing systems, but also the corresponding physical manufacturing

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[5] Erl, Thomas. "Service-oriented architecture (SOA): concepts, technology, and design." (2005).

[6] Simon, Herbert A. *The sciences of the artificial*. MIT press, 1996.

[7] www.mtconnect.org

[8] Lu, Yan, Katherine C. Morris, and Simon Frechette. "Current standards landscape for smart manufacturing systems." *National Institute of Standards and Technology, NISTIR* 8107 (2016).

components and services. Interoperability of virtual and/or physical systems requires them to agree on a set of *interchangeable* features, properties, and principles that are common to all interoperating systems. The classical principle of interchangeability in mechanical assemblies defines a notion of equivalence between mechanical components with respect to mechanical fit. Interchangeability of components enables interoperability of manufacturing operations and processes, becoming the key catalyst for mass production and economies of scale in the twentieth century.[9] Among many economic advantages, interchangeability enabled rapid response to market change, short design-to-manufacturing cycle, flexibility, fast repair, and distributed manufacturing. A similar but much more general concept of interchangeability must be developed to support cybermanufacturing; informally, it must allow matching the producer's capabilities with the consumer's needs throughout the manufacturing enterprise. As such, the notion of interchangeability in cybermanufacturing must apply not only to parts and models, but also to systems, products, and functions.

To reap full benefits of modular and composable manufacturable systems, they must be *scalable*, *verifiable*, and *resilient*. Scalability of software over a variety of heterogeneous system architectures and distribution networks demands new interoperability protocols for operating in large-scale (e.g., "data-center" scale as opposed to "desktop" scale) computational cloud-based infrastructure spanning data structures, algorithms, memory management, and task scheduling. Verification of a system's correctness (with respect to target properties and measures) is essential to ensure composability of these independent systems into a coherent distributed infrastructure. System resilience, i.e., its ability to recover from unpredictable failures appears to be the key to composability by sustaining scalability and preserving verified properties. Such fault tolerance and recovery may be designed through redundancy, but it is important that they are intrinsic to the system and not tackled on as an afterthought.

Modularity and composability will allow breaking complex data and processes into purposeful modules and identifying its critical features, enabling quantitative planning, *decision making* as well as uncertainty analysis. Hence it is important to be able to *quantify and measure* the performance and benefits of cybermanufacturing systems. Traditional measures include productivity, manufacturing costs, and time measures, including product time-to-market, on-time completed shipments, and new product introductions. But cybermanufacturing is also expected to have measurable impact on a system's agility (speed of response to system disturbance), innovation, and sustainability (measured in terms of efficient use of global and local resources). These measures must be complemented by new methods to measure product performance (strength, fatigue life, fit, etc.), as well as its functionality and aesthetics, balanced between different views of product function and structure. There is every reason to expect that this rich diversity of measurable criteria in cybermanufacturing systems is likely to make decision making

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[9] Hounshell, David. *From the American system to mass production, 1800-1932: The development of manufacturing technology in the United States*. No. 4. JHU Press, 1985.

more challenging and more impactful than with traditional manufacturing. Finally, not only such measures differ widely between different industries, but they also evolve with industry-specific asymptotic trends. For example, development times and cost as a function of complexity are decreasing in automotive industry, plateaued in semiconductor sector, and are being rapidly reduced in aerospace enterprise.

Modular and composable *virtualization* of manufacturing tasks and services is one of the distinguishing characteristic of cybermanufacturing. It applies to a range of technologies and services that serve not only traditional large-scale enterprise manufacturing of mission (e.g., mission critical parts) but also a broader generation of makers, artists, and consumers. The latter allows for unprecedented levels of *customization* and *flexibility*, supported by advanced simulation and virtualization tools that allow rapid experimentation and validation of products, processes, and systems. Examples of such flexible and customizable cybermanufacturing include "DIY" fabrication (the maker movement), rapidly growing fashion CAD/CAM (customized apparel), and customized functional material development (including composites and textiles). This trend is expected to accelerate in the future and will demand development of new means for automated acquisition of product design requirements that will include the voice (and body) of the customer.

1.2. Issues and Challenges

The term 'manufacturing' encompasses a wide range of technologies that span all human needs and activities. Hence it is unreasonable to expect that we can find all skills and knowledge needed in cybermanufacturing in any one discipline. Furthermore, this observation seemingly calls into question feasibility of identifying a collection of unified principles that are common to all cybermanufacturing activities.

Modularity

- Modularity comes at an added cost: it usually restricts and constrains the design space. Thus, this powerful conceptualization may come at the cost of diminished optimality. In fact, the modular design are almost never optimal, and one could argue that latest advances in additive manufacturing exhibit trends contrary to modularity. This appears to be a fundamental recurring question: are modularity and composability fundamentally at odds with efficiency?

- Modularity is particularly challenging for mechanical systems (virtual and physical) where subsystems may operate at different power levels and change their behavior when they are composed with each other.[10]

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[10] Whitney, Daniel E. "Physical limits to modularity." (2002), MIT Technical Report.

- Modularity rans contrary to the concept of "function sharing" in mechanical systems[11] – where the same physical component or subsystem may serve multiple functions. This concept is not well understood and is not characterized mathematically. Informally, it can be summarized by observing that, in contrast to electronic and software systems, functional modularity does not necessarily correspond to component modularity.

- The broad concept of modularity masks significant differences between modular design (structure, behavior, function, components, and systems) and modular manufacturing (unit processes, tools, and services). It should not be confused with many possible ways such systems can be decomposed into subsystems.

- Modularity is not a purely technological issue; there are often many other issues (economic, social, legal, security, etc.) that will either support or discourage modularity.

- Recognizing that people are an integral part of any manufacturing enterprise, all frameworks for modular and open manufacturing must account for numerous collaborative activities between humans, as well as between humans and machines (computers, tools, robots). Examples of critical collaborative activities include: human-computer interaction, interaction with customers, collaborative design process, education and training, and so on. Many of these collaborative activities are now supported and powered by the cloud-based technologies. Human's role and interaction within the cybermanfacturing ecosystem is a major research issue.

Composition

- The above points demonstrate that modularity of cybermanufacturing systems requires solving challenging conceptual, mathematical, and computational aspects of composability for such systems: across models, components, functions, and systems. It remains to be seen whether modularity in manufacturing can be approached using the traditional layered approaches.

- Common approaches to composition in manufacturing include severely restricting the design space, often to ensure a priori manufacturability of computed designs and to support their composition via "design rules" by analogy to VLSI. While this approach was effective in early research projects such as Cybercut/Cyberbuild and underlies practice at modern manufacturing services (e.g., Plethora and Protolabs), it does not support full automation and does not support rapid advances in representation schemes and manufacturing technologies.

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[11] Ulrich, Karl T., and Warren P. Seering. "Function Sharing in Mechanical Design." *AAAI*. Vol. 88. No. 1. 1988.

- Composability must account for variability in system models, states, behaviors, processes, and functions in cybermanufacturing -- just like GD&T standards accounts for proper fit in mechanical assemblies of interchangeable parts.

Interoperability

The workshop participants observed the paucity of abstractions for interoperability in cybermanufacturing systems which severely limits modularity and composability in practice. For example, the ability to define and test "functional equivalence" appears to be important in many applications, but the meaning of this concept is ambiguous. Most of the design and manufacturing software tools are not well integrated and rely on human ingenuity to solve problems and interpret solutions, with results are highly operator-dependent. It was also observed that the level of technical sophistication varies greatly in cybermanufacturing, with deep human expertise and guidance required to produce high quality products in many segments of industry. Thus, it is important for interoperability scenarios to support proper architectures and design patterns that assign suitable roles to humans, machines, and computers. Furthermore, interoperability for cybermanufacturing must enable exchange and composition of both virtual and physical component systems. More specific issues and challenges include:

- Interoperability based on data formats and translations is inadequate for supporting advanced cybermanufacturing scenarios; it may work in some narrowly defined and limited scenarios but such data-centric approaches do not capture the semantics and intent of applications, hence are unable to support composability in cybermanufacturing.

- A notion of interoperability that supports open manufacturing is rooted in the notion of interchangeability (of models, behaviors, functions, processes, systems, and manufacturing capabilities) so that they can be virtualized, exchanged, composed, and implemented by interoperable services and facilities.

- Vertical (i.e., local) interoperability is difficult, but has not been even attempted across the manufacturing service-oriented architecture. Challenging examples include decades old CAD-CAE and CAD-CAM interoperability that remain unsolved largely due to semantic differences across variety of representations, as well as a more recent need for CAE-CAM integration of simulation tools with in situ sensing. Interoperability should span not only different activities and semantic layers, but also different physics, time, and physical scales.

- Based on conclusions of the recent NIST workshops on smart manufacturing,[8] current exchange standards are deemed inadequate to support interoperability in cybermanufacturing. They are difficult to use, provide overlapping or missing capabilities, and have limited adoption. A new approach to standardization is needed.

- It is widely recognized that successful standardization may fuel and enable technological developments. In manufacturing, standardization plays a critical role of providing "how to" instructions to conduct disciplined activities within domains, facilitating communications and software integration. But standardization can both spur and stifle innovation, with the outcome critically depending on timing. It is important not to prematurely standardize early in the technology cycle. Standardization of interoperability should be viewed as a dynamic process. There are lessons to be learned from the SDN community, where for example, the OpenFlow standard is constantly evolving enabling richer interfaces between the network controller and individual routers/switches.

- Peer-to-peer interoperability (system to system translation, customized protocols) has been the most successful type of interoperability, but it is expensive (grows quadratically in the number of peers) and is not easily extendable. A preferred alternative is to standardize on communication protocols via well-defined queries that are standardized with respect to common reference semantics. Its effectiveness has already been demonstrated at machine tool level by MTConnect.[7] Reference semantics for higher levels of abstraction is lacking and depends on the identification of proper abstractions.

- Interoperability may become a particularly thorny issue for legacy systems and manufacturing applications (many of which are decades old) where system design is connected to particular execution platforms and models that are connected to specific representations. These difficulties are compounded by proprietary data protection and outdated standards/interfaces that do not prioritize information exchanges.

- Software architecture and infrastructure challenges are amplified by the use of open source (e.g., open robotics and manufacturing libraries) – from installation and deployment to building and sharing data sets. These challenges undermine the vision of production/manufacturing-as-a-service (PaaS/MaaS).

Quantification, Security, and Verification

- There is a wide metrology gap between the objectives in cybermanufacturing (e.g., value-per-cost) and our ability to measure them. In particular, things we measure poorly include function and local information (e.g., microstructure, residual stress, temperature, local material flow, etc.)

- Simulation (multi-scale, multi-physical, multi-process, stochastic, data-based connected, computationally efficient) and sensing technologies are needed to bridge the functional metrology gap. This in turn requires seamless interoperability between such measurements and tools.

- Many performance measures have not been quantified, but are well recognized informally. For example, manufacturing industry is known for being labor intensive, resistance to change (in capital), and slow-to-adapt culture. It is also well known that impact is best affected at design time, but it is not clear how it should be measured.

- Intellectual property (IP) and proprietary information are integral parts of many cybermanufacturing scenarios. It is rarely quantified explicitly but is often embedded in design and manufacturing constraints, process plans, quotes, and other procedures and services. This means that in some instances, IP is being "sold" while in others, it is given away in the course of production.

- Verification of systems should proceed top-down: global properties of the composed systems are verified given assumptions about local behavior of system components. In contrast, bottom-up verification is extremely detailed and difficult – and it only verifies what we already understand.

1.3.   Recommendations & Research Questions

The time is ripe for a major inter-disciplinary research initiative that would bring together scattered industrial and academic research attempts in the area of cybermanufacturing. There seems to exist a great need to formalize the notions of modularity and composability, find the right abstractions to express them in concrete mathematical language (without premature standardization), and formulate principles that support building generic (but not too generic) cybermanufacturing systems. However, it is important to recognize that any such framework should be conceived as a dynamic and evolving process rather than a fixed framework.

Cybermanufacturing is a major technological component in the global movement towards open manufacturing, as witnessed by many initiatives such as DARPA's Open Manufacturing Initiative and Industry 4.0 (e.g., in Germany). These initiatives embrace the notion of "design anywhere, manufacture anywhere" motto and envision globally distributed manufacturing services and centers supported by cloud, modular, and interoperable technologies. However, many technological challenges needed to achieve the promise of open manufacturing are yet to be solved. It is worth noting that social and economic aspects of open manufacturing are not well understood and should be systematically investigated.

Interoperability and interchangeability have emerged as major technical issues underlying the challenges in composition of components, systems, and services (both virtual and physical) in cybermanufacturing. Solving these issues require major theoretical advances in developing reference semantics supporting cybermanufacturing communication protocols. Such semantics must be firmly rooted in tangible and abstract properties of the relevant objects, including geometric, topological, computational, and

physical properties. Ontologies, category theory, and other computer science tools of abstractions appear to be highly applicable to formulating, organizing, and structuring domain specific semantic properties.

More generally, the goals of modular, composable, and open cybermanufacturing may require revising foundational issues in computer-aided design and manufacturing. The revised foundations must include and anticipate provisions for dealing with semantic issues and interoperability. For example, design for cyber-physical service composition should prioritize downstream interoperability.

Interoperability should not be confused with standardization, which is a critical means for achieving interoperability. Standardized semantics should be prioritized over rigid syntax and necessarily incomplete formats. Premature standardization may leads to myopia that can inhibit measurable progress. Instead, standardization should be considered a dynamic process of evolving abstractions that are developed based on solid experimental evidence. Thus, experimental development of transformative solutions, prototype tools and systems, and experimental scenarios should be highly supported and encouraged. An important outcome of such research should include relevant long-lasting abstractions that may be useful in cybermanufacturing for extended period of time.

Manufacturing-as-a-Service (MaaS) is already a reality that is disrupting and transforming traditional workflows; the trend is only expected to accelerate with increased availability of vast amounts of data, improved software tools, and emergence of new manufacturing technologies. MaaS takes many familiar forms, including on-demand manufacturing and plug-and-play manufacturing where custom design models (created anywhere) are automatically translated into machine instructions to produce physical parts at any time or location. But significant progress is needed to support modularity, to combine functionalities, and to make these services open. Wide availability of manufacturing apps that combine designer's knowledge and manufacturing expertise in a variety of production sectors. These applications will not be static; they will evolve based on their demonstrated usefulness and adapt with changes in design and manufacturing technology.

Synergetic relationship between human and machines in the context of cybermanufacturing brings out a number of major issues that require an urgent attention from the research community. Human role spans all aspects of cybermanufacturing, including design and manufacturing expertise, ownership of intellectual, virtual, and physical properties, operators of computer and physical equipment, interaction with customers, collaborators, and suppliers; it further extend to complex economic, social, and political issues, both locally and globally. It is important to understand the causal relationships in the context of cybermanufacturing, to enable users to comprehend them and make informed organizational and technological decisions based on them.

Quantification, measurement, and rational decision making about trade-offs in presence of design and manufacturing constraints are integral parts of cybermanufacturing and should be approached as important research challenges. Tools from market design, game theory, and distributed optimization for on-demand agents and protocols appear to be particularly relevant. These issues may take different forms in the context of cybermanufacturing activities. For example, front end interfaces may reference specific performance criteria, materials, and structure, but may need to refer to manufacturing facilities with specified process requirements and options defined in terms of time, cost, quality, etc. At the back end, scheduling, routing, and negotiating algorithms may balance production request and existing tasks, optimize over cost, time, and quality. Model-based simulation is likely to be a key to rational decision making.

Sample Research Questions:

- Design-centric versus manufacturing-centric approach to cybermanufacturing: when (and how much) should manufacturing modularity drive (or be driven by) design modularity?
- What are the useful forms of standardization, how much standardization, and how much abstraction is practical (based on which to standardize)?
- How to define and test interchangeability of digital information (geometry, physics, materials, etc.) including tolerances and errors, based on which to formulate and solve interoperability of systems and components?
- How to mitigate the added cost of modularity in terms of performance?
- What is the an optimal division of labor between humans and machines in cybermanufacturing that makes people more productive and efficient, but does not hinder interoperability and automation?
- What are the approaches to design and manufacturing solutions with redundancy so that they can recover from failure?
- What is a conceptual organizational structure of cybermanufacturing? Is it hierarchical? What are the relevant scales?
- How and when do we know which abstractions must be standardized?
- How will the transition to cybermanufacturing affect workers? What skills do they need and how are they going to be educated in the future?
- How do we design cyber-manufacturing software tools and services that not only enable, but also enhance and incentives cooperation and collaboration?
- What are the key technical differences between cybermanufacturing as practiced by small and medium enterprises (SME) versus large industrial enterprises?

2. Data, Models, and Representations

The information constructs for describing engineering systems and processes may appear weakly connected (or even orthogonal) to openness, modularity, and composability of cybermanufacturing systems. But in fact, data, models, and representations are the very fabric of cybermanufacturing systems. Open systems interact through information exchange, where consistent interpretation of data, interoperability, and composability of open modules rest upon common models and interchangeable representations.

It is important to distinguish between raw data, mathematical models (i.e., abstractions), and computer representations (i.e., implementations). As the same models are typically representable in different ways, it is common to witness a diversity of opinions about the choices of representations, especially when a field is in its infancy. Cybermanufacturing is no exception to this trend, and a discussion of alternative information models is paramount.

2.1. Objectives

Mathematical models and computational representations must be able to support *all* of the cybermanufacturing activities mentioned in the previous section. These activities include processing sensory data, model-based simulation and data-driven analytics, interfacing between systems and components including human-computer interaction, search and optimization for inverse problems (e.g., design), manufacturing process planning, and others. For each activity, there is a distinction to be made between models and representations of (1) the *states* that describe static or dynamic objects (i.e., "things") comprising a system or module; and (2) the *processes* that are transformations of state.[6] Both are critical (and dual to each other) for enabling cybermanufacturing activities.

Modern design and manufacturing information are *heterogeneous*, both in type (e.g., shape, material, and process) and scope (e.g., as-designed, as-analyzed, as-planned, as-built, and other views). Thus multiple "views" of the same digital prototype are often needed, with different representation schemes needed for each view,[12] as opposed to the traditional approach with a single shape (topology and geometry) centric view.[13] In fact, the notion of informational completeness that underlay solid modeling has to be adapted to this multi-view scheme, and has to be extendable upon availability of new information or views. The validity of a collection of views is contingent upon interchangeability and interoperability between them with respect to common properties. In addition, there needs to be mapping mechanisms for automatic compilation and conversion across the views. These maps abstract processes and

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[12] Regli, W., Rossignac, J., Shapiro, V. and Srinivasan, V., 2016. The new frontiers in computational modeling of material structures. Computer-Aided Design, 77, pp.73-85.
[13] Requicha, A.G., 1980. Representations for Rigid Solids, Theory, Methods and Systems. ACM Computing Surveys, 12(4).

activities ranging from functional design specification to manufacturing planning, fabrication (e.g., sending instructions to a 3D printer) and physical inspection. Moreover, as cybermanufacturing systems grow in complexity, models and representations need to be described at multiple levels of abstraction or detail (e.g., system level, assembly level, and component level).

Virtualization in cybermanufacturing demands that models and representations support simulations of many different types, ranging from prediction of product performance and verification of manufacturing process plan to planning and scheduling tasks over the entire supply chain network. Efficient multidisciplinary simulation tools are essential for *forward* analysis throughout the entire supply chain, which enable a systematic approach to *inverse* synthesis (i.e., design and optimization problems) through search, diagnosis, feedback, and iteration.

2.2. Issues & Challenges

Cybermanufacturing is composed of multi-faceted applications, as well as diverse activities within the same application. This comes with the need to deal with a myriad of modeling paradigms and representation schemes, and to make sense of data from very different sources. Even for the same manufacturing process (additive, subtractive, textile, composites, electronics, etc.) the range of different activities throughout the product lifecycle leading to the manufacturing process require different "views" of interchangeable models and representations of data and processes. The workshop participants identified a number of challenges in this context.

Interchangeability

- There is a consensus that diversity of representation schemes is a necessity that will continue to increase in cybermanufacturing suites of the future. There is no universal scheme that fits all purposes. Different schemes have different advantages and drawbacks, thus lend themselves better to some activities than others. The challenge is in reconciling these different schemes with respect to a common framework and reference semantics.

- Interoperability (which is necessary for composability) across systems or different views in the same system relies on interchangeability (i.e., an *equivalence relation*) between representations and algorithms with respect to their models and operations. There is a need for defining formal semantics for interchangeability that can be extended to shape (topology and geometry), material structures, physical properties, and manufacturing processes.

- Compared to other domains such as the semantic web, EMR/EHR, and VLSI circuits, it appears far more challenging to formally define interchangeability protocols for cybermanufacturing systems that are heterogeneous, multiscale, and multi-physical.

- The common models and invariant properties vary significantly across activities in the supply chain. It is unlikely that a standard file format can capture all necessary information throughout the digital thread. The monumental STEP effort[14] has been successful to some extend in traditional manufacturing (e.g., CAD-CAM integration), but cannot support the complexity of information in cybermanufacturing. Moreover, it has led to various flavors of the file format that defeats the standardization purpose. For example, the legacy STL format for additive manufacturing is not expressive enough to support the complex material structures and physical properties. Promising enriched formats (e.g., the more recent 3MF) regularly emerge but usually fall short of expectations due to unresolved semantic issues and the familiar problem of flavor diversity.

- Errors and uncertainty are among the main sources of practical complication for enforcing interchangeable representations and algorithms. Uncertainty in data and product representations built around them are inevitable in almost every step of the cybermanufacturing workflows, from raw data acquisition (e.g., from sensors) to analytics, simulation, optimization, and process planning. Furthermore, inaccuracies are inherent to various computations as well, not only due to rare failures, but also arising regularly from algorithmic approximations, probabilistic methods, finite-precision computations, heuristics, and other common sources of imprecision. Models and representations of *tolerances* to errors and uncertainty are crucial to defining practical interchangeability certificates that are enforceable with realistic (but precise) guarantees. Although existing standards (e.g., ANSI Y14.5 standard on GD&T) have come a long way for tolerance specifications of parts for traditional manufacturing, defining tolerancing schemes and uncertainty propagation models for shape, behavior, material structure, physical properties, and fabrication processes for cybermanufacturing remains challenging.

Ontology and Knowledge Representation

- Ontologies provide vocabularies and shared understanding of concepts in a domain and their relationships (including attributes, properties, and constraints). As with traditional representation schemes and file formats, it is unlikely that a single ontological structure (e.g., in OWL or UML) can be created for an entire domain of cybermanufacturing.

- Traditionally, mechanical product representation is centered around nominal shape (topology and geometry), while other aspects such as bulk material properties, tolerances, behavior and function are annotated as "attributes" that are assigned to geometric features. This approach needs to evolve to a paradigm in which product semantics are central, and its relationships to shape, structure, behavior, function,

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[14] Kemmerer, Sharon J. "STEP: the grand experience." *Special Publication (NIST SP)-939* (1999).

corporate knowledge, process knowledge, constraints, and meta-data are sketched out.

- In addition to shape, informal notions such as structure, behavior, function, and design intent should be formally defined and precisely instantiated across all cybermanufacturing activities. While these concepts are ubiquitous in different communities (e.g., design theory and methodology, [15] model-based systems engineering, [16] and computational material science [17]), their meaning varies widely. It is unclear whether more universal definitions are feasible or desirable.

Complexity of Models and Representations

- Design tools are once again falling behind manufacturing technologies. Traditional CAD tools have been developed specifically to support design and manufacturing of large assemblies of homogeneous components. These tools do not scale to handle the structural and behavioral complexity that is apparent in many modern manufacturing processes.

- The next generation of design tools must be based on models and representations of engineered material structures at *multiple size scales*, reconciling them with geometric operations of traditional solid modeling, physical analysis tools, and manufacturing planners.

- Cybermanufacturing critically depends on the ability to compute with increasingly complex models of intent, function, and behavior, that can be described, represented, edited, parameterized, and matched to manufacturing capability.

- Specialized manufacturing processes such as 3D printing of lattice structures or foams, knitting of textile or composites, and others need to be either encoded into the models and representations to enable a priori manufacturable designs, or should support a posteriori manufacturability analysis. For example, topological models of composites and their knitting process are supported using graph or grid structures with codified ordering relationships for "CNC stitching." Different models and representations are needed for various other microstructures (grains, fibers, etc.)

- Increased complexity of manufacturing processes and manufacturable material structures makes manufacturability of such structures a major research challenge.

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[15] Gero, John S. "Design prototypes: a knowledge representation schema for design." *AI magazine* 11.4 (1990): 26.

[16] Friedenthal, Sanford, Alan Moore, and Rick Steiner. *A practical guide to SysML: the systems modeling language*. Morgan Kaufmann, 2014.

[17] Olson, Gregory B. "Computational design of hierarchically structured materials." *Science* 277.5330 (1997): 1237-1242.

For example, in additive manufacturing, the relevant research issues include but are not limited to analyzing accessibility, generating support structures, optimizing build orientation, and so on. The challenge is compounded by the great diversity of manufacturing technologies, each constrained by domain-specific factors.

Simulation and User Interaction

- As human-computer interfaces will be a vital component of cybermanufacturing, *interactive real-time* simulation tools should be supported by enhanced models and representations. Although interactive visualization is well-supported for current CAD systems, it will be a challenge for real-time simulation to keep up with increasingly complex models of materials and processes.

- Regarding geometric processing tools, even queries as basic as proximity and collision predicates, contact measures, morphological operations, and other shape and motion related computations remain challenging even for solid models.

- Regarding physics-based simulation, accurate model discretization, proper material specification, and high-fidelity numerical solvers are among the difficulties. Every attempt to making the simulations more accurate – e.g., from rigid to articulated, from ODEs to PDEs, from linear to nonlinear, and from single- to multi-physics – will come at a cost of impairing performance and interactivity.

- Cybermanufacturing activates will depend on simulations of unprecedented levels of computational complexity, ranging from predicting thermoelastic properties of 3D printed structures resulted from phase change to predicting collective human behavior in large markets or traffic patterns of autonomous vehicles.

- Specifying, interpreting, and solving for various constraints are another source of challenge in simulation. Representation scheme constraints, multi-physics laws, manufacturing constraints, human limitations, design requirements, and uncertainty are but a few classes that need to be accounted for.

2.3. Recommendations & Research Questions

A new discipline is emerging, which reaches beyond computer-aided manufacturing. It must bridge the design, computation, and fabrication, as well as social and economic issues. Such an integrated and multidisciplinary view has major consequences for education and research planning. It requires investment into the science of computational design and manufacturing as opposed to design theory and methodology; and demands the ability to deal with heterogeneity, diversity, and complexity of data, models, and representations.

Workshop participants observed a communication gap between disciplines such as mechanical engineering, computer science, networking and security, artificial intelligence, business administration, and others. They all are vital to the evolution of cybermanufacturing, yet they use different lexicons and attach different semantics to overloaded terms (e.g., what is "cyber"? What constitutes "behavior"?). Focused effort by funding agencies, particularly the NSF, is key to bringing experts from diverse fields together and encourage unification of language and semantics.

A concerted effort is necessary to research formal theories, computational tools, and technologies. This ranges from developing higher-level abstractions that can be expressed using ontologies, category theory, model theory, and possibly other tools; to further advances in more traditional, domain-specific CAx tools such as geometric modeling, physical analysis, and process planning (CAD/CAE/CAM). The two are complementary to each other, as the former will serve to abstract and unify heterogeneous models across the cyber landscape, while the latter facilitates detailed prediction, diagnosis, optimization, and design in each subspace of concentrated knowledge.

It is important to spend a substantial effort on advancing both model-based simulation tools and data-driven analytics – including shape, material, physics, human factors, etc. – that support forward problems (i.e., analysis) as well as inverse problems (i.e., synthesis) and optimization across all supply chain and resources. New approaches to dealing with the enormous complexity of data, models, and representations are necessary. The rapidly growing AI technology including machine learning and planning are promising to leverage evidence-based and data-driven models.

More investment in the development of mathematical models and semantic standards are needed for notions of intent, function, behavior, and structure. These notions must be treated as first-class objects that are computer-interpretable and executable. These notions must be bridged with data analytics on big data from sensor networks and factory shop floor on the one extreme, and conceptual design at another.

Given the rich informational content and complexity in cybermanufacturing, it is critical to investigate new approaches to interchangeability. The key is to standardize on common properties rather than common data structures or file formats (such as STEP).

Connecting and unifying new and existing models and theories require further investigation; for example, geometric models articulated by solid modeling and reasoning, computational models of material performance, properties, structure, and process,[17] and machine-specific models of unit fabrication processes, must be reconciled. The resulting paradigm should be extendable to accommodate new and emerging concepts such as additive manufacturing, composite knitting, etc.

Further research in alterantive approaches to modeling and design of products and processes should be encouraged. In particular, several views of design as a "program"

were articulated. A transition from an imperative (i.e., action-based, as in traditional digital threads) to a declarative (i.e., requirement-based, as in functional programming) paradigm appears to be gaining momentum. In the new paradigm, higher-level design specifications and functional requirements are mapped to structural and behavioral models with the aid of a "design compiler." Procedural approaches in which designs are specified as design recipes (i.e., programs) that capture intent and behavior in a machine-readable language also appear to be promising, especially in applications where they can be both evaluated to both virtual prototypes and compiled to machine instructions for manufacturing (e.g., stamping, printing, knitting).

High-performance computing (HPC) and efficient storage technologies continue to advance rapidly. The evolution of models and representations for the 20th century design and manufacturing was restricted by severe computer time and memory limitations that had to trade off modeling accuracy and fidelity with available resources. The cybermanufacturing suites of the 21st century will have access to high-throughput, massively parallel and distributed computing resources (CPU, GPU, and databases) that are increasingly more available and affordable. One could argue that the prospects of HPC should not be overestimated; for example, no matter how many processors are used, linear speedup achieved through parallel computing cannot solve non-tractable (e.g., exponentially complex) problems. However, a more important consequence of advances in HPC is a fundamental shift where new abstractions, models, and representations with higher degree of expressiveness, fidelity, and interoperability will emerge to replace the traditional less efficient models and representations, eliminating the computational bottlenecks throughout cybermanufacturing ecosystem. Such a shift should be encouraged and further investigated.

Sample Research Questions:

- Can reduced order models help dealing with complexity in cybermanufacturing by navigating across the size scales and levels of abstraction?
- Can we leverage patterns and symmetries in structures to reduce apparent complexity of models?
- How does one reconcile the mathematical complexity of abstractions and models in cybermanufacturing against the intuitiveness and simplicity of interactive applications ("apps")?
- What is an appropriate hierarchy of views and layers in cybermanufacturing?
- What is an optimal combination of linguistic, pictorial, symbolic, algorithmic, and virtual terms in describing knowledge and relationships
- Can category theory be used to unify abstractions across heterogeneous domains and applications within cybermanufacturing?
- Can system interfaces be viewed as "first-class" objects supporting query-based interoperability?

- Is it possible to leverage the cyber-infrastructure to capture intent through user interaction?
- What abstractions can adequately capture the roles of human actors in cybermanufacturing?
- What are the ultimate limitations of HPC in advancing models and representations for cybermanufacturing?
- Can we exploit the vast body of knowledge in functional programming, denotational semantics, and lambda-calculus, to conceptualize a declarative approach to design?

3. Cybermanufacturing Ecosystem and Infrastructure

3.1. Objectives

Thanks to the rapid advancements in cyberphysical systems and their enablers – ranging from ubiquitous computing and on-demand fabrication technologies to data analytics and internet of things (IoT) – the cybermanufacturing ecosystem is on the brink of a network- and information-centric revolution. This will transform the technologies ranging from user interfaces and exchange mechanisms to persistent data storage, simulation-based decision making, data mining, and knowledge re-use.

The cybermanufacturing architectures are organized in multiple layers. They require smart tether-free connections (i.e., plug-and-play) and sensor networks; smart analytics for generating information from raw data (e.g., for health monitoring, data correlations, and performance prediction); "digital twin" of components and machines to replicate and predict their evolution in time (see previous section for models and representations); integrated analysis and synthesis tools for simulation, remote interactive visualization, collaborative diagnosis, and decision making; and means for self-adjustment, self-optimization, and reconfiguration. Importantly, re-configurability leads to resilience to disturbance and unpredictable modes of failure. As such, cybermanufacturing distinguishes itself from traditional computer-aided manufacturing by its ability to transfer raw data to actionable operations, provide means for human-machine interaction, and ensure both resilience and re-configurability through evidence-based decision making.[18]

Viewing cybermanufacturing as a large-scale business enterprise, it has to fulfill many objectives ranging from system re-configurability (through modularity and composability), ease of integration (through interoperability), flexibility and resilience (through predictive data analytics and simulation), response to dynamic changes in providers and customers (supply and demand), and scalability with the advent of new enabling technologies.

3.2. Issues & Challenges

In a global manufacturing enterprise, companies and service providers face a constantly changing economic, social, political, and commercial environment. Adapting quickly and cost-effectively to the complex and fluctuating requirements, sustaining positive growth, timely introduction of new products, and acquisition of new markets prove to be more challenging than before in this new arena. The workshop participants identified some of the main challenges that must be overcome to support a sustainable cybermanufacturing ecosystem and infrastructure. These challenges include:

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[18] Lee, J., Bagheri, B. and Jin, C., 2016. Introduction to cyber manufacturing. Manufacturing Letters, 8, pp. 11-15.

Self-Awareness and Plug-and-Manufacture

Self-awareness of manufacturing services is key to their agile, adaptive, and automated response to changing requirements and interactions. The future cybermanufacturing enterprise is a network of interconnected and interoperating suppliers and consumers that sense, communicate, and react to each other and the environment in which they operate. Data and process interoperability remains to be a big challenge for such interactions, more specifically:

- Machine and data analytics are indispensable tools to make manufacturing services "smart" and self-aware; however, in spite of their availability for more than two decades, their usage in cybermanufacturing is likely to face several challenges. The sensory data collected from the physical space (i.e., shop floor) is analyzed by process-specific data analytic tools and is fed back to the cyber space to signal adaptation. But the technological support for closed-loop control and data analytics on enormous amounts of sensory input is lacking (i.e., "big data" analytics).

- Effective cyberphysical interfaces (CPI) that are capable of handling and processing such information in real-time are key to self-aware closed-loop systems.

- Unlike most electronic hardware and computer software, mechanical systems in general (and manufacturing services in particular) are not "plug and play" devices.

- The future cybermanufacturing ecosystem will rely on standard protocols for automatic (i.e., tether-free) discovery of such devices in the network without a need for manual physical device configuration or user intervention in resolving resource conflicts. In such a global network, a manufacturing device or service ranging from a desktop 3D printer to a fully automated shop floor mock-up will be automatically detected by the operating system (OS) (e.g., appear in OS Device Manager alongside other basic devices). Developing such protocols is a nontrivial undertaking, but existing frameworks such as system level agreements (SLA) can be leveraged.

- For a true plug-and-manufacture paradigm, multiple services need to be able to exchange information with the OS and each other without restricted access or manual intervention, which depends on interoperability of their data, models, representations, and processes.

- A preliminary form of this plug-and-play (on-demand) manufacturing is emulated by some service providers (e.g., Shapeways, Protolabs, Ponoko, Plethora, and others). Although they provide useful design tips and pre-print checklists to reduce the failed designs, they are miles away from being able to integrate seamlessly into a plug-and-play environment. They are limited to manufacturing processes (e.g., 3-axis milling

or FDM), deliver non-critical parts with no or trivial tolerancing requirements, and at times require fairly time-consuming manual labor to supervise the process planning.

Cybermanufacturing Repositories

- A global cybermanufacturing infrastructure will rely on compilation of different databases of material microstructure, physical properties, experimental results, and more. Standardization of such repositories for use in interconnected platforms in not a trivial step.

- In addition to structure and material databases, there is a need for integration of multi-physical and multi-scale (in size) and multi-level (of abstraction) analysis tools able to operate from atomistic to bulk properties evaluation and material processing. For example, multi-physical modeling and integration of local additive manufacturing processes remain challenging. Composite material modeling and manufacture planning, on the other hand, requires a global concept of material structure, and so on.

- Conceptual structures of individual databases and tools have to be integrated to create the global conceptual infrastructure.

Cyber-Security, Privacy, and Safety

- *Security* is one of the major hurdles in implementing cybermanufacturing especially when it is realized as a network of connected machines and systems in a cloud environment.[18] The mechanisms that will guard against cyber-attacks of potentially malicious intruders do not easily extend from existing cyber-systems to cybermanufacturing, as sensitive product data and its semantics are different.

- *Privacy* continue to be important challenges as well, as sensitive business and personal information needs to be protected from visibility to third parties during manufacturing related transactions. Applying techniques from differential privacy and privacy-preserving computation paradigms are among the research challenges. Moreover, reputation-based trust will be a big differentiating factor as privacy challenges remain to ensure competitive advantages for businesses.

- Workspace ergonomics, human safety, and other human-in-the-loop aspects of cybermanufacturing will become increasingly more relevant. Identifying new forms of precautionary measures to avoid workspace tragedies are among the most important challenges.

App-Based Customization Ecosystem

- There is a need for a holistic view of the custom product (e.g., clothing) and materials (e.g., textile) that is centered around consumer needs. This human-centric approach appears in designing the workflow from placing the order to receiving the product. For example, cybermanufacturing of customized apparel begins with simple-to-use 3D body measurements by a mobile device, and goes through stages of interactive design optimization (on the cloud), reliable visual inspection, predictable virtual try-on, and adept fabrication with different fabric materials.

- *Systematic frameworks* are key to end-to-end cybermanufacturing architectures for customized design and delivery. The process starts with the customer's specification of functional requirements (which include personal customization), continues with its mapping to detailed design specifications guided by simulation, design optimization guided by interactive user feedback, and concludes with shipping. For the customized apparel example, these steps correspond to full body measurement at home, automated creation of fabric pieces and stitching, virtual try-on, and delivery, respectively.

- "Programmable" manufacturing of advanced materials and customized meta-materials (e.g., knitted/braided/woven composites) requires a data flow process model including computational simulation, digital fabrication (e.g., knitting), testing and evaluation of performance, as well as search and optimization.

3.3. Recommendations & Research Questions

A number of enabling advancements for cybermanufacturing ecosystems are emerging. These enablers range from technological infrastructure such as Cyberphysical systems (CPS) and platforms, internet of things (IoT), service-oriented architecture (SOA), Industry 4.0, industrial Internet, data analytics, cloud computing/storage, and high-performance computing (HPC), low-cost sensing, and data fusion to business models (based on the value of data and computing, crowd sourcing), economic models (supply and demand) and workforce. The workshop participants have identified opportunities to leverage these enablers to facilitate the evolution of an integrated ecosystem:

CPS is the core driving technology of cybermanufacturing, as it provides a platform for seamless integration between computational models and physical components contingent upon interoperability and resilience.[18] In particular, IoT comprises uniquely identifiable physical objects (connected to the internet) and their virtual representations. IoT has also enabled rapid collection of manufacturing data from diverse sources. The key issues in IoT and its role as a cybermanufacturing enabler include connectivity, identification of critical assets, components, and data, and how to conduct analysis. In fact, the enormous business values of IoT lie in the predictive analytics that translate raw

data into actionable information. Although complete solutions to connectivity are difficult to come up with, there are working partial solutions that are popular in networking (e.g., middleboxes).

SOA provides application functionality (in this case, manufacturing) as a service to other applications, consumers, and vendors. For cybermanufacturing, it enables virtualizing both fabrication and computing resources to enable transformation of manufacturing to a service-oriented paradigm. In spite of challenges in implementing SOA such as minimizing threats, preserving proprietary information, and costs analysis, SOA is identified by major consensus in this workshop as a fundamental enabler. Further investment in both research and implementation of SOA should be encouraged.

Big data analytics provides tools to enrich and empower cyber-physical interface (CPI). It provides a systematic transformation of raw sensory data into meaningful information and actionable operations with the aid of smart analytics. The marriage of IoT, industrial big data, and predictive technologies creates a networked data-rich cybermanufacturing environment in which previously *invisible factors* in decision making are automatically revealed and systematically comprehended.**Error! Bookmark not defined.** A good example of such a network of sensor data is illustrated by MTConnect data machine dashboards.

Powerful convergence of CPS, IoT, cloud and cognitive computing technologies signifies the current trend of smart automation as another industrial revolution, as exemplified by Industry 4.0 in Europe. The focus has shifted from mass-driven, consumer-driven, and computation-driven to network-driven manufacturing based on autonomous, agile, on-demand, and distributed collaboration, with business models based on service and data monetization. It is expected that cybermanufacturing will be subject to the same trend as a specialized subset of the smart automation movement.

The cybermanufacturing revolution requires not only technological enablers, but also a shift in our conceptualization of workflows from a state-based, platform-dependent, and imperative view comprised of low-level actions to a declarative view defined by high-level semantics (i.e., intent). In addition, the industry is starting to acknowledge that a single vendor solution is not practical or desirable. The future of manufacturing will rely more heavily on distributed systems of highly specialized manufacturers integrated into custom workflows in a supply chain. From a software implementation perspective, large monolithic product lifecycle management (PLM) solutions are likely to be replaced with smaller services (i.e., microservices) composed and operated through centralized or decentralized network-orchestration. Standard reference semantics and information models are required to orchestrate modular services, as exemplified by MTConnect. An alternative direction was sketched by the evolution of PLM into a more closed-loop model of sustainable lifecycle information management (SLIM), whose wide adoption will depend on efficient product information models that allow capturing a wide range of product data, easy and quick information exchange, and seamless interoperability. One

way or another, network-centric manufacturing is likely to require a hierarchical distribution, where some decisions are centralized while others are taken locally.

Other enablers of cybermanufacturing should not be overlooked; these include cloud computing and storage services, HPC technologies that facilitate rapid parallel and distributed computation for real-time analytics and feedback, tested microcontroller units (e.g., Arduino, PIC, and MyRIO), tested communication protocols (e.g., Zigbee, Wi-Fi, and Bluetooth), knowledge-based CAD repositories, direct and interoperable CAE tools, immersive environments (i.e., virtual reality), interface standards, sustainable lifecycle information management, and supply chain analysis and integration methodologies.

To manage the vast variety of fabrication processes[19] and the heterogeneous data models associated with them, cybermanufacturing services should be organized with respect to scale/scope of their application. The problems at each level (part vs product vs system) is very different and integration across the levels for computation and planning is crucial.

Cybermanufacturing markets and economy should be analyzed in the context of a global business enterprise. It is made of information systems for customers and service providers, service level agreement (SLA) protocols facilitating information exchange, manufacturing exchange (ME) brokers that handles discrete (e.g., job shop) and continuous (e.g., network flow) processes. As such, ME serves as a "compiler" that generates the executable code and interacts with a global OS for task management, scheduling, and reconfiguration. Market forces may lead to the instantiation of multiple MEs, while different organization take roles as buyers and sellers of products and services, market makers, etc.

Last but not least, the workshop participants identified a promising model of a cybermanufacturing ecosystem in which an intermediary (analogous to Amazon) brings together the designers, suppliers, manufacturers, and customers and matches makers with production facilities. The marketplace (i.e., "app-store") will help app federation and expedite app sales and subscriptions to the MaaS services.

Sample Research Questions:

- The cybermanufacturing ecosystem needs to be properly defined. An ontological diagram that lists the entities in this ecosystem and highlight the relationships could help. What are the dependencies?
- Cyberphysical/manufacturing systems are designed like enterprise software. But can we compose manufacturing systems and their models like web services?
- Sensor instrumentation and standards for connectivity have already arrived. What type of data analytics will be able to take advantage of such developments?

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[19] https://en.wikipedia.org/wiki/List_of_manufacturing_processes

- There appears to be a chasm between the modern tools that have led to the birth of the maker community, and the classical methods of production (casting, turning, and milling). Between large enterprise production (e.g., Boeing 787) and making (DIY, printing at home, etc.): which one is the future of cybermanufacturing?
- Can we engage the community to collectively organize manufacturing knowledge, potentially as an alternative to formal standards or at least a precursor?
- What is the right language to educate the next generation of researchers, engineers, and practitioners, and for cognitive offloading in a changing workforce?
- Can we use gamification as an effective education method (e.g., Minecraft™)? What are other training opportunities in that come with democratized analysis and making for developing a collaborative and response workforce?
- What about the business/management aspects of cybermanufacturing, particularly supply chain management?
- How to balance competing incentives (i.e., value propositions) in the new ecosystem such as performance requirements, price points, and completion deadlines for buyers in contrast to maximizing throughput and profit for sellers?

4. Closing Remarks

The field of cybermanufacturing is in its nascency, and so are its defining concepts, enabling technologies, and surrounding industries. The participants of this workshop brought together a diverse set of ideas, insights, and experiences form several disciplines that intersect over cybermanufacturing. A major hurdle faced by the workshop participants was to define the scope and the nature of cybermanufacturing, as well as its distinguishing characteristics as a discipline. Different points of view were discussed, such as defining the scope in terms of

- Technical characteristics, such as openness, modularity, interoperability, composability, connectivity, scalability, resilience, agility, flexibility, re-configurability, productivity, service-oriented architecture, plug-and-play, diversity of manufacturing processes, nearly free computation and storage, and so on.
- End-to-end workflows from consumer customization, iterative design, interactive prototyping, specialized services, and online testing, to automated manufacturing, quality control, inspection, and delivery in a network of disparate, individual designers, suppliers, consumers, and providers.
- Enabler technologies: cyber-physical interfaces, IoT, cyber-security, networking protocols, big data, smart analytics, machine learning, cloud computing, HPC, communication and control, diagnosis and fault detection, and so on.
- Implications in ecosystem evolution, business strategies, market making, supply chain management, workforce development, education, bidding and negotiation, and so on.
- Implications in democratizing and crowd-sourcing design and manufacturing for the 90% of small-scale innovators and businesses, DIY communities ("makers"), in contrast to optimizing productivity and performance for the 10% of large-scale industrial enterprise manufacturers.
- Best practices in design and manufacturing: imperative versus declarative design, built-fast-fail-fast approach to architectures, focusing standardization on semantics rather than representation schemes/formats, and other lessons learned from the Internet/world-wide-web, traditional models and representation, CAx integration, PLM monoliths versus micro-services, and more.

Although the precise boundaries of cybermanufacturing as a discipline may not be clear at this point in time, this workshop provided a unique opportunity to examine its nature and the technical characteristics. One area where the workshop participants easily achieved consensus is the importance of recognizing the unique nature of cybermanufacturing as an emerging field and urgency of further investment in its future.

It is our hope that the workshop findings reflected in this report will help researchers, engineers, and practitioners from academia, industry, and government in shaping the future directions for developing and advancing the cybermanufacturing suites of 2030.

Appendix 1: Workshop Organization & Agenda

Organizing Committee:
- Vadim Shapiro, University of Wisconsin, Madison, Chair
- Dave Dornfeld, University of California, Berkeley
- Daniela Rus, Massachusetts Institute of Technology
- Placid Ferreira, University of Illinous, Urbana-Champaign
- Deborah Crawford, International Computer Science Institute.

June 2, 2016

8.30 a.m. **Opening Remarks**: Scott Shenker (ICSI) and Bruce Kramer (NSF)

9.15 a.m. **Introductions**: Vadim Shapiro (ICSI and University of Wisconsin)

10:00 a.m. Break

10:15 a.m. **Modular, Composable and Open Manufacturing**

    Composable Interoperability, Saigopal Nelaturi (PARC) & William Sobel (System Insights)

    Transformative Design, Jan Vandenbrande (Defense Sciences Office, DARPA)

11.30 a.m. Lunch

12.45 p.m. **Modular, Composable and Open Manufacturing** (cont'd)

    Provocateurs: Rich Baker (Proto Labs), Jian Cao (Northwestern), Krishnendu Chakrabarty (Duke), Ken Goldberg (UCB), Horea Ilies (U. Connecticut), and KC Morris (NIST)

2.30 p.m. Break

2.30 p.m.　Tour of Autodesk Pier 9

6.00 p.m. Working Dinner

9.00 p.m. Return to Venue

June 3, 2016

8.30 a.m. **Data, Models, Representations**

    From Specs to Parts: A Programmer's Perspective and Ontology, Jarek Rossignac (Georgia Institute of Technology)

    The Role of Ontologies in Enabling Smart Manufacturing, Ram Sriram (NIST)

9.45 a.m. Break

10:00 a.m. **Data, Models, Representations** (cont'd)

    Provocateurs: David Breen (Drexel), Johan de Kleer (PARC), Dinesh Manocha (UNC Chapel Hill), Sara McMains (UC Berkeley), Xiaoping Qian (UWI, Madison), and Ye Wang (Onshape)

11.45 a.m. Lunch

12:45 p.m. **Cybermanufacturing Ecosystem and Infrastructure**

             Cyber-Manufacturing of Customized Apparel, Ming Lin (UNC – Chapel Hill)

             Creating the Amazon Ecosystem for Manufacturing, Tom Kurfess (Georgia Institute of Technology)

2.00 p.m. Break

2.15 p.m. **Cybermanufacturing Ecosystem and Infrastructure** (cont'd)

             Provocateurs: Damian Borth (DFKI), Jay Lee (U Cincinnati), Miron Livny (UWI, Madison), Z. Morley Mao (U Michigan), Bahram Ravani (UC Davis), and Ryan Schmidt (Autodesk)

4.00 p.m. Wrap up

4.30 p.m. Adjourn

Appendix 2. Workshop Attendees

Rich Baker	Protolabs
Morad Behandish	University of Connecticut
Damian Borth	DFKI
David Breen	Drexel University
Jian Cao	Northwestern University
Krishnendu Chakrabarty	Duke University
Gregory Chirikjian	National Science Foundation
Kershed Cooper	National Science Foundation
Deborah Crawford	George Mason University
Jonathan DeKleer	PARC
Rida Farouki	University of California, Davis
Placid Ferreira	University of Illinois Urbana Champaign
Ken Goldberg	University of California, Berkeley
Deborah Goodings	National Science Foundation
Christoph Hoffman	Purdue University
Horea Ilies	University of Connecticut
Bruce Kramer	National Science Foundation
Tom Kurfess	Georgia Institute of Technology
Kincho Law	Stanford University
Jay Lee	University of Cincinnati
Ming Lin	University of North Carolina, Chapel Hill
Miron Livny	University of Wisconsin, Madison
Dinesh Manocha	University of North Carolina, Chapel Hill
Morley Mao	University of Michigan
Sara McMains	University of California, Berkeley
KC Morris	National Institute of Standards and Technology
Saigopal Nelaturi	PARC
ZJ Pei	National Science Foundation
Xiaoping Qian	University of Wisconsin, Madison
Bahram Ravani	University of California, Davis
Jarek Rossignac	Georgia Institute of Technology
Ryan Schmidt	Autodesk
Vadim Shapiro	University of Wisconsin, Madison, International Computer Science Institute
Scott Shenker	International Computer Science Institute
Will Sobel	Systems Insight
Robin Sommer	International Computer Science Institute
Ram Sriram	National Institute of Standards and Technology
Jan Vandenbrande	Defense Advanced Research Projects Agency
Ye Wang	Onshape
Paul Wright	University of California, Berkeley