Additive Manufacturing

Rethinking CAD

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The Need

- **Efficient** exploration of geometry, material/ microstructure and processing trade-offs in an integrated environment
  - Eliminate the need for expert designers to spend inordinate amounts of time using multiple software tools to develop a point-wise optimized geometry/ material/process
- Direct control of mfg machines based upon outputs from the CAD tool

Questions Posed to Attendees
(at various times during workshop)

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- What capabilities are needed?
- What are the competing paradigms?
  - How do they represent geometry, physics, materials, etc.
  - Can shape grammars and/or shape languages describe function and shape so that computation/ optimization can be done directly?
- Are there new or emerging paradigms for 3D design?
- If you were a program manager, what would you fund?
  - A roadmap for key technological & algorithmic development to guide investment
- If we held another workshop, what should we focus on?

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The Agenda for the Meeting

- First Day:
  - Morning: Why do we need to Rethink CAD?
  - Afternoon: New Paradigms for CAD
  - Evening: Dinner and Informal Discussions
- Second Day:
  - Hod Lipson
  - 3-minute Lightning Talks – everyone here is an expert
  - Breakout sessions
  - Report Back & Adjourn

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Breakout #1

- CAD Foundations
  - Design, simulation/analysis & mfg. all in one package
  - Location-specific design (beyond geometry to mat'l)
  - Framework that is representation-independent
    - Supports multiple representations for geometry, material, physics, etc.
  - Framework that is multi-scale for materials/properties, etc.
  - Tools for modeling & refining design **intent**
  - Consensus that researchers need to identify candidate frameworks, and fight it out via research.

  - TAKEAWAY NEEDS – (1) FRAMEWORK & (2) INTENT

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Breakout #2

- User Interface
  - Input Technologies – need multiple ways
  - User Understanding
    - Expert vs. novice modalities
      - User overload, what questions are they interested in, etc.
    - Computers learning from users and adapting…
  - Design System (not CAD)
    - Human to Computer plus Computer to Human interactions
    - User-specific interfaces within the same system
    - Help user converge to a good design (with level of detail given to the user fitting the state of design between conceptual vs detailed design)
    - How do we provide templates and primitives without overly constraining or pushing the designer to a particular solution modality?

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Breakout #3

- Synthesis & Matter Compilers
  - Need a design language for human-computer interaction
    - Geometry, material, function, accuracy, modularity, fidelity, uncertainty, speed, etc…
    - Decoupling of form and function at multiple scale
  - Natural interface, with ease of use that is user-specific, and feedback from the computer that is meaningful to the user
    - …it will only last two weeks, versus fatigue or crack propagation statistics
  - Synthesis across scales
    - simulate and generate geometry, material, function at all relevant length scales
  - Framework where people can put domain-knowledge-expertise information into the environment…

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Breakout #4

- Novel Applications
  - Digital Duct Tape
    - In the field… get it done (MacGyver)
    - Need software, hardware, etc. built just for this: flexible, adaptable, reconfigurable.
  - Needs for new applications
    - New optimization tools
    - Control systems implemented into design tools, mechatronics systems, trade-off weight for control system complexity
    - Function-specific tools (instead of the one-size-fits-all tool)
    - Privacy and protectability of design (make the good guys better than bad guys at staying ahead of "hacking" of info).

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Summary of Research Needs

- **Physics-Based CAD**
- **Design Intent** (or Design Specification) **Language (DIL)**
- **Synthesis** Tools for Generating Design Alternatives Based on DIL Descriptions
- **Trade-Off Engine** that enables evaluation of alternative designs: trade-offs among weight, stiffness, performance, cost, control system, power consumption, etc.

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Physics-Based CAD

- No one has integrated geometry, materials & properties
  - No analysis of physical feasibility interactively (real-time)
- Need to integrate materials into CAD for discrete parts.
  - Function-based rep's and discrete methods accept some mat'ls info
  - Need: specify distributions of physical properties and have the system figure out material or material composition
    - Requires geometry + material process-structure-property relationships
      - Process simulation capabilities at the right level of abstraction for the stage of the design process (i.e., conceptual, preliminary, detailed).
      - Multi-scale representations that can generate models at any desired level
- We can't deal with multiple functions in CAD
  - No formal methods to distinguish the electrical circuit from the mechanical component it's embedded in (some ad hoc methods)

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Design Intent Language

- A language of function and behavior is needed.
  - Describe function, requirements, and constraints in a clear, computer-interpretable manner.
  - Specifications should be the primary representation for a design and as the basis for analysis and evaluation of design artifacts (not geometry).
- A language of physical principles is needed that can relate behavior to the structures that generate that behavior
- Borrow from computational languages and AI
  - Medical diagnosis and treatment (e.g., Bioportal, SNOMED), earth and environmental terminology (e.g., SWEET, fpl.nasa), and general reasoning (e.g., Cyc) are more advanced than mechanical design ontologies.

Synthesis

- Generation of design alternatives for a certain objective.
  - Topology and shape optimization of structures are well developed
  - For other types of devices and for multiple objectives (e.g., compliant mechanisms), there is a significant lack of methods.
- Need to explore non-traditional trade-off spaces
  - Synthesizing devices from an understanding of behavior, physical principles and (simplified) geometric models fall into AI
    - Research underlying DIL, qualitative reasoning, and function-behavior-structure, analogical reasoning, and search can serve as the foundation
  - Weight vs. control systems (space shuttle arm, inflatable devices).
    - For example: an objective implies a region of the design space that is defined by physical principles that underlie the relationship between behavior and structure. A robot arm consisting of rigid metal links and servo motors relies on different physical principles than an inflatable arm with pneumatic actuators, many sensors, and a robust control system.

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Trade-Off Engine

- Given a description in a Design Intent Language, generate alternative designs, analyze them, and iterate
  - Evaluation of trade-offs between competing objectives (e.g. weight, cost, power, controls intelligence, performance, etc.)
- Each main objective implies a design space of alternatives
  - With some uncertainty modeling methods, estimates can be made of device properties without having to enumerate each alternative design within the design region.
  - If such estimates can be computed, then trade-offs among competing objectives need to be explored. Exploring trade-offs among design space regions in the context of a DIL and the synthesis topic just presented would be worthy of investigation.

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What went right

- The topic is timely
  - Huge felt need from industry, academia, DoD
  - Almost everyone we invited accepted the invitation
- 3-minute lightning talks were excellent
  - Used a 3-minute countdown timer that was visible to the speaker and made an audible noise when time expired
- Short presentations the first morning went well
- Assigned breakout discussions mixed people up and gave them a direction for starting their conversations
- Identified gaps in knowledge that are critical research topics for enabling Matter Compilers

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What went Wrong

- Invited too many “established experts” to present and not enough “up-and-coming” creative thinkers
- Wanted 25 minute presentations plus 20 minutes discussion in afternoon session, but speakers saw 45 minutes on the agenda and filled it all…
- Should have had shorter “keynote” presentations and multiple times for interactions to build upon knowledge…
- People talked too much about what they do instead of what we should be doing
- People weren’t good at putting themselves in DARPA PM’s shoes

- Only a couple DARPA PMs showed up…
  - Quite hard to get DARPA PMs to show up for something at the intersection of I2O, DSO & TTO
- Only a few ISAT Members showed up

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What Next? Follow-up Workshops?

- Computational Languages for Matter Compilers
  - Purpose: a language that captures design intent (translator between mechanical design natural language and a computational language)
    - Geometry, function, properties, physical principles, performance, weighting of trade-off functions, manufacturing constraints, etc.
    - Relevant to experts and novices
  - Once we have a "computational design language," how do we do synthesis based upon that language
    - Flesh out ideas for
      - How to make "function" languages operational
      - What is needed for mechanical synthesis, plus its extension to complex systems design with mechanical, electronic, and software subsystems?
- 1 day, focused workshop with only 15-20 key thinkers

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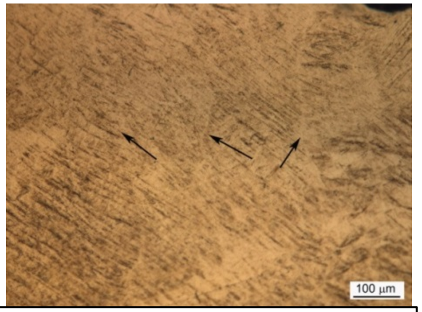
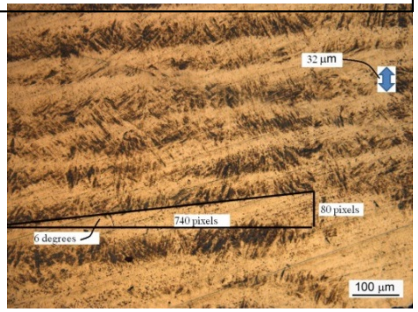
Related Flash Workshop … Authenticated Parts

- Hide "authentication" code inside
  - Unique physical response to stimulus due to local/ microstructural tweaks and patterns in the material
    - Can "read" authenticity using multi-spectral waves (EM or ultrasonic) from thermal, magnetic or stress response
  - Asymmetric
    - Cheap to Implement
    - Prohibitively Expensive to Reverse Engineer
  - Requires "CAD" link between Geometry, Microstructure/Composition and Structure-Properties-Performance Relationships at the Local & Global Level
    - Need knowledge of how to manufacture with local control…



Thermal/Strain History during mfg. determines local microstructural features



- Same infrastructure needed for anti-tamper and reverse engineering resistant structures for DoD applications