DESIGN DECISION SUPPORT FOR MBE WITH INFORMATION MODELING

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Overview

- MBE considerations of: 1) semantics and 2) Additive Manufacturing (AM) capabilities

- Toward semantic knowledge management for design/manufacturing

- Method to use information for design/manufacturing decisions

- How we can integrate knowledge domains

- A way to apply this approach for industry
Semantic knowledge management for design / manufacturing

• Motivation
  • Capturing and using AM information in early design
  • Compare AM alternative to other processes early
  • Choose the best process combination early

• Prior approaches for conventional manufacturing
  • Work by Dr. Ameri at Texas State and others

• Approach to integrate AM information

• Process to execute decision rules

• Case study: => Should we AM this part or not?

• Discussion – recent breakthrough
Background

- Why ontologies?

- Engineering examples:
  - E-Design framework at UMass
  - Works at:
    - Georgia Tech
    - Clemson
    - Virginia Tech
    - Purdue
    - Wayne State

Semantic Web is ...
- a metadata based infrastructure for reasoning on the Web
- an extension, not a replacement of the current web

Courtesy of: http://www.w3c.it/talks/2005/openCulture/slide7-0.html
Prior work at Texas State

- Manufacturing Service Description Language (MSDL) ontology

Prior work at Texas State

- Computer Aided Process Planning (CAPP) with MSDL

- Executed for machined part based on its STEP information
Taxonomy development

Standard Terminology for Additive Manufacturing Technologies

This standard is issued under the fixed designation F2792; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (e) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This terminology includes terms, definitions of terms, descriptions of terms, nomenclature, and acronyms associated with additive-manufacturing (AM) technologies in an effort to standardize terminology used by AM users, producers, researchers, educators, press/media and others.

Note 1—The subcommittee responsible for this standard will review definitions on a three-year basis to determine if the definitions are still accurate as stated. Revisions will be made when determined to be necessary.

2. Referenced Documents

2.1 ISO Standards


3. Significance and Use

3.1 The definitions of the terms presented in this standard were created by this subcommittee. This standard does not purport to address safety concerns associated with the use of AM technologies. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use of additive manufacturing.

4. Additive Manufacturing Process Categories

4.1 The following terms provide a structure for grouping current and future AM machine technologies. These terms are useful for educational and standards-development purposes and are intended to clarify which machine types share processing similarities. For many years, the additive manufacturing industry lacked categories for grouping AM technologies, which made it challenging educationally and when communicating information in both technical and non-technical settings. These process categories enable one to discuss a category of machines, rather than needing to explain an extensive list of commercial variations of a process methodology.

binder jetting, n—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

direct energy deposition, n—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

material extrusion, n—an additive manufacturing process in which material is selectively deposited through a nozzle or orifice.

material jetting, n—an additive manufacturing process in which droplets of build material are selectively deposited.

powder bed fusion, n—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

sheet lamination, n—an additive manufacturing process in which sheets of material are bonded to form an object.

vat photopolymerization, n—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

5. Terminology

5.1 Definitions

3D printer, n—a machine used for 3D printing.

3D printing, n—the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology.

Discussions—Terms often used synonymously with additive manufacturing, in particular associated with machines that are low end in price and/or overall capability.

Process capability definition

- Using Protégé v. 3.4.8
- Defined by property restrictions
  - Some inherited from conventional process definitions:
    - SAMPro:PowderBedFusion
      - SAMPro:Metal
        - SAMPro:ElectronBeamMelting
        - SAMPro:SelectiveLaserMelting
      - SAMPro:Sintering
        - SAMPro:SelectingHeatSintering
        - SAMPro:SelectiveLaserSintering
    - SAMPro:Metal
      - MSML acceptsMaterial some (MSDL:Metal and MSOL:Polymer)
      - MSML acceptsMaterial some MSML:Powder
      - MSML ChangesGeometry has true
      - MSML ChangesProperty has true
      - MSML hasProcessInput some (MSDL:ProcessInput and (MSDL:hasMatterState some MSOL:Powder or MSOL:Solid))
      - MSML hasProcessOutput some (MSDL:ProcessOutput and (MSDL:hasMatterState some MSOL:Solid))
  - Others unique to a specific AM process:
Knowledge management framework

- AM information fits into prior structural framework
- This way, AM processes can be compared to the others.
- Enables Semantic Additive Manufacturing PROcess Planning (SAMPro)
Decision rule process of SAMPro

- Aligned with traditional DFM principles
- Executes on information – prior to any CAD
- Early high level comparison => best path to proceed

Constraints

- Identify non-feasible processes and penalize

Features

- Identify single processes capable of given features
- Identify process combinations based on feature capabilities

Combinations

- Add a secondary process
  - No
  - Yes
  - Same process combination

- Adjust process costs based on high or low tolerance range position
- Formulate total costs of each process combination alternative
- Select the process combination with the lowest total cost
Case study – steel spur gear

- How should we make it? =>
- Part information

<table>
<thead>
<tr>
<th>Information given about part design</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSL.hasShape</td>
</tr>
<tr>
<td>MSL.isMadeOf</td>
</tr>
<tr>
<td>MSL.hasTolerance</td>
</tr>
<tr>
<td>MSL.hasSurfaceFinish</td>
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<tr>
<td>MSL.hasDiameter</td>
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<tr>
<td>MSL.hasLength</td>
</tr>
<tr>
<td>MSL.hasWidth</td>
</tr>
<tr>
<td>MSL.isStandard</td>
</tr>
<tr>
<td>SAMPro:hasCostPerUnit</td>
</tr>
<tr>
<td>SAMPro:hasBestProcessCombination</td>
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<tr>
<td>SAMPro:isFeasibleProcess</td>
</tr>
<tr>
<td>SAMPro:hasProductionTimePerUnit</td>
</tr>
<tr>
<td>SAMPro:hasToolingAndSuppliesCostPerUnit</td>
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</table>

<table>
<thead>
<tr>
<th>Information to be determined by SWRL rules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
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<tr>
<td>-------</td>
</tr>
<tr>
<td>5.0E-5</td>
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<tr>
<td>5.7E-5</td>
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<tr>
<td>120</td>
</tr>
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</table>
Modeling the information about processes

• Compared to information about the part’s requirements

• Utilizes the same framework for AM and conventional manufacturing
  • Note that slots are labeled as MSDL here.
  • Common slots for all processes

  \[
  \text{SAMPro:PowderBedFusion}_{\text{for Spur Gear}} = >
  \]
Candidate process combinations

Examples
- Several alternatives to compare
Case specific rules

- Example: What combination of processes are needed to EDM the part?
- SWRL rule to check for tolerance by EDM:

```swrl
MSDL:Part(SAMPro:SpurGear) \∧ MSDL:WireEDM(SAMPro:WireEDM_Spur_gear) \∧ MSDL:hasTolerance(SAMPro:SpurGear, ?y) \∧ MSDL:hasAccuracyLower(SAMPro:WireEDM_Spur_gear, ?x) \∧ swrlb:greaterThan(?x, ?y) → 
SAMPro:hasSeparateSecondaryProcess(SAMPro:CombinationOfProcesses_EDM_for_spur_gear, SAMPro:GearHobbing_Spur_gear_teeth) \∧ 
SAMPro:hasSeparateThirdProcess(SAMPro:CombinationOfProcesses_EDM_for_spur_gear, SAMPro:Reaming_bore_for_spur_gear) \∧ 
MSDL:hasProcessOutput(SAMPro:CombinationOfProcesses_EDM_for_spur_gear, SAMPro:ProcessOutput_completely_finished_spur_gear)
```

- Inferred information from rule that determined additional processes are necessary:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSDL:hasProcessOutput</td>
<td>SAMPro:ProcessOutput_completely_finished_spur_gear</td>
</tr>
<tr>
<td>rdf:type</td>
<td>SAMPro:CombinationOfProcessesForSpurGear</td>
</tr>
<tr>
<td>SAMPro:hasSeparatePrimaryProcess</td>
<td>SAMPro:WireEDM_Spur_gear</td>
</tr>
<tr>
<td>SAMPro:hasSeparateSecondaryProcess</td>
<td>SAMPro:GearHobbing_Spur_gear_teeth</td>
</tr>
<tr>
<td>SAMPro:hasSeparateThirdProcess</td>
<td>SAMPro:Reaming_bore_for_spur_gear</td>
</tr>
</tbody>
</table>
Addressing OWL limitations for calculations

- Import of swrlm built-in
  - Eval function for multiple operations
- Example: \( y = mx + b \)
- Execution of the rule below returns the value of
Discussion

Pros
- Consistent with emerging Semantic Web technologies
- Advantage of using prior work to add new concepts
- Shows that AM can fit within conventional manufacturing framework
  - Suitable for consistent logical comparisons => process selection
- Conceptual proof of this concept
  - Potential for early design decisions with transparency
- Extendable to accept constantly expanding knowledge base

Cons
- Time to create rules
- Learning syntax
- Functionality of rules
- User friendliness of the tools needs improvement
Higher level challenges

- Basic Formal Ontology (BFO) alignment
  - Theory developed by Barry Smith from U at Buffalo and others
  - Can domain concepts be represented consistently and related with other domains?

- Later, how we address these challenges
- Next, methodical prescription for use...
Method to inform design decisions

- **Motivation**
  - Right decision made early – AM or not AM?

- **Decision Support System for Additive Manufacturing (DS-SAM)**
  - Usable template
  - Rationale

- **Design process**

- **Case study**

- **Recent improvements to the method**

Background

- **Some current AM research gaps**
  - Design and manufacturing integration
  - Early design stage process planning
  - AM process capabilities vs. conventional manufacturing
  - When and how to best use DFAM
    - When should we not use AM?

- **Objectives:**
  1. Decision making method
     - With early stage information
  2. Usable template to assess and compare alternatives
How can we:
1. decide correctly? (effectiveness)
2. decide early? (efficiency)
Where does it fit?

1. Identify needs. Plan for the design process.
   - Form design teams.
   - Develop tasks.
   - Schedule project.
   - Decompose into subproblems.

2. Develop engineering specifications.
   - Identify who the customers are.
   - Generate customers' requirements. What do they want?
   - Evaluate competition. How is it done now?
   - Generate engineering specifications. How will the requirements be measured?
   - Set targets. How much is good?
   - Design review.
   - Terminate.

3. Develop concepts.
   - Generate concepts.
   - Evaluate concepts.
   - Decompose into subsystems.
   - Communicate concept information.
   - Update plans.
   - Design review.
   - Terminate.

4. Develop product.
   - Generate product.
   - Design for manufacture.
   - Design for assembly.
   - Communicate product information.
   - Decompose into components.
   - Evaluate performance.
   - Design review.
   - Terminate.

5. Linear or holistic?


7. Release product.

Rationale for approach

- Manufacturing influence on design
  - Conventional manufacturing => reduce complexity
  - DFAM => increase complexity to improve design

- Increases array of design concepts

- Holistic comparison of alternatives
  - Parameterized
  - Multiple attributes
DS-SAM approach

1. Conceptual design
   - Conceptual Design for Additive Manufacturing (DFAM)
     - Functional Specifications
     - Critical to Function (CIF) Requirements
     - Conceptual Design for Manufacturing (DFM)

2. Parameterization
   - Geometric Requirements
   - Material Property Requirements
   - Part Volume
   - Quantity
   - Other (e.g., customer preferences, time, etc.)

3. Evaluation of alternatives
   - Define Design Attributes
   - Idea Generation
   - Formulate Aggregated Scoring of Alternatives
   - Check Estimated Costs
   - Concept Selection

4. Decision making
   - AM or Conventional?

5. Detailed design and manufacturing planning
   - Design for Manufacturing
   - CAPP

6. Cost verification
   - Cost Exceed Estimate?

7. Design optimization
   - Design Finalized?
   - Appropriate Design

Case Study: Animal Subject Test Mechanism

- Parts used in mouse-leg mounting rig for cancer research lab
  - Originally CNC machined of aluminum
- **Goal:** Use DS-SAM to determine whether correct process was used, analyze for various quantities
- Collaboration with Prof. Maureen Lynch at UMass Life Sciences Lab

Ankle Fixture  Knee Fixture  
Original Configuration  

Proposed AM Parts
Function specifications and requirements

**Functional Specification**
- Must be attachable and detachable from rig
- Must allow mouse to be mounted easily
- Must be capable of gripping the mouse securely
- Must be able to be cleaned without damaging parts
- Must not cause injury or pain to mouse

**Critical to Function Requirement (CtF)**
- Dimensions of knee and ankle slot must be exact
- Knee and ankle fixtures must be detachable
- Dimension of bore on mounting disk must be snug and parallel to the shaft
- Material must be sufficiently strong to withstand cyclic loading

Conceptual Design for Additive Manufacturing (DFAM)

Functional Specifications

Critical to Function (CtF) Requirements

Conceptual Design for Manufacturing (DFM)
# Alternatives identified

## 2. Parameterization
- Geometric Requirements
- Material Property Requirements
- Part Volume
- Quantity
- Other (i.e. customer preferences, time, etc.)

## 3. Evaluation of alternatives

<table>
<thead>
<tr>
<th>Material</th>
<th>Method of Fabrication</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Plastic</td>
<td>Injection mold as 8, separate parts</td>
</tr>
<tr>
<td>2 Metal</td>
<td>Machine as 8, separate parts</td>
</tr>
<tr>
<td>3 Plastic</td>
<td>Injection mold as 2 parts</td>
</tr>
<tr>
<td>4 Metal</td>
<td>Machine as 2 parts</td>
</tr>
<tr>
<td>5 Plastic</td>
<td>Rapid Injection Mold as 2 parts</td>
</tr>
<tr>
<td>6 Plastic</td>
<td>AM as 8, separate parts</td>
</tr>
<tr>
<td>7 Metal</td>
<td>AM as 8, separate parts</td>
</tr>
<tr>
<td>8 Plastic</td>
<td>AM as 2 parts</td>
</tr>
<tr>
<td>9 Metal</td>
<td>AM as 2 parts</td>
</tr>
</tbody>
</table>
Formulate aggregated scoring

- Scoring from expert with AHP
  - Preference
  - Performance
- DFA for “Ease of Assembly”
  - 8 part efficiency = 32%
  - 2 part efficiency = 100%

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<tbody>
<tr>
<td>Cleaning</td>
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<td>10</td>
<td>7</td>
<td>10</td>
<td>7</td>
<td>7</td>
<td>8</td>
<td>7</td>
<td>8</td>
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<tr>
<td>Withstand Fatigue Load</td>
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<td>Geometry</td>
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<td>6</td>
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<tr>
<td>Mouse Safety/Comfort</td>
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<td>8</td>
<td>10</td>
<td>3</td>
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</tbody>
</table>
Comparative results

Final formulation: \[ \text{PerfCost}(N) = [(\text{PerfScore}) \times (\text{PerfWeight})] + [(\text{CostNorm}(N)) \times (\text{CostWeight})] \]

<table>
<thead>
<tr>
<th>Performance Rankings of Alternatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(^{st}) Metal Machine 8 Parts (0.1649)</td>
</tr>
<tr>
<td>2(^{nd}) Metal Machine 2 Parts (0.1519)</td>
</tr>
<tr>
<td>3(^{rd}) Metal AM 2 Parts (0.1353)</td>
</tr>
<tr>
<td>4(^{th}) Metal AM 8 Parts (0.1274)</td>
</tr>
<tr>
<td>5(^{th}) Plastic AM 2 Parts (0.1036)</td>
</tr>
<tr>
<td>6(^{th}) Plastic IM 8 Parts (0.0984)</td>
</tr>
<tr>
<td>7(^{th}) Plastic AM 8 Parts (0.0958)</td>
</tr>
<tr>
<td>8(^{th}) Plastic IM 2 Parts (0.0711)</td>
</tr>
<tr>
<td>9(^{th}) Plastic Rapid IM 2 Parts (0.0515)</td>
</tr>
</tbody>
</table>

Animal Test Part Performance-Cost Score vs. Part Quantity With Weighted Preference

Best choice
Discussion

Contributions:

- Practical guidance
- Useful methodology
- Recent improvements

Important guidelines:

1. Is it grounded in established principles?
2. Can we make the best decision as early as possible?
3. Is it as efficient as possible?
4. Can we combine for fit with other approaches?
   - a) How does it compare with others?
   - b) And within high level domain concepts?...
How can we solve the high level information modeling problem?

A proposed integration of knowledge domains:

- **BFO**
- **Core Product Model (CPM)**
- **Business Model & Entrepreneurship (BME)**
- **Functional Basis (FB)**
- **MSDL**
- **Innovative Capabilities in AM (ICAM)**
- **SAMPRO**
- **Capability Driven Innovation (CaDI)**
- **Design and Manufacturing Performance**
- **Case Studies in AM (CSAM)**
- **New Ontology**
- **Published ontology**

Dependency arrows indicate relationships between the domains.
Industry relevance

The disconnect between CAD and metal AM operations gets expensive!

- **Problem:** Nothing tells a CAD operator whether their model will produce a good or bad part until it’s too late!

- **Solution:** An effective tool would alert the CAD operator by a green light or red flag.
Problem statement

There’s a lack of open qualification and certification data tools for metallic AM parts!

- Potential data includes: tool parameters, result targets, scan paths, process data, and measured results.
- Existing CAD tools can not acquire and manage such data
- Framework required to manage, store, and manipulate data

Courtesy of: http://ftllabscorp.com/
How it works

1. Part-file
2. Interface
3. Extract part feature information
4. Inference with AM Best practices

- Predictive model
- Reasoning on voxel/sloxslocel information
- Visual voxelization using G-Code
- Analysis of voxel location and status
- Reasoning on process information
- Results visualization

Our Role
Visualization tool flow

- **CAD Software + part files**
  - Computational Geometry tool
  - Solidworks Plugin Interface from CAD agnostic suite of plugins
  - .stl files for features
    - CAD based feature ontological framework tied with AM Capabilities
    - Unity Visualizer tool
CAD feature ontology in BFO

- BFO
- Core Product Model (CPM)
- CAD Based Feature Ontology
- SAMPro
- MSDL
- DED-LENS Ontology

Dependency
Ontology module
Summary

- Represent knowledge for AM with that of other manufacturing semantically (based on context)
- Information can be used in methodical decision making.
- Method addressed early decision making about AM or not AM assessments.
- Future work could link information domains at the highest level of concepts.
- Application can relate part features to AM capabilities to influence design/process decisions.
Questions?