Sustainable Manufacturing via Multi-Scale Physics-Based Modeling

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Project Objective

- What are we trying to do?
  - Develop and demonstrate a new **manufacturing-informed design paradigm** to dramatically improve manufacturing productivity, quality, and costs of machined components

- What is the problem?
  - Current machining processes and cutting tool designs are slow and too conservative, leading to high costs and significant waste
  - Currently, design teams are “manufacturing-aware,” but not necessarily “manufacturing-informed”
  - Performance, Cost and Quality problems are found too late in the Product Development Process

- Why is it Difficult?
  - Lack of sufficient fundamental understanding of process physics
  - Lack of physics-based process design and optimization tools for finish and semi-finish operations
  - High computational costs of modeling at multiple length and time scales for process optimization
  - Statistical variability of tooling, equipment and materials
Technical Innovation

- **State-of-the-art**
  - “Manufacturing aware” part and process design – No knowledge of process outcomes (cost, quality, performance) until manufacturing trials
  - Long and slow trial-and-error design of machining processes and cutting tools
  - Resulting manufacturing processes and cutting tool designs are conservative – unnecessarily slow, sub-optimal and expensive

- **Innovation**
  - **Multi-scale Physics-based Modeling** can provide detailed knowledge of process outcomes before manufacturing trials
  - **Physics-based Optimization** can squeeze significant productivity from state-of-the-art machining processes
  - **Reduce** (rough and finish) **machining costs and cycle times**, while **extending tool life** and maintaining **component performance**

- **Numerical simulation / optimization**
  - Very challenging but preferred to trial-and-error
  - Over 20 years of continuous development and software deployment
Technical Innovation

- **Distributed or hybrid parallelization of AdvantEdge**
  - Shortening time-to-solution and project size demands of customer are increasing
  - Employ multiple computers connected with a fast interconnect
    - Substantial change in programming paradigm; data-dependencies are explicit
    - Method has been exploited in other field of simulation for decades
    - Hardware: MPI, Intel Haswell CPUs 36 core, Infiniband (tested extensively)
  - Allows for larger problems to be made tractable than present technology
  - Faster assessment of accuracy via rapid mesh resolution studies
  - **Cost:** implementation requires substantial development effort

- **CAM system integration with Production Module and advanced optimization algorithm to recommend optimization values**
  - Seamless bi-directional integration with CAM system
  - Allows physics-based optimized manufacturing data to be centrally managed in Product Lifecycle management workflow
  - Converts decision making know-how in physics-based optimization domain into software system to benefit expanding end user bases
  - Allows physics-based toolpath optimization to be automated from CAM to Production Module to CAM
Technical Approach

- **Distributed parallelization of AdvantEdge**
  - Domain decomposition (ParMETIS, DSDE), parallel mesh adaptation, parallel contact algorithm based on one-sided communication

- **Algorithmic challenges**
  - Parallel mesh adaptation strategy and implementation
  - Parallel surface contact algorithms and efficient collision detection
  - Domain decomposition / load-balancing must be driven by the physics simulated

- First generation distributed solver is meeting most objectives; needs work
Technical Approach

- CAM Integration and Recommended Optimization Values

- Optimized toolpath by physics-based toolpath optimization model
- Optimization settings
- Version controlled information

- CAM tooling library
- Toolpath
- Postprocessor data
- Stock geometry
- Material data

Physics-based Toolpath Optimization
Recommend Optimization Values
Baseline Analysis

Production Module
Material Model
Project Settings File
Transition and Deployment

- Technology will be incorporated into existing commercial products; transition has begun
- Cutting Tool Manufacturers Care
  - **Who**: Kennametal, Ceratizit, Ingersoll, Sandvik, Allied Tools
  - **Why**: Improve cutting tool designs - specifically coolant delivery and tool life-related improvements, faster tool design iterations
- Aerospace, Auto, Medical, O&G manufacturers
  - **Jet Engine**: GE, Pratt & Whitney
  - **Airframe**: Boeing, GKN Aerospace, NexTech
  - **Auto**: GM, Ford
  - **Why**: Higher tool life, reduced cycle times, reduced costs, reduced energy consumption, effective coolant usage, improved final microstructure properties and performance, accelerated insertion of new materials
Transition and Deployment

- Heavy Equipment (Caterpillar)
- Medical Implants (e.g. DePuy Synthes)
- Oil & Gas and Power Systems (GE)
- Technology Sustainment Strategy
  - Partner with early adopters and market leaders to interface and integrate into their systems and validate the business case
  - Partner with industry leading PLM system developer to speed up deployment and collaborate in the early stage of development
- Transition results to date
  - Core technology from DoE program resulted in the sale of 40 software licenses across 20 companies in 2015
  - Sales were primarily to automotive and aerospace companies interested in efficient manufacturing
Measure of Success

• Impact and Metrics
  • Metrics (fundamental level): Correlation (error %) with experimental data for Forces, Torque, & Microstructure
  • Metrics (tool-path level): Achievement of 50% reduction in machining cycle time on representative components

• Energy and Economic Impact Estimates
  • Achieve 50 percent reduction in machine tool tare energy and water consumption in machining via reduced cycle times, coolant and tooling consumption.
  • Achieve a 50 percent reduction in cycle times and energy consumption for machining.
  • Save over 4.1 trillion BTUs per year and 7.2 million metric tons of CO2-equivalent per year for machining processes.
  • Estimated savings of $1.14 billion in tooling costs, reduction of $24 billion in cutting fluid costs
### Project Management & Budget

- **Project Duration**: 36 months
- **Project task and key milestone schedule**
  - Project Plan has Qualitative and Quantitative Milestones
  - Comparison against experiments (validation metrics)
- **Have met all the go / no-go gates and milestones**

<table>
<thead>
<tr>
<th>Number</th>
<th>Go/No-go Description</th>
<th>Verification Method</th>
<th>Planned Completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coolant model implementation</td>
<td>Simulate 27 turning cases, achieve 90% completion success rate</td>
<td>End of Budget Year 1</td>
</tr>
<tr>
<td>2</td>
<td>Tool wear model prediction</td>
<td>Simulate 18 conditions, achieve 90% success rate of completion</td>
<td>End of Budget Year 2</td>
</tr>
<tr>
<td>3</td>
<td>Cutting force prediction</td>
<td>Predicted and measured forces within 30% agreement</td>
<td>End of Budget Year 2</td>
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### Total Project Budget

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<tbody>
<tr>
<td>DOE Investment</td>
<td>$4,069,880</td>
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<tr>
<td>Cost Share</td>
<td>$964,719</td>
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<tr>
<td><strong>Project Total</strong></td>
<td><strong>$5,034,599</strong></td>
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Results and Accomplishments

- Ported AdvantEdge technology to high performance computing on multi-core, distributed memory systems
  - Work is on-going; building multi-level parallelization (decoupled approach)
- Seamless bi-directional CAM integration
  - Deployed at several customers sites
  - Improved: productivity, traceability, manufacturing data management, process of design change, and optimization turnaround cycle time
- Optimization values recommendation “Expert System”
  - Tested and verified with 200+ customer toolpath programs
  - Advanced algorithm and enhanced workflow significantly improve the efficiency and effectiveness of using physics-based toolpath optimization