UTC/RTC Institute for Advanced Systems Engineering: Fusion of Physics-based Modeling and AI for the Predictive Maintenance of Precision Machining

featuring

Dr. George Bollas
Director, UTC Institute for Advanced Systems Engineering at UCONN

Hosted by Connecticut Center for Advanced Technology, Inc. (CCAT) & Advanced Manufacturing Employer Partnership (AMEP)

December 3, 2020

By participating in this webinar hosted by Connecticut Center for Advanced Technology, Inc. (CCAT), you automatically agree to authorize recording of audio and visual content presented during the live event and consent to subsequent use of the recording in the public domain by CCAT unless otherwise stated. The audio and visual recording of the live webinar includes documents and materials exchanged or viewed during the live event; questions asked and poll answers provided by you during the live event; the closed captioning transcript; and the chat box transcript.

If you do not consent to the audio and video recording of the live webinar event, please do not join the session.
Presenters

• Ron Angelo, CCAT, President & CEO
• AMEP Co-Chairs
  – North CT: Glenn Ford, President, Phoenix Manufacturing
  – Central CT: Charles Daniels, Chief Financial Officer, Wepco Plastics
• Ari Santiago, President, IT Direct
• Colin Cooper, Chief Manufacturing Officer, State of CT
• Dr. Kelli Vallieres, Executive Director, CT Office of Workforce Strategy
  Vice Chair: Governor’s Workforce Council
• Dr. George M. Bollas, UTC Endowed Chair Professor, Chemical & Biomolecular Engineering and Director, UTC Institute for Advanced Systems Engineering, UConn
• McAllister & Quinn
  – Chris Fish, Vice President
  – Jake Parduhn, Director of Federal Affairs
Agenda

• A Conversation with Made in America’s Ari Santiago
• CT State Updates (Colin Cooper and Dr. Kelli Vallieres)
• Modeling & AI for Predictive Maintenance of Precision Machining (Dr. George M. Bollas)
• CT Manufacturer’s Perspectives (Glenn Ford, Charles Daniels)
• Federal Updates from McAllister & Quinn
• CCAT Program Updates (Ron Angelo)
A Conversation with Ari Santiago

Host of the Made in America Podcast - we’ve got lots of great CT manufacturing stories!

Where can you find the podcast?
- Podcast website: madeinamericawithari.com
- YouTube channel: youtube.com/user/itdirect151

Read our featured article in the Hartford Business Journal:
https://tinyurl.com/MIA-HBJ
STATE UPDATES

Colin Cooper, Chief Manufacturing Officer, State of CT

Dr. Kelli Vallieres, Executive Director of CT Office of Workforce Strategy and Vice Chair of the Governor’s Workforce Council
Fusion of physics-based modeling and AI for the predictive maintenance of precision machining

George M. Bollas

UTC Endowed Chair Professor, Chemical & Biomolecular Engineering
Director, UTC Institute for Advanced Systems Engineering
School of Engineering – University of Connecticut
Phone: 860-486-6037
gorge.bollas@uconn.edu
http://www.utc-iase.uconn.edu/
Agenda

• Problem Statement and Motivation
• Project specifics
• Precision Machining Data and Modeling
• Use of Artificial Intelligence for PHM
• Data/Physics/AI Fusion
• Use Cases
• Conclusions
Manufacturing digital twin. What is it?

*Digital twin refers to a digital replica of potential and actual physical assets (physical twin), processes, people, places, systems and devices that can be used for various purposes.*

**Digital Twin types**
- Systems Engineering (architecture & requirements in descriptive form)
- Physics-based models that exchange data and are continuously updated
- AI models that learn from the system
- Hybrid forms (integrated descriptive analytical, physics-informed ML, causal)

**Digital Twin applications**
- System architecture design and life-cycle requirements validation/verification
- System design and discovery
- System optimization and control
- System maintenance and health management

**Digital Twin application domains**
- Manufacturing, aerospace, automotive, energy, power, medical ...
Industry 4.0 – Cyber-Physical Systems

Connection: designed to self-connect and self-sense
Information: conversion of data to features enables self-awareness and human interpretability
Cyber Cloning: information characterizes machine through analytical redundancy
Cognition: cyber cloning enables self-assessment and decision support.
Configuration: reconfiguration enables resiliency and trustworthiness

<table>
<thead>
<tr>
<th>AI supports all CPS capabilities:</th>
</tr>
</thead>
<tbody>
<tr>
<td>☑ Connection automation (e.g., CPS control)</td>
</tr>
<tr>
<td>☑ Data Analytics (e.g., data reduction)</td>
</tr>
<tr>
<td>☑ Cyber cloning (e.g., digital twin)</td>
</tr>
<tr>
<td>☑ Cognition (e.g., diagnostics)</td>
</tr>
<tr>
<td>☑ Configuration (e.g., disturbance rejection)</td>
</tr>
</tbody>
</table>

CPS capabilities:
- Connection automation
- Data Analytics
- Cyber cloning
- Cognition
- Configuration

Sensor Networks
Advanced Controls
Always Connected
Inter-Connected

Data & Information
- Data to Information
- Smart Analytics
- Information Management
- Prognostics Health Management

Cyber Cloning
- Digital Twin / Digital Thread
- Variation Identification
- Clustering and Classification

Cognition
- Integrated simulation and synthesis
- Visualization and translation
- Diagnostics & Decision Support

Dynamic smart CPS require sensing, computation, information management, learning, decision support and (re)configuration in real time. Complex physical dynamics can be captured and explained through the combination of physics-informed AI, which in turn can enable the design, operation and decision support of CPS.
Manufacturing PHM

What could go wrong?

• Tool wear (even minor) responsible for serious part inconsistencies in precision machining, rework and high scrap yields
• Poor temperature control leads to unacceptable surface roughness
• Motor failure leads to significant downtime

Machine operates in a manufacturing floor

• “Job-shop scheduling” needs replanning.

Just the issue of tool wear inference or forecasting has been the driving force for research for over a decade (hard problem)

Credit: CCAT
Energy Management Systems for Precision Manufacturing

**PROBLEM STATEMENT:**
Coordinated utilization of systems engineering, modeling, advanced controls, and data analytics will enable energy efficiency improvement in the precision machining and hybrid manufacturing of metals/alloys to support cross-industry platforms, including aerospace and orthopedics.

**PROJECT GOAL:**
The objective of this effort is to mitigate energy waste in manufacturing facilities, and specifically subtractive precision manufacturing, using model-based systems engineering principles.

<table>
<thead>
<tr>
<th>Project Cost</th>
<th>Member % Cost Share</th>
<th>CESMII % Cost Share</th>
<th>Project Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total $</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2,075,019</td>
<td>58%</td>
<td>42%</td>
<td>24 Months</td>
</tr>
</tbody>
</table>

222 Pitkin Street – Suite 101, East Hartford, CT 06108 | 860.291.8832 | www.ccat.us
Approach & Activity

Precision machining modules for the Smart Manufacturing Platform:
• platform-based systems engineering to enable requirements formalization and reusability,
• multi-level, heterogeneous and hybrid modeling of manufacturing and ancillary equipment,
• predictive analytics for anomaly detection using sensory information and data analytics,
• context-driven supervisory control architectures enabling model/control interoperability,
• scheduling of manufacturing operations to maximize energy savings,
• big data analytics, reduction and secure IoT communication protocols.
"Modeling-Data" Challenge

Data and physics-based model available
- Focus on AI
- Focus on fusion

Can we use all the data?

Machining data:
- machine power
- spindle power
- spindle vibration
- video
- audio

Physics-based models

Post-machining data:
- chip properties
- surface roughness
- tool wear

AI models

In partnership with RTRC & CCAT

*Optimization in the DT*

***Constant feed (Traditional approach)***

*Optimized feed to achieve constant load*

Feed

Machining time

Savings
## Inputs

**Tool conditions**  
Material, diameter, Teeth

**Cutting Condition**  
Cutting speed, spindle speed, depth of cut, width of cut, cut type

**Workpiece**  
Material, Hardness, size

---

## Digital Twin

### Power consumption

\[ P = \frac{2\pi M \Omega}{60} \]

### Force Components

\[
\begin{align*}
F_x &= F_t \cos(\phi) + F_n \sin(\phi) \quad F_n : \text{Normal force} \\
F_y &= F_t \sin(\phi) - F_n \cos(\phi) \quad F_t : \text{Tangential force}
\end{align*}
\]

### Torque

\[ M = r F_t \]

### Cutting fluid utilization

\[
\dot{m}_{\text{Fluid}} = \dot{m}_{\text{chip}} + \dot{m}_{\text{workpiece}} + \dot{m}_{\text{Evaporation}} + \dot{m}_{\text{Recirculation}}
\]

### Scrap generation

\[ V_{\text{Scrap}} = a_c \times a_p \times f \]

### Temperature

\[ T = \text{func}(P_s + P_f) \quad P_s = F_s \nu_s \quad P_f = F_f \nu_c \]

---

## Outputs

**Power consumption**  
Cutting force components  
Torque  
Scrap generation  
Cutting fluid utilization  
Temperature
Test Plan

**Tool properties (Material data sheet)**
- 90° Cutting tool insert
- five teeth
- Diameter: 63.5 mm
- Width of cut: 0 mm - 63.5 mm
- Depth of cut : 0 -12.15 mm
- Spindle speed (max): 22000 RPM

**Material Properties**
- AISI 4340
- Hardness: 20 HRC
- Friction factor: 0.1-0.5
- Volume: 254 x 254 x 38.1 mm³

- Based on the sensitivity analysis performed in Awasthi and Bollas (2020), width of cut, depth of cut, feed rate and spindle speed were identified as important factors.

- Design of experiments was performed for parameter values shown below for model validation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Minimum value</th>
<th>Maximum Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of cut (mm)</td>
<td>5</td>
<td>63.5</td>
</tr>
<tr>
<td>Depth of cut (mm)</td>
<td>1.5</td>
<td>12</td>
</tr>
<tr>
<td>Feed rate (mm/min)</td>
<td>200</td>
<td>800</td>
</tr>
<tr>
<td>Spindle Speed (RPM)</td>
<td>1000</td>
<td>2000</td>
</tr>
</tbody>
</table>
Model Validation

Model Predicts: Power, Force, Temperature, chip volume. Power shown here for face milling
Sound & Vibration

• “Non-traditional signals”
• Significant prior work on their analysis. Gaps:
  – No integrated tool-chain for signal analytics
  – Benchmarking of AI algorithms
  – Regression vs. classification
  – Complete machine state inference
Tool chain I

Audio Signal Sample

Signal Decomposition

Audio

Vibration

Feature Extraction (PCA)

Data Acquisition

Audio Data

Vibration Data

Data Preprocessing

Signal Decomposition (FFT)

Feature Extraction (PCA)

Data Prediction

Classification

KNN

CNN

SVM

Regression

NNR

SVR

Machine state prediction
Tool chain II

Confusion matrix of KNN, CNN and SVM for classification: (a) depth of cut, (b) width of cut, (c) feed rate and (d) spindle speed.

Regression model using: (a) audio, (b) vibration, (c) fused audio/vibration data.

Table 6: Root mean squared error of SVR and NNR for each audio and vibration data

<table>
<thead>
<tr>
<th></th>
<th>Depth of cut</th>
<th>Width of cut</th>
<th>Feed rate</th>
<th>Spindle speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio</td>
<td>SVR</td>
<td>NNR</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0070</td>
<td>0.0049</td>
<td>0.0093</td>
<td>0.0099</td>
</tr>
<tr>
<td>Vibration</td>
<td>SVR</td>
<td>NNR</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0046</td>
<td>0.0031</td>
<td>0.0029</td>
<td>0.0037</td>
</tr>
</tbody>
</table>

Table 7: Root mean squared error of SVR and NNR for fused data of audio and vibration

<table>
<thead>
<tr>
<th></th>
<th>Depth of cut</th>
<th>Width of cut</th>
<th>Feed rate</th>
<th>Spindle speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>SVR</td>
<td>0.0027</td>
<td>0.0017</td>
<td>0.0016</td>
<td>0.0020</td>
</tr>
<tr>
<td>NNR</td>
<td>0.0019</td>
<td>0.0012</td>
<td>0.0013</td>
<td>0.0010</td>
</tr>
</tbody>
</table>
Generic CNC PHM

- Case study: Paragon Cutter for fabric cutting
- Cutter operates at 3,500RPM and 10,000hz sampling rate for four machine states:
  - baseline
  - loose knife
  - no knife
  - no belt

  Standard deviation (4 repeats) was excellent
  PCA not needed here
  Simple classification works perfectly...

- Audio only data collected with a GRAS General Purpose Array Microphone (50 mV/Pa) from National Instruments, a DataTranslation DT9837 Module, and QuickDAQ data logging software.
• Information-theoretic test/sensor selection / synthetic data generation
• Hybrid modeling approaches delivering explainable AI diagnostic tools

Use Cases
- Prognostics & Health Management
- Maintenance Scheduling
- Fault-tolerant supervisory control
- Energy-aware supervisory control
- Scheduling

Confusion Matrices at various fault levels determine capability for early detection
Next Step: Real Fusion

- Data-driven models can interpolate, but not extrapolate and are sensitive to outliers & noise
- Physics-based models provide context and correctness
- Integration allows the development of a digital twin that can be used for:
  - Process Monitoring
  - Control
  - Optimization
  - Prognostics
Next Step: Control

**Objective:** Develop a local reconfigurable control strategy that determines the input control parameters of a machine, depending on the fault severity and type, to:

- Mitigate energy efficiency losses
- Reduce chance of producing scrap & increase yield
- Increase reliability

**Control Inputs to Machine:**
- Feed rate
- Spindle speed
- Depth of cut
- Width of cut
- On/idle/off state

**Directly affects:**
- Power consumption
- Processing time
- Applied force
- Temperature

**System Constraints:**
- Material to be processed requires a feed rate and spindle speed to be within a narrow range to prevent chattering or excessive temperatures
- Depth and width of cut depend on cutting tool parameters
- Processing time is constrained by on-time delivery requirements
- Reconfigured loads depends on available machine reserve capacities

**Machine scheduling requirements**

**Local Supervisor**

- Nominal controller applies standard control configurations
- Resilient controller applies modified set points to mitigate fault effects (e.g. reduced speed) depending on fault and health of other machines
- Machine is off either to save power or due to failures

**Switching Command**

**Equipment health status**

- Tool Degradation
- Material to process
- To equipment health monitoring

**Controller inputs:**
- Amount of material to process
- Processing time requirements

**Nominal Controller**
- Resilient Controller 1
- Resilient Controller 2
- Machine Off

**Switching Command**
- Feed rate
- Spindle RPM
- Depth of cut
- Width of cut
- On/off
Work area on Haas Mill at CCAT Advanced Manufacturing Center
Initial Tool Wear Assessment – Qualitative Photographs
Tool Wear Assessment Using “Plunged Holes”

1. Cut single hole using new cutting inserts
2. Cut subsequent holes after cutting tests are completed
3. Measure geometry of each hole; geometric deviations to be attributed to tool wear
Conclusions

• Well... listen to it!
• We have our understanding in books but there is more information (than we think) in what is never (?) going to be in books
• This is still a very hard problem
  – Sensor selection still uncertain
  – Labeling of data still uncertain
  – Impact of uncertainty still not well-understood
Acknowledgment

This material is based upon work supported by the U.S. Department of Energy’s office of Energy Efficiency and Renewable Energy (EERE) under the Advanced Manufacturing office Award Number DE-EE0007613.

Partners:
Tom Maloney (CCAT)
Nasir Mannan (CCAT)
Zhigang Wang (RTRC)
Tim Wagner (RTRC)
Ken Creazy (J&J)
Maria Araujo (J&J)

Graduate Students:
Utsav Awasthi (machining modeling)
Seulki Han (audio/vibration analysis)
Qian Yang (CUSUM FDI)
James Wilson (Control)
Employers’ Perspectives

Charles Daniels, CFO, Wepco Plastics
Glenn Ford, President, Phoenix Manufacturing
McAllister & Quinn Federal Update

• Annual defense policy bill, the National Defense Authorization Act (NDAA) nears enactment.
  • This important bill authorizes defense procurements (ex. Columbia-Class Submarines) for Fiscal Year 2021. Important to the State of Connecticut defense manufacturing supply chains and OEMs.

• Short-Term funding measure to fund the federal government expires on December 11th. Congress is close to an agreement to fund the federal government through Fiscal Year 2021 (9/30/21).

• COVID-19 Stimulus Package negotiations have started again after pre-election delay.
  • $908 billion bipartisan pandemic relief proposal under negotiation. Includes funding for a version of the Paycheck Protection Program, State/Local government aid, education/workforce aid, and federal unemployment assistance.

• Rep. Rosa DeLauro (D-CT-3) is in position to become the next House Appropriations Committee Chairwoman
  • Rep. DeLauro has been recommended to become the next Chairwoman, subject to full House Democratic Caucus vote. If finalized, this would be important for Connecticut. Rep. DeLauro will lead the powerful Appropriations Committee, which controls about $1.4 trillion in annual federal funding.
LAST CHANCE to access Wage Subsidies & FREE Technical Training to Add New Hires or Re-Hire Laid Off Manufacturing Talent

- Subsidies up to $20/hour for new or returned COVID-impacted employees
- Retroactive wage subsidies for hires beginning 9/1/20 through 12/27/20
- Supports such as laptops for training and childcare subsidies
- Free Customized Technical Training – online plus hands on with mentor
- Management and Administrative hires are include – prior employment in manufacturing company required!

Contact Eileen Candels | ecandels@ccat.us TODAY!
Attend a Virtual Tour of
Your Advanced Manufacturing Center

Wed. Dec. 9th | 1:00 - 1:45 PM

Learn about the AMC’s technologies

• Additive Manufacturing
• Precision Machining
• Metrology & Inspection
FREE Online Trainings for CT Manufacturers

180skills.ccat.us

Great Tech Training and More Including:

Workplace Communications Conflict Resolution Problem Solving Virtual Teams Excel Training

Watch the webinar to learn more:

Rethink, Recommit, Re-engage Your Current Workforce - Use 180 Skills as part of your Incumbent Worker Training
Celebrate manufacturing **all year long**!

Send us your 2-3 min. video to add to the Virtual CT MFG Fair

CTcreates.org
CCAT Program Updates

- Voucher Programs (CTMVP, IVP, AMAP)
- Industry 4.0 Demonstrations & Trainings
- High Rate Additive Manufacturing
- REV-UP! Re-hire and Upskill
- 180 Skills Free Online Trainings
- Small Turbine Engine (AFRL)
- Defense Communities Grant – MBE/MBD
FREE Industry 4.0 Workshops
For CT small to medium sized aerospace & defense manufacturers
On Demand Any Time

• Design to Print Technology
• Data Dashboards & Applied AI
• Predictive Maintenance Technologies
• IoT/Cloud & Cognitive Computing
• Modernization Strategies
• High Speed Contact Metrology
• High Speed, Automated, 3D Scanning for Part Inspection
• Low-Cost 3D Scanning-Part Digitizing & Parametric Models
• Machine Tool Probing for Industry 4.0
• Augmented Reality Solutions in Manufacturing
• Industry 4.0 and Smart Manufacturing
• The Digital Twin aka Model Based Definition

ccat.us/incumbent-worker-training
THURSDAY, DECEMBER 10 @ 12 –1 PM
2020 Finale – Hear about next year’s plans for Manufacturing with DECD Commissioner David Lehman
Follow-Up

Slides have been posted on the CCAT website:
https://www.ccat.us/events/2020-12-03-webinar/

• CCAT Point of Contact:
  Lynn Raicik, Associate Director, Workforce Pipeline Programs
  lraicik@ccat.us, (860) 982-6637

• For questions or suggested topics for upcoming webinars, email:
  workforce@ccat.us

This information is provided for general informational purposes only and should not be relied on by any party for any reason. All liability with respect to actions taken or not taken based on the information provided are hereby expressly disclaimed. The information is provided “as is” and no representations are made that the information is “error free”. We reserve the right to change or delete any information contained herein at any time without notice.