Cyber-Physical Systems in Construction: Development Lessons and Future Directions

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Preamble

• University of Florida:
  – Top 10 public research university
  – Over 50,000 students
  – Located in Gainesville (North Central Florida): ~120,000 population
  – Gainesville is 2hrs from Orlando/Disney; 2 hrs from Tampa, 5hrs from Miami, 5hrs from Atlanta, GA

• College of Design, Construction and Planning (DCP):
  – One of 16 Colleges at the University of Florida
  – College-wide Programs in Sustainability and the Built Environment, and Historic Preservation
  – Approx. 1500 students
  – About 80 faculty
  – Degree Programs: Bachelor, Master and PhD programs in the various schools
Context

• Construction projects growing in complexity due to:
  • Globally distributed project teams
  • Increased use of sensors and other data acquisition technologies
  • Demand for more data for various purposes
  • Use of variety of devices to generate and access project and asset information
  • More iconic/signature facilities
  • Etc.
  • Advances in ICT have increased volume of available data/information
Context: Project Information Management

- Unprecedented volumes of data and information now generated in projects
- Global context exacerbates:
  - Data complexity
  - Data/Information flows
  - Cultural problems in interactions
  - Etc.
- Project information management now more complex
- Project information needs to transcend facility lifecycle...
- Need for value-added management of project information ...

Context: Project Information Management

- Value-Added Management of Project Information:
  - Several approaches to this...
  - Improved visualization, data mining, knowledge discovery, delivery mechanisms, context specificity, etc.
  - Cyber-Physical Systems (CPS) offer another mechanism...
- Questions addressed by this presentation:
  - What value is added by CPS?
  - What CPS have we developed so far?
  - What lessons have been learnt from these systems?
  - What are the future directions in CPS development?
Cyber-Physical Systems (CPS)

Cyber-Physical Systems: Definitions

• A system featuring tight combination of, and coordination between, the system’s computational and physical elements (Wikipedia, 2013).

• Cyber-physical systems bridge the virtual world and the physical world through the use of sensors (Wu et al. 2011).

• Current application areas in the built environment:
  – Structural Health Monitoring (bridges, etc.)
  – Building Energy Management Systems
  – Construction Engineering and Management
  – Transportation Systems
Key Elements of the CPS Approach

Enabling Technologies...

- Virtual models
- Wireless sensors (including RTLS/RFID tags)
- Mobile devices (tablets, iPad, smartphone, etc.)
- Mobile communications networks
- Cameras
- 3D laser scanners
- UAVs
- Etc.
Why the Need for Bi-directional Coordination?

- Design changes
- Capture and document construction changes and as-built information
- Track construction progress from virtual model
- Manage constructability provisions
- Improve tracking and management of assets
- Control components and sub-systems
- Etc.

CPS APPLICATIONS:

1. CPS for Construction Component Tracking and Management
System Architecture

Deployment Scenario - 1:
Steel Placement – design changes, constructability...
Deployment Scenario – 2: Design Changes in Retrofit Project

1. Architect updates changes in the virtual model and a door location needs to be changed.
2. Door location change is written to affected door tag.
3. Contractor writes door specification change to door tag.
4. Loadbearing wall is tagged.
5. Contractor comments on door tag.
6. Loadbearing wall is tagged.

Deployment Scenario – 3: Light Fixture Tracking and Control

1. Light fixtures are tagged with RFID tags.
2. The tagged light fixtures are installed on site.
3. Electrical contractor bonds installed fixtures with virtual fixtures in the model.
4. Facility manager interfaces with virtual model to identify and control with fixture.
5. Model is shared by the Facility Manager.
6. TCP/IP server.
7. Device Server.
CPS Applications Developed

Light fixtures

Automated Component Placement Tracking

Doors, Steel and HVAC components

Fixture Tracking, Monitoring and Control

The alignment and convergence of the physical and virtual environments can then achieve immersion, where information mobility is perfected through mobile devices serving as cursors into digital "hypermodels.”

– Greg Bentley

Key Enabling Technology: RTLS

• Real-Time Location Sensing (RTLS) system

SOFTWARE

POSITION SERVER

Gateway

i-PORT M 350 RTLS

i-SAT 300

Reader Module

i-Q350 RTLS

Tag
Overview of Prototype System

- Database
  - Web-Interface
    - i-Share
      - RTLS Reader
        - i-SAT Nodes

Laboratory Experimentation...

- Bi-directional coordination

- Detachable Physical Components
Results - 1

• Element highlighted and property updated with information from RTLS tag

Results - 2

• Door and Roof element status changed to ‘uninstalled’ (red)
CPS APPLICATIONS:

2. CPS for Temporary Structures Monitoring

Scaffolding Used as Example

<table>
<thead>
<tr>
<th>OSHA Top 10 (Number of Violations)</th>
<th>Fiscal Year 2012</th>
<th>Fiscal Year 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Violator Code</td>
<td>Description</td>
<td>Violator Code</td>
</tr>
<tr>
<td>1. Fall Protection-General Requirements (OSHA 1926.501)</td>
<td>7,597 violations</td>
<td>1. Fall protection to construction (OSHA 1926.512)</td>
</tr>
<tr>
<td>2. Boom or Ladder (OSHA 1926.451)</td>
<td>7,290 violations</td>
<td>2. Boom or Ladder (OSHA 1926.451)</td>
</tr>
<tr>
<td>3. Ladders (OSHA 1926.412)</td>
<td>7,290 violations</td>
<td>3. Ladders (OSHA 1926.412)</td>
</tr>
<tr>
<td>4. Machine Guarding (OSHA 1926.175)</td>
<td>1,131 violations</td>
<td>4. Machine guarding (OSHA 1926.175)</td>
</tr>
<tr>
<td>5. Scaffolding (OSHA 1926.501)</td>
<td>1,131 violations</td>
<td>5. Scaffolding (OSHA 1926.501)</td>
</tr>
<tr>
<td>6. Fall Protection-General Requirements (OSHA 1926.501)</td>
<td>1,131 violations</td>
<td>6. Fall protection to construction (OSHA 1926.512)</td>
</tr>
<tr>
<td>7. Caterpillar or other work vehicle (OSHA 1926.606)</td>
<td>1,131 violations</td>
<td>7. Caterpillar or other work vehicle (OSHA 1926.606)</td>
</tr>
<tr>
<td>8. Fall protection to construction (OSHA 1926.512)</td>
<td>1,131 violations</td>
<td>8. Fall protection to construction (OSHA 1926.512)</td>
</tr>
<tr>
<td>9. Equipment requirements (OSHA 1926.500)</td>
<td>1,131 violations</td>
<td>9. Equipment requirements (OSHA 1926.500)</td>
</tr>
<tr>
<td>10. Machine guarding (OSHA 1926.175)</td>
<td>1,131 violations</td>
<td>10. Machine guarding (OSHA 1926.175)</td>
</tr>
</tbody>
</table>


Recognized safety problems

Applicable to other structures
Temporary Structures Monitoring

Physical Laboratory Mockup

Virtual Model

Experimental Setup

Virtual Model and Physical Scaffolding Structure
Temporary Structures Monitoring

TSM App Interface
CPS APPLICATIONS:

3. CPS for Mobile Crane Safety and Efficiency

Mobile Crane Safety and Efficiency

• Recently, major problems with mobile cranes on sites (with numerous fatalities)
• Issues include:
  – Stability/overturning
  – Collisions
  – Falling objects
  – Striking people/vehicles
  – Etc.
• CPS offers potential solutions...
• New NSF project: UF, PSU, UIUC
Project Introduction

*A Cyber-Physical System for Safe and Efficient Crane Operations*

NSF Project Objectives

- Capture the context of crane operations through integrated planning, sensing, equipment data
- Create a CPS system with the following components:
  - Virtual construction site models
  - Crane stability analysis model
  - Sensing, actuation and control modules to improve safety and predictability of the operations
  - Cyber-physical feedback to the operator for control purposes
Current Progress

- Review of crane accident records
- Developing algorithms for automatic mobile crane recognition using UAVs
- Site layout modeling for planning crane lifts and safety analyses
- Developing a taxonomy for mobile cranes
- Undertaking a FMEA of mobile cranes to establish critical failure modes and key hazardous situations
- Design options for ‘transparent cockpit’ for crane operator
- Computer vision systems for tracking workers...

Prototype Development

[1] Physical Site

Use of:
- BIM model
- Laser scanner
- Photogrammetry
- Computer vision
- Real-time location system

Data to be collected through sensors:
- Crane location
- Boom length
- Location of the load
- Amount of the load
- Levelness of the crane
- Contact state with the ground
Prototype Development

[3] Virtual Model

Static site environment data are to be collected and later to be updated

Site Environment Data -- Static & Mobile Objects

Sensor Data

Crane Motion

Reconstruction

Visualization, Interaction and Warning

Crane Model in Parts

Control Feedback

 ■ A Bi-directional CPS System

Site environment data obtained are used as basis for modelling

Site Environment Data - Static & Mobile Objects

Static site environment data are to be collected and later to be updated

Sensors are to be installed on mobile crane to collect its operational data
3 Lessons and Future Directions:
- Lessons Learned from Developing CPS Systems
- Future Directions
Lessons from CPS Development

• Essential to have clear understanding of problems being tackled by CPS
• Accurate and up-to-date virtual models very important
• Design of bi-directional coordination mechanism probably most vital aspect of CPS development
• Choice of sensors/sensor networks also critical
• Laboratory experimentation helpful for proof-of-concept prior to real-life deployment
• Numerous practical considerations in moving from laboratory to real-life implementation (e.g. scalability, cost, power, wiring, etc.)

Future Directions

• Difficult to make accurate predictions...
• Future directions will be governed by:
  – New construction applications of CPS
  – Technological developments
New Construction Applications

• Facilities Management (FM)
• Smart Cities
• Integrated Infrastructure Management
• District-scale Energy Management
• Content-aware Constructed Facilities
• Etc.

Technological Developments

New CPS developments will leverage the following technologies:

• Context-awareness
• UAVs
• 3D Printing
• Cloud computing
• Non-volatile Memory
• Communications Networks (5G and beyond)
• Sensor developments/IoT
• Etc.
UAV-based Aerial Imaging and Laser Scanning

Sample UAS Imagery

Laser Scan Point Cloud Model

M.E. Rinker, Sr. School of Construction Management: Perry Construction Yard

Center for Advanced Construction Information Modelling, University of Florida

3D Printing

Concrete Printing
(@Loughborough University)
Summary and Conclusions:
- Benefits of CPS in Construction
- Conclusions

Conclusions

Benefits of CPS in Construction Projects

- Real-time information exchange b/w site and design office
- Reduction of construction risks (as activities and processes can be more closely monitored and controlled)
- Accurate as-built models useful for operation, FM, deconstruction, etc.
- Improved opportunities for sustainable construction practices
- Improved safety through proactive hazard monitoring
- Numerous benefits from real-time process tracking and active component control
- Etc.
Conclusions

• Project information management growing in complexity
• Value-added information management needed
• Cyber-physical systems (CPS) can offer this ‘value-add’
• Applications in construction are growing...
• There are considerable potential benefits
• Many lessons have been learnt from CPS development
• Future directions will focus on new application areas and integration of CPS systems with emerging technologies...

Thank you!