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
  - Includes Schools of Architecture, Construction Management, Architecture, Landscape Architecture, Urban and Regional Planning, and Interior Design.
  - 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

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- Context
- Cyber-Physical System (CPS) Applications:
  - Construction Component Tracking
  - Temporary Structures Monitoring
  - Mobile Crane Safety and Efficiency
- Development Lessons
- Future Directions
- Summary and Conclusions

Outline

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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

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?

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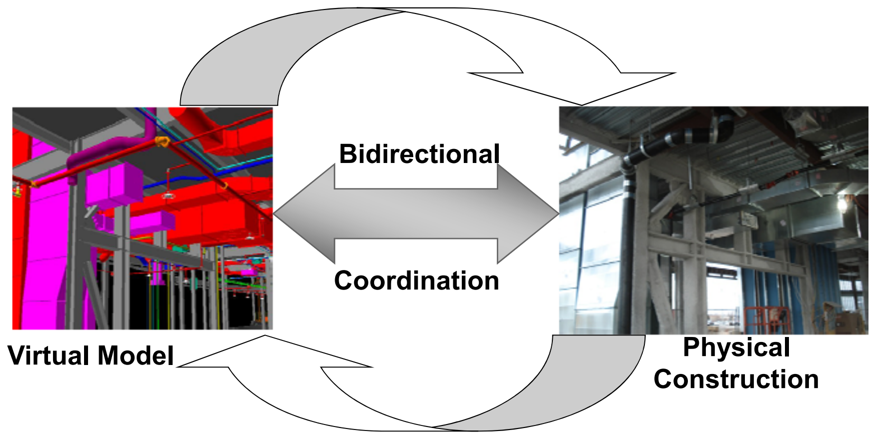
Cyber-Physical Systems (CPS)

Cyber-Physical

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.

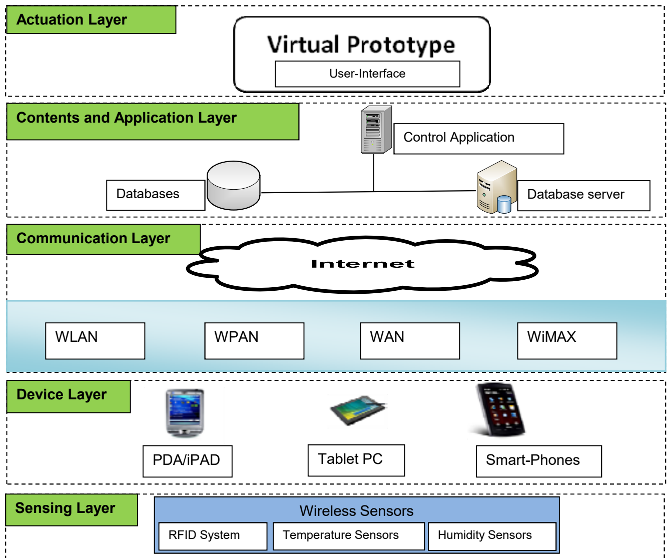
Why the Need for Bi-directional Coordination?

- 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:

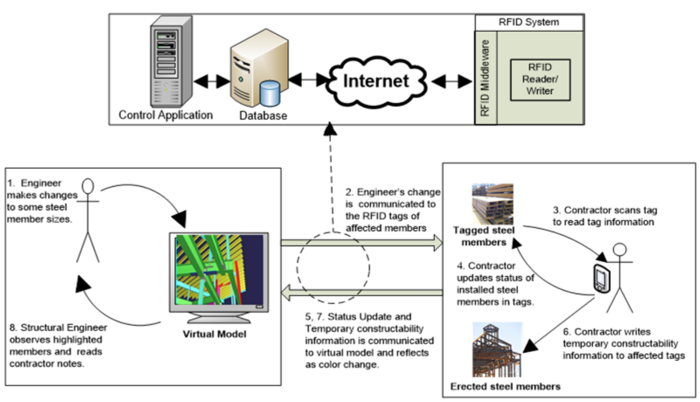
1. CPS for Construction Component Tracking and Management

System Architecture

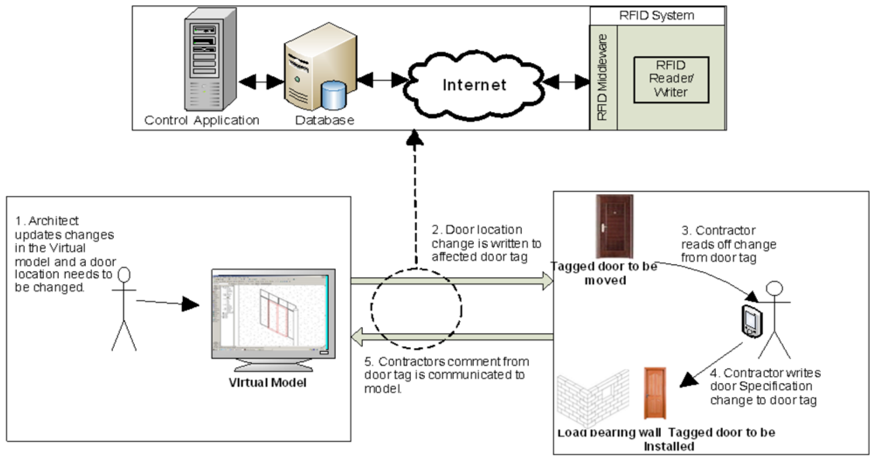


Deployment Scenario - 1:

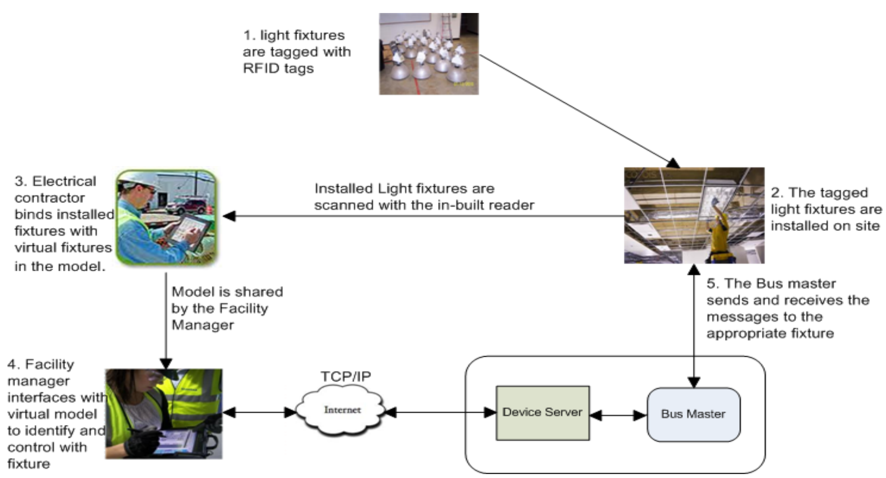
Steel Placement – design changes, constructability…



Deployment Scenario – 2:
Design Changes in Retrofit Project

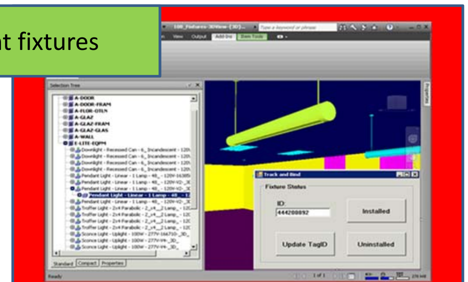


Deployment Scenario – 3:
Light Fixture Tracking and Control



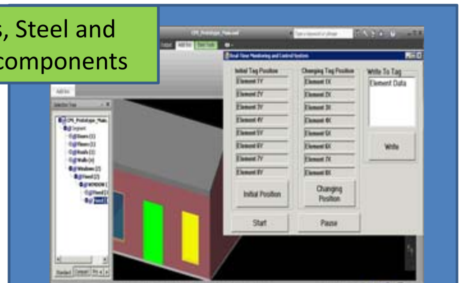
CPS Applications Developed

Light fixtures



Fixture Tracking, Monitoring and Control

Doors, Steel and HVAC components



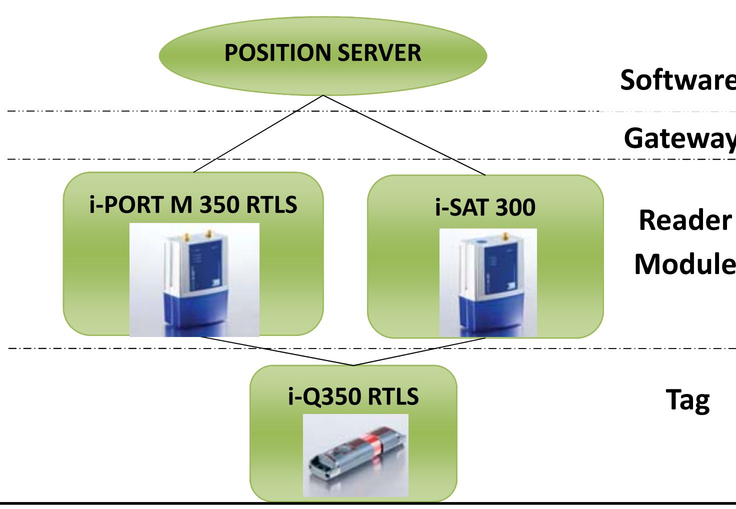
Automated Component Placement Tracking

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."

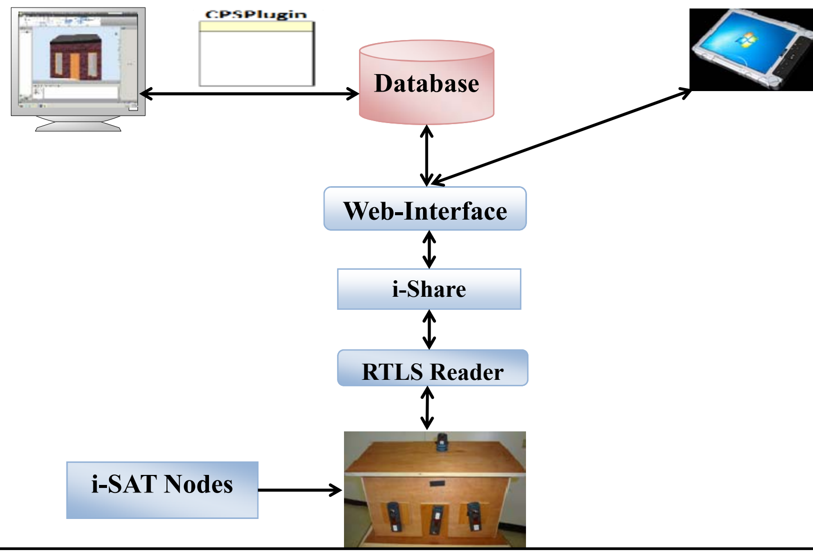
– Greg Bentley

Key Enabling Technology: RTLS

- Real-Time Location Sensing (RTLS) system

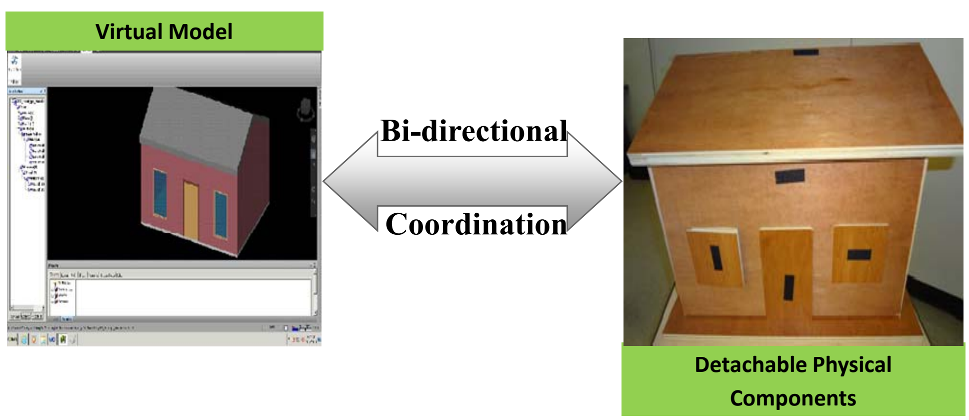


Overview of Prototype System



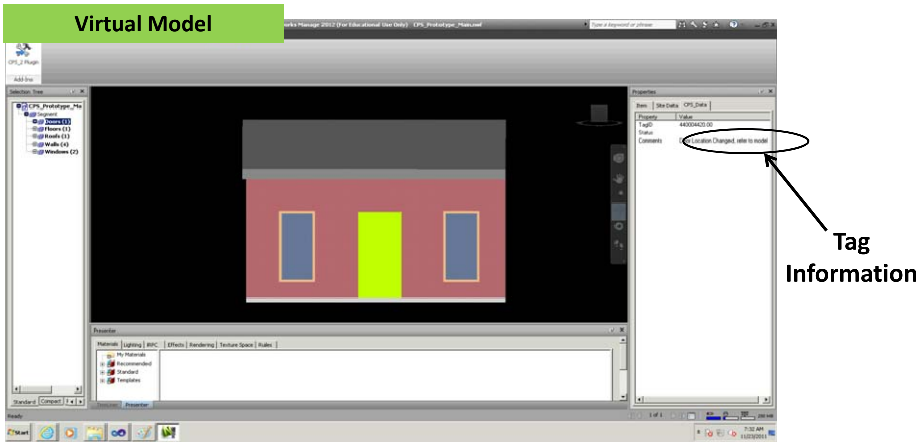
Laboratory Experimentation…

- Bi-directional coordination



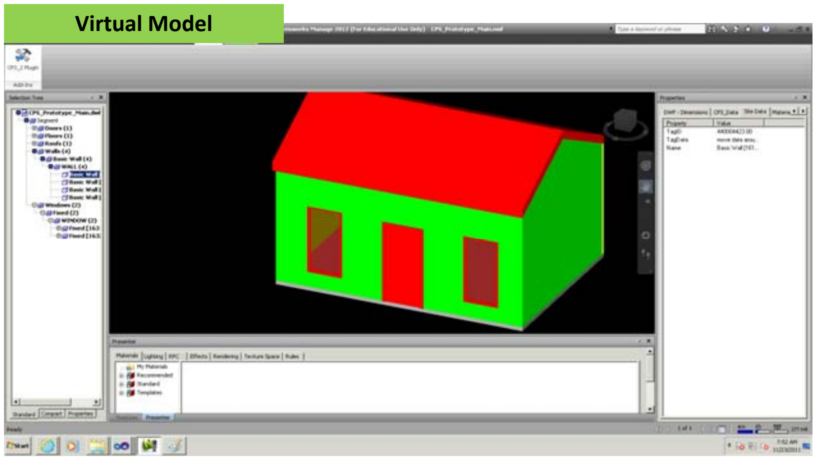
Results - 1

- 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

Recognized safety problems

OSHA Top 10 (Number of Violations)	
Fiscal year 2012 (October 2011 through September 2012)	**Fiscal Year 2011** (October 1, 2010 to September 30, 2011)
1. Fall Protection – General Requirements (1926.501) Total violations: 7,250	1. Fall protection in construction (1926.501): 7,139 violations.
2. Hazard Communication (1910.1200): 4,696	2. Scaffolding in construction (1926.451): 7,069 violations.
3. Scaffolding (1926.451): 3,814	3. Hazard communication (1910.1200): 6,538 violations.
4. Respiratory Protection (1910.134): 2,371	4. Respiratory protection (1910.134): 3,944 violations.
5. Ladders (1926.1053): 2,310	5. Lockout/tagout (1910.147): 3,639 violations.
6. Machine Guarding (1910.212): 2,097	6. Electrical wiring methods (1910.305);:3,584 violations.
7. Powered Industrial Trucks (1910.178): 1,993	7. Powered industrial trucks (1910.178): 3,432 violations.
8. Electrical – Wiring Methods (1910.305): 1,744	8. Ladders in construction (1926.1053): 3,244 violations.
9. Lockout/Tagout (1910.147): 1,572	9. Electrical general requirements (1910.303): 2,863 violations.
10. Electrical – General Requirements (1910.303): 1,332	10. Machine guarding (1910.212): 2,748 violations.

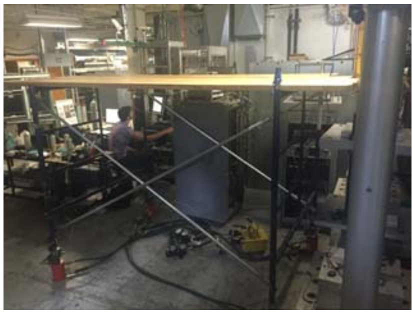
***Source:** SafetyNewsAlert, Top 10 of 2012: OSHA Enforcement, 17Dec2012*

Applicable to other structures

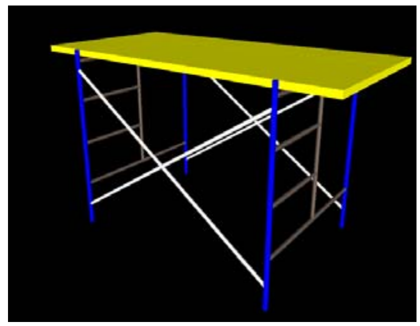
Scaffold

Falsework

Temporary Structures Monitoring

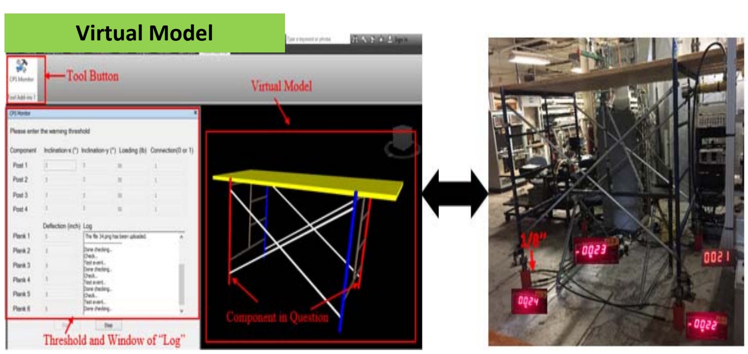


Physical Laboratory Mockup



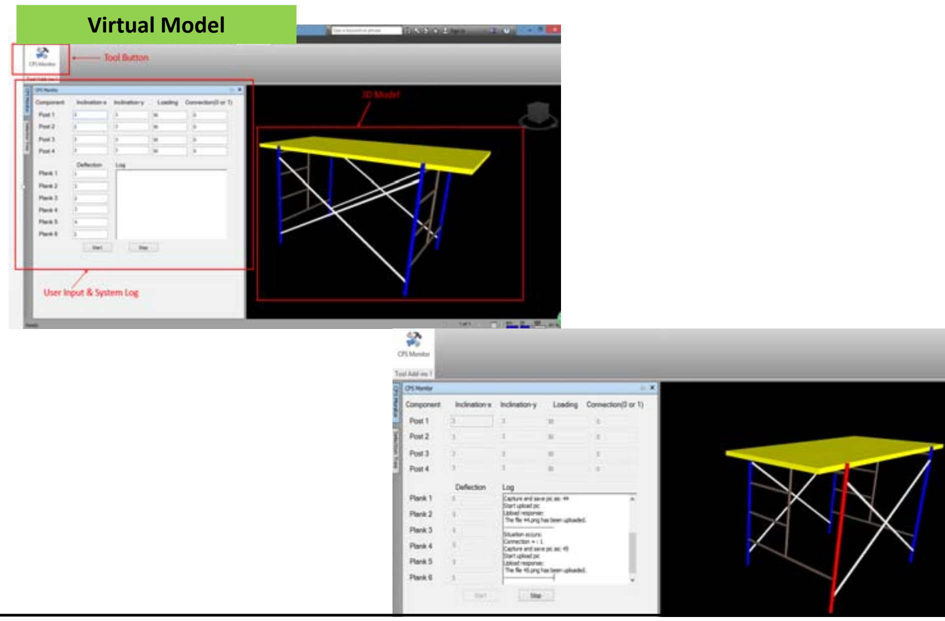
Virtual Model

Experimental Setup

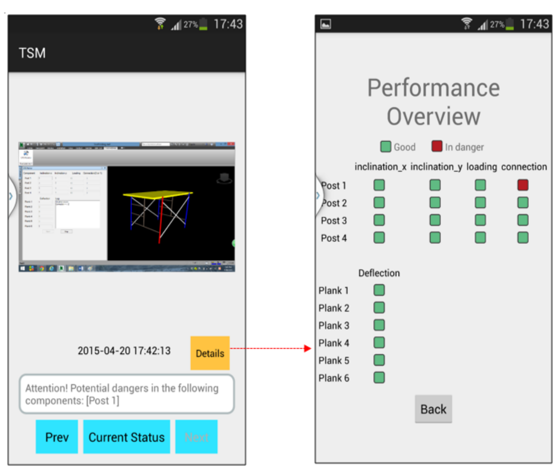


Virtual Model and Physical Scaffolding Structure

Temporary Structures Monitoring



TSM App Interface



CPS APPLICATIONS:

3. CPS for Mobile Crane Safety and Efficiency

Mobile Crane Safety and Efficiency

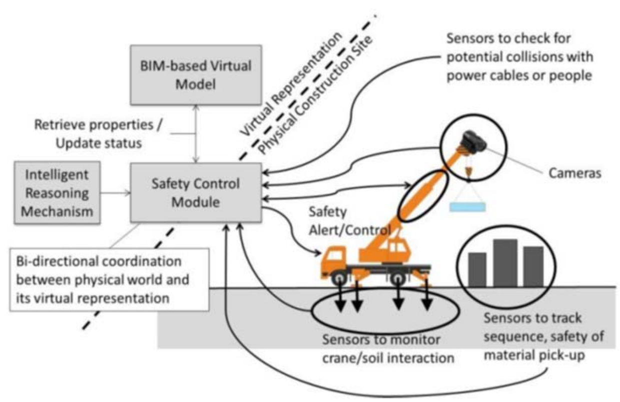
- Recently, major problems with mobile cranes on sites (with numerous fatalities)
- Issues include:
  - Stability/overturning
  - Collisions
  - Falling objects
  - Striking people/vehicles
  - Etc.
- CPS offers potential solutions…
- New NSF project: UF, PSU, UIUC

■ **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

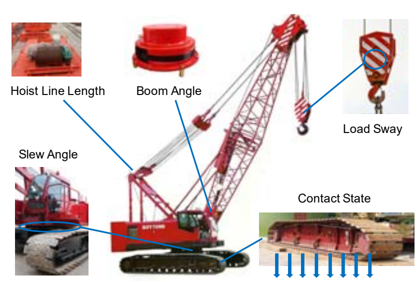


Current Progress

- 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



Site Environment Data

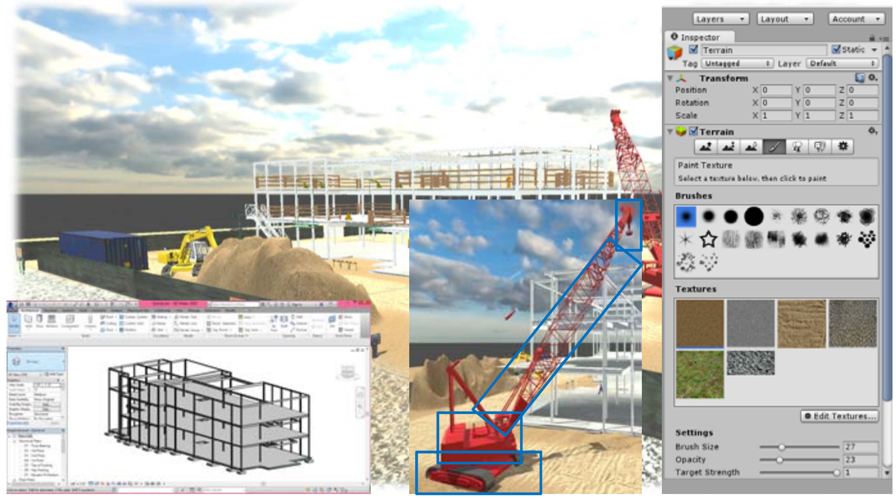
Use of :
- BIM model
- Laser scanner
- Photogrammetry
- Computer vision
- Real-time location system

Crane Motion Data

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



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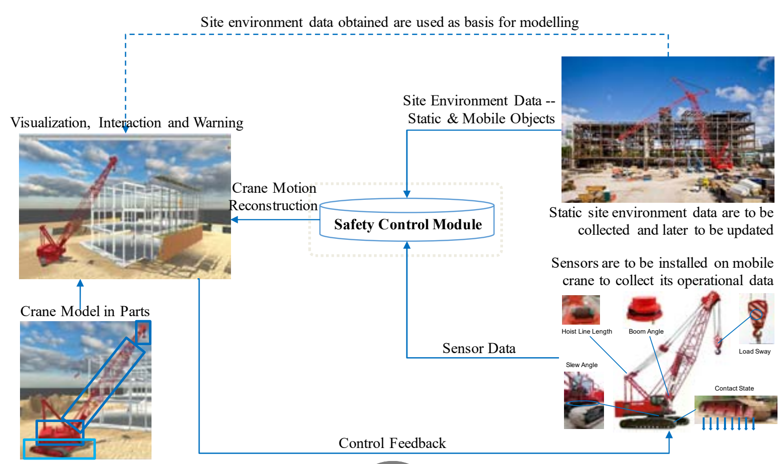
Prototype Development

A Bi-directional CPS System



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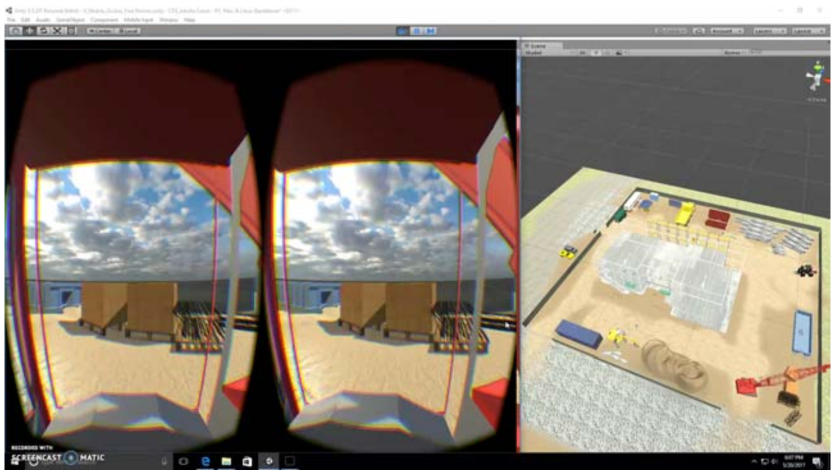
■ **Prototype Development**

[3] Virtual Model



3 Lessons and Future Directions:

- Lessons Learned from Developing CPS Systems
- Future Directions

Lessons & 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.)
- 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

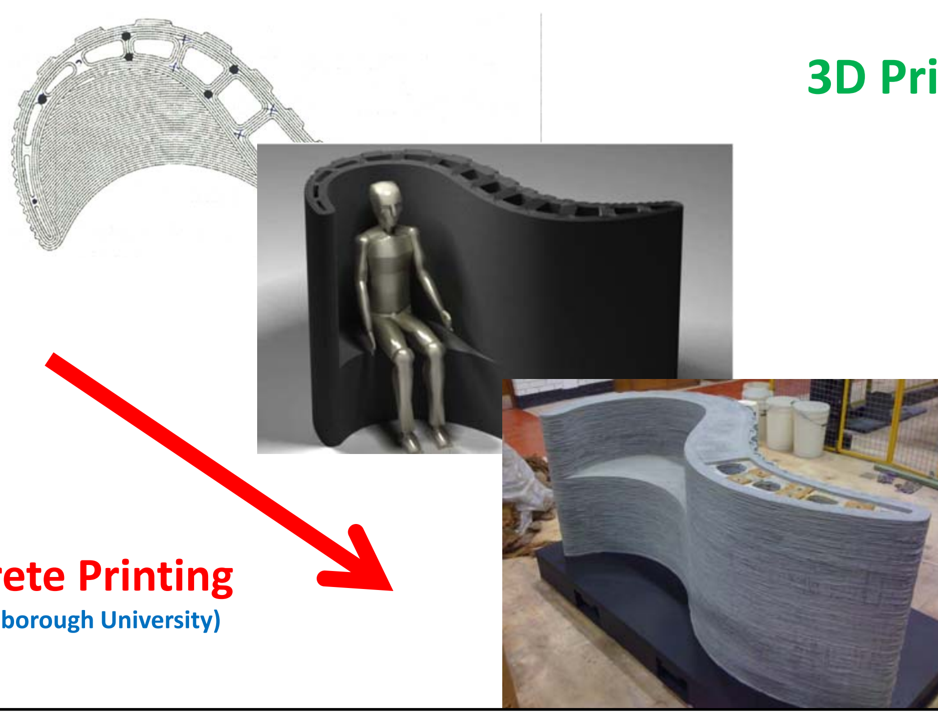
Sample UAS Imagery

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)

4 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!