Multi-agent System for Improved Safety and Productivity of Earthwork Equipment Using Real-time Location Systems

Faridaddin Vahdatikhaki
Prof. Amin Hammad
Seied Mohammad Langari
Introduction

• Earthwork refers to a set of operations leading to reshaping of the natural surface of earth (de Athayde Prata et al. 2008) and accounts for:

• More than 20% of the total cost of the road building projects (Smith et al. 1996).

• A considerable amount of fatalities, i.e. 74 out of 775 only in 2012 (BLS 2012).
Introduction (cont.)

- A **Location-based Guidance System** (LGS) is a system that combines a location tracking system and other sensory data with On-Board Instrumentation (OBI) to perform complex real-time monitoring of the equipment and provide necessary guidance.

![AMC/G Hardware](Adapted from Leica Geosystems 2013)
Problem Statement

• Current application of LGSs is limited to the machine-level productivity improvement.

• The high cost of procuring available LGSs limits their availability for small and medium size contractors.

• Real-time data coming from LGS is not efficiently use to update the cycle time of operation.

• LGS application for safety is limited to real-time proximity-based object detection and warnings.
Objectives

- To enable the fleet-level application of LGS.

- To provide a method for improving the pose estimation performance of low-cost RTLSs for use in LGSs.

- To devise a generic framework for Near Real-time Simulation (NRTS) based on data from LGS.

- To develop a mechanism for improving the safety of earthwork operations using LGS.
Literature Review

- **Operation Management System and Autonomous Excavation**
  

- **Near-real Time Simulation (NRTS)**
  
  (Lu et al. 2007, Akhavian and Behzadan 2012, Song and Eldin 2012, Pradhananga and Teizer 2013, Akhavian and Behzadan 2013)

- **Collision Avoidance using Workspaces**
  

- **MAS Application in Construction Industry**
  
Multi-agent Architecture

Images are extracted from multiple sources (Stanford Business Mapping, Wikipedia, Google 3D Warehouse, Autodesk)
MAS Functions Covered in this Research

**OA**
- Pose/State Identification
- Tactical Planning
- Generation of DEW
- Safety Check
- Task Execution
- Look-ahead Risk Calculation
- Cycle-time Calculation
- Equipment Monitoring
- Utility Detection
- Updating DTM

**TCA**
- Task Assignment
- Task Rescheduling
- LAEW Generation
- Safety Check
- NRTS
- Progress Monitoring
Pose Estimation

\[
\text{Fitness Function} = \min [P \times \sum_{j=1}^{4} \frac{C_j}{r} + \sum_{i=1}^{6} \frac{|D_i - d_i|}{D_i} + \frac{|\alpha - \beta|}{\alpha} + \frac{R}{r}]
\]
Pose Estimation (cont.)

\[ \alpha = 14.77^\circ \]

\[ D_1 = 12.5 \text{ cm} \]
\[ D_2 = 5.5 \text{ cm} \]
\[ D_3 = 18 \text{ cm} \]
\[ D_4 = 16 \text{ cm} \]
\[ D_5 = 1.5 \text{ cm} \]
\[ D_6 = 14 \text{ cm} \]

\[ \text{Error of } D_1 = 0.234 \text{ m} \]
\[ \text{Error of } D_2 = 0.043 \text{ m} \]
\[ \text{Error of } D_3 = 0.277 \text{ m} \]
\[ \text{Error of } D_4 = 0.119 \text{ m} \]
\[ \text{Error of } D_5 = 0.262 \text{ m} \]
\[ \text{Error of } D_6 = 0.496 \text{ m} \]
\[ \text{Error of } \alpha = 0.003^\circ \]

Cor. of DC1 = 0 m
Cor. of DC1 = 0 m
Cor. of DC1 = 0 m
Cor. of DC1 = 0 m
State Identification

Fixed Zones for Truck

If the bucket is relatively stationary:
- it is the closest to the bed with the bucket's bed
- its velocity is zero

Then the excavator is dumping.

Then the truck is dumping.
Agent-based Safety Management System

Dynamic Equipment Workspace

Look-Ahead Equipment Workspace
Dynamic Equipment Workspace (cont.)

Traversal State
(moving on the tracks)

Swinging State

Loading/Dumping State
Look-ahead Equipment Workspace
Look-ahead Equipment Workspace (cont.)

Risk Map

Look-Ahead Equipment Workspace
Equipment Used in Case Studies

- **Bucket Right**
- **Bucket Left**
- **Cab**
- **Body**
- **Crane front**
- **Crane back**
- **Track front**
- **Track back**
- **Truck Right**
- **Truck Left**
- **Dome Camera**
- **Ubisense UWB**
Case Study 1: Error Analysis for Pose

![Graphs showing location and orientation error analysis](image)

**Experimental Data**

- **Location Error (cm)**:
  - Before Correction: 98.5%
  - Correction with All Constraints: 53.5%

- **Orientation Error (degree)**:
  - Before Correction: 81.3%
  - Correction with All Constraints: 28.6%

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**Case Study 1**

**Introduction**

**Problem Statement**

**Objectives**

**Literature Review**

**Proposed Method**

**Case Studies**

**Conclusions**
Case Study 2: Lab Test
Case Study 2: Excavator Pose Estimation

Video

Comparison of captured and corrected data
Case Study 2: State Identification
Case Study 2: Dynamic Equipment Workspace

Proposed

Symetric

Cylindrical

Buffer
Case Study 2: Dynamic Equipment Workspace (Cont.)

<table>
<thead>
<tr>
<th>Case</th>
<th>Proposed DEW</th>
<th>Symmetric DEW</th>
<th>Buffer DEW</th>
<th>Cylindrical DEW</th>
</tr>
</thead>
<tbody>
<tr>
<td>False Positive</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Space Savings Compared to Cylindrical DEW</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>Detection Clearance Compared to Cylindrical DEW</td>
<td>80</td>
<td>90</td>
<td>100</td>
<td>110</td>
</tr>
</tbody>
</table>
Case Study 2: Look-ahead Equipment Workspace
Case Study 3: Workspaces in Simulated Construction site

- The feasibility of DEW-based safety monitoring is studied in this case study.

- Truck A is hauling the material to the dumping spot and Truck B is returning to the excavation points.
Case Study 3: Dynamic Equipment Workspace
Case Study 3: Look-Ahead Equipment Workspace

- Applying LAEWs for collision-free path planning.

**Actual Site**

**Current poses and Initial Paths**

**Risk Map of Excavator 1**

**Final Path of Excavator 2**
Case Study 3: Look-Ahead Equipment Workspace
Conclusions

• Safety issues and conflict-prone activities are addressed using a two-layer mechanism that accounts for a wide range of human factors and uncertainties.

• The proposed approach, in addition to the demonstrated operational advantages, can offer benefits at the managerial level, allowing managers to make informed decisions about the project using real-time data and simulation data.

• The MAS structure can offer faster conflict resolution, owing to the faster identification of the problem area and communication and negotiation between the agents.
The Scope of the Proposed Method

<table>
<thead>
<tr>
<th>Planning</th>
<th></th>
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<tbody>
<tr>
<td>Operation and Task Assignment</td>
<td></td>
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<tr>
<td>Strategic and Tactical Planning</td>
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<table>
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<tr>
<th>Execution and Monitoring</th>
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<tbody>
<tr>
<td>Visual Guidance to Equipment Operators</td>
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<tr>
<td>Collecting and Processing RTLS Data</td>
<td></td>
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<tr>
<td>Equipment Pose Identification</td>
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<tr>
<td>Equipment State Identification</td>
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<tr>
<td>Near Real-time Simulation</td>
<td></td>
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<tr>
<td>Workspace Generation</td>
<td></td>
</tr>
<tr>
<td>Reporting (Progress Tracking, Safety Warnings, and Delay Notice)</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Re-planning</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Task Re-assignment</td>
<td></td>
</tr>
<tr>
<td>Re-planning</td>
<td></td>
</tr>
<tr>
<td>Design Change Request</td>
<td></td>
</tr>
</tbody>
</table>
Dynamic Equipment Workspace (cont.)

**Alt**

- **[Equipment in Vicinity == True]**
  - **Send Priority and DEW1**
  - **Send Priority and DEW2**

**Alt**

- **[Eq1 has priority == True]**
  - **Collision Detection**
  - **Stop**

- **[Collision Detected == True]**
  - **Send Warning**

**[Eq2 has priority == True]**

- **Collision Detection**
- **Stop**

- **Send Warning**

**[Else]**

- **Collision Detection**
- **Collision Detection**

- **[Collision Detected == True]**
  - **Stop**
  - **Send Warning**
  - **Send Warning**
Look-ahead Equipment Workspace (cont.)

Proximity Risks
Based on:
(a) Shortest Distance to Equipment \( (L_i) \)
(b) Time to Shortest Distance \( (t_i) \)

Visibility Risks
based on:
Equipment Blind Spot
Look-ahead Equipment Workspace (cont.)

(a) Shortest Distance to Eq

(b) Time to Shortest Distance

(c) Time in the Equipment Blind Spots

Equipment Risk Map
Publications:


## Dynamic Equipment Workspace (cont.)

<table>
<thead>
<tr>
<th></th>
<th>Stationary States</th>
<th>Traversal States</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Excavator</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stationary States</td>
<td><strong>Excavator should avoid</strong></td>
<td><strong>Excavator should avoid the truck</strong></td>
</tr>
<tr>
<td></td>
<td><em>the truck</em></td>
<td></td>
</tr>
<tr>
<td><strong>Truck</strong></td>
<td><strong>Truck should avoid</strong></td>
<td><strong>Equipment with the lower operation costs and productivity rate (usually truck) should avoid the other one</strong></td>
</tr>
<tr>
<td>Stationary States</td>
<td><strong>the excavator</strong></td>
<td></td>
</tr>
<tr>
<td>Traversal states</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Look-ahead Equipment Workspace (cont.)

Current and Final Pose of Excavator

Motion Path During Loading

Motion Path During Swigging

Motion Path During Dumping
Look-ahead Equipment Workspace (cont.)

Value of DOF_j

Loading

Swing to Truck

Dumping

θ_1,3

θ_1,0

θ_2,2 & θ_2,3

θ_2,0

θ_4,2 & θ_4,3

θ_3,2 & θ_3,3

θ_2,1

θ_1,1 & θ_1,2

θ_3,0 & θ_3,1

θ_4,0 & θ_4,1

Curl the bucket

Pitch the stick

Pitch the boom

Swing the upper body

a_1,0 \times t_0

a_2,0 \times t_0 c_2,0 \times t_0

a_2,1 \times t_1
c_2,1 \times t_1

a_3,1 \times t_1

c_3,1 \times t_1

c_4,1 \times t_1

c_{1,2} \times t_2
Data Processor

\[ \text{Fitness Function Type 1} = \min \left[ P \times \sum_{j=1}^{4} \frac{C_j}{r} + \sum_{i=1}^{6} \left| \frac{D_i - d_i}{D_i} \right| + \frac{|\alpha - \beta|}{\alpha} + \sum_{j=1}^{4} \left[ \frac{s_j}{s_{\max}} \right] + \frac{R}{r} \right] \]

Subject to \( C_j \leq r \)
Case Study 2: LAEW

![Graph showing computation time per simulated second vs. dimension of the cell (cm). The graph includes data points for computation times of 1.5 S, 2.5 S, 3.5 S, 4.5 S, and 5.5 S.](graph.png)
Case Study 1: Layout
Near Real-time Simulation

• The conventional simulation models are based on the statistical data

• Near-real Time Simulation (NRTS) (Lu et al. 2007, Akhavian and Behzadan 2012, Song and Eldin 2012, Pradhananga and Teizer 2013, Akhavian and Behzadan 2013)
LGS in Research

- **Autonomous excavation** (Singh and Cannon 1998, Bradley and Seward 1998, Stentz et al. 1999)

- **Automated compaction** (Kaufmann and Anderegg 2008)
LGS in Industry

- Automated Machine Control/Guidance (AMC/G)
  - Input Data
  - Hardware
  - Tracking Technologies

**DTM (Stanford Business Mapping 2013)**

**AMC/G Hardware (Leica Geosystems 2013)**
LGS in Industry (cont.)

- AMC/G–supported operations (Singh 2010)

(a) Excavation  
(b) Grading  
(c) Milling  
(d) Paving  
(f) Curb installation  
(e) Barrier installation
Project Monitoring and Control

- Monitoring and control of the project is needed to contain delays and variations in the earthwork projects

Performance Control Cycle (Navon 2007)
Project Monitoring and Control (cont.)

- Conventional methods for the measurement of Project Performance Indicators (PPI) are manual.

- New methods use variety of data capturing technologies:
  - RFID (Motamedi and Hammad 2009, Montaser and Moselhi 2012)
  - GPS (Alshibani and Moselhi 2007, Perkinson et al. 2010)
  - UWB (Teizer et al. 2008, Zhang et al. 2011a)
  - Computer Vision (Rezazadeh Azar and McCabe 2011, Golparvar-Fard et al. 2013)
Safety of Earthwork Operations

• Safety systems using different types of technologies:
  – RFID (Chae and Yoshida 2010, Yang et al. 2012)
  – UWB (Teizer et al. 2008, Carbonari et al. 2011, Zhang and Hammad 2012a)
  – Computer Vision (Talmaki et al. 2010, Chi and Caldas 2011)
Multi-agent Systems (MASs)

- An agent is defined as an entity situated in an environment with the capability to form a perception of the environment and act upon it (Russell and Norvig 2003)

Agents’ interaction with Environment (Russell and Norvig 2003)
MAS areas of Application

- **Enhanced decision making**: agents are used to partially or completely substitute humans in decision making
- **Simulation of complex process**: the prevalent type of available information is the behavior of actors in a process
MAS in Construction

• Claim negotiation (Ren and Anumba 2002)

• Task Planning for earthwork (Kim and Russel 2003a and 2003b)

• Data communication (Lee and Bernold 2008)

• Collision avoidance and path planning (Zhang and Hammad 2012a)
Cade Study on Construction Site in Vancouver
Cade Study on Construction Site in Vancouver

- Fiberglass Sheet
- UWB Sensor
- Wireless Bridge
- Cable Container

Diagram:
- Sensor 1
- Sensor 2
- Sensor 3
- UWB Covered Area
- 20 m
- 36.5 m
Cade Study on Construction Site in Vancouver
Cade Study on Construction Site in Vancouver