Automated Collection of Mixer Truck Operations Data in Highly Dense Urban Areas

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Abstract: Our research has investigated the feasibility of directly sourcing autonomous operations data from a construction-vehicle positioning system, so as to enable productivity analysis and simulation modeling in the practical context of ready mixed concrete production and delivery. In this paper, we first review research efforts related to applying radio frequency identification tags and global positioning system components of an automated data collection (ADC) solution to accumulating concrete delivery operations data, which is extended from a construction-vehicle positioning system tailored for highly dense urban areas. We further elaborate on how our ADC system captures, transforms, and analyzes data of mixer truck operations. Truck-tracking experiment results based on field trials are presented to demonstrate the usefulness of data sourced from our ADC system with respect to: (1) analyzing truck-waiting time versus truck-unloading time on site; and (2) predicting truck’s plant-to-site travel time. In conclusion, the ADC solution resulting from this research not only allows sophisticated analysis of mixer truck resource utilization at concreting sites situated in highly dense urban areas, but also provides an accumulation of input data that will enable concrete plant operations simulation modeling.

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Introduction

Project performance data in the construction supply chain are commonly collected using traditional manual methods (Navon and Shpatnitsky 2005). The data collection process is labor intensive, costly, and error prone; the resulting data are often kept as paper-based records, which need to be postprocessed into digital format for computer-based analysis. In consequence, the absence of up-to-date information on construction projects exacerbates the variability in construction operations, severely hampering effective control and management (Sacks et al. 2005). Besides, it is crucial to maintain a balance between the data collection effort and the productivity analysis technique (Kannan and Vorster 2000). The traditional means for obtaining productivity data serves conventional time study techniques well, but falls short of satisfying data needs in implementing simulation modeling. Data acquisition has constituted the bottleneck in state-of-the-art productivity studies employing “data-thirsty” simulation methods (Lu and Anson 2004).

Research into automated data collection (ADC) in construction engineering has advanced rapidly in the past decade. Preliminary applications of ADC in construction are largely focused on how to track and monitor construction resources, including material, labor, tool, and equipment. In particular, radio frequency identification (RFID) tags and global positioning system (GPS) have matured to afford cost-effective, unobtrusive solutions for tracking various resources and acquiring operations data in the relatively harsh and hectic environment of construction sites.

RFID tags operate on radio frequencies of particular bandwidths to capture and transmit data and facilitate materials management, time and attendance keeping, tools and capital equipment tracking, and asset management (Navon et al. 2004). Naresh and Jahren (1997) conceptualized RFID systems for discrete point positioning in tracking construction vehicles, complemented by: (1) continuous vehicle position tracking by GPS; and (2) commercially available radio bands for transmitting text-based signals. Jaselskis and El-Misalami (2003) implemented passive RFID tags to receive and keep track of a variety of pipe spool components used in process-piping construction. Song et al. (2006) utilized active RFID tags for tracking the delivery and receipt of fabricated pipe spools in laydown yards and under shipping portals; 100% accuracy was reported in automatically identifying pipe spools when spools were driven at a speed less than 3.22 km/h through a portal gate equipped with four antennas. Goodrum et al. (2003) developed a tool tracking system with active RFID tags embedded in tool casings. Their field trials found the active RFID technology has significant potential to improve tool inventory and allocation on site. Notably, one practical constraint in applying RFID in construction is that the communication distance between RFID tags and readers could decrease...
considerably with the existence of metals in their vicinity (for example, reinforcement mesh, steel scaffold, shoring, or shutter, metal door and boarding) (Erken et al. 2007; Lu et al. 2007). Additional limitations of implementing RFID tags in construction were identified as: (1) economics of active RFID technology; (2) lack of standardization; and (3) lack of directional and range data (Goodrum et al. 2006).

The current stand-alone GPS can lock positions with accuracy around 10 m in open areas. The positioning accuracy of 1–2 m is obtainable with differential GPS (DGPS), which uses a GPS base receiver located at a fixed known point to correct the observations made by a rover receiver. With special algorithms, real-time kinematic GPS (RTK GPS) further enhances GPS positioning accuracy to centimeter (even millimeter) levels by combining measurements of signal carrier phases from both base and rover receivers. In a relatively open environment (for example, in earth-moving operations or road construction), GPS proves to be the ideal technology for automated data collection in the following applications: (1) real-time quality control of compaction operations in highway construction (Li et al. 1996); (2) aiding autonomous control and guidance of asphalt paver or bulldozer (Roberts et al. 1999; Peyret et al. 2000); (3) equipment tracking, collision detection, and resource utilization in earthmoving projects (Olo-ufa et al. 2003; Navon et al. 2004); (4) locating the movement of a tower crane (Sacks et al. 2005); and (5) receiving, storing, and issuing fabricated pipe spools in lay down yards at a process piping site (Caldas et al. 2006).

Nonetheless, the performance of GPS positioning in an enclosed or partially covered environment could be severely degraded due to blockage, deflection, and distortion of satellite signals (Lu et al. 2004). Thus, the use of GPS for tracking resources at building sites situated in a highly dense urban area presents distinctive challenges to the technology itself (Mattos 2003). One reported attempt was to apply the same positioning principles as GPS in conceptualizing ground-based radio frequency (RF) stations to track labor input in on-site activities (Navon and Goldschmidt 2003). In addition, researchers have also attempted hybrid use of RF-based technologies to customize resource tracking solutions oriented toward construction applications. For example, Ergen et al. (2007) reported an approximately 60% success rate in applying a RFID-GPS integrated solution for positioning precast concrete components; the position of the picking bar of a gantry crane was tracked by a GPS receiver while GPS data were written into RFID tags attached on the precast units being lifted.

In our previous research, we developed a special-purpose simulation tool (called HKCONSIM) for rapidly building a simulation model of a typical one-plant-multisite system of concrete production and delivery (Lu et al. 2003). The simulation modeling of concrete plant operations aimed at facilitating the study of the complicated relationships between the patterns of demand for concrete, the resources available to the system, and the service levels achieved together with the utilization levels achieved for the resources involved. We further exposed limitations of applying GPS for tracking construction vehicles in a highly dense urban area by conducting extensive field tests in Hong Kong. A continuous, all-location, real-time solution was proposed for positioning construction vehicles in highly dense urban areas and partially covered building sites by: (1) integrating GPS with the vehicle navigation technology called “dead reckoning” (DR); and (2) using Bluetooth for short-range wireless data communication and commercial mobile phone networks for long-range wireless data communication (Lu et al. 2007).

As a continuous effort, the present research looks into the possibility of directly sourcing autonomous operations data from the GPS-DR integrated positioning system to enable productivity analysis and simulation modeling. The chief obstacle of the research lies in the difficulty of distinguishing the truck’s waiting and unloading states on site based on the truck tracking data obtained from the truck positioning system. To separate the two states, we first augmented our truck tracking system into an ADC solution with additional wiring design, which allows the collection of electrical pulses from the concrete-unloading button near the dashboard of a mixer truck. Then, we assembled the ADC system in house and installed it on a mixer truck of a concrete plant to undergo 10-month field trials in Hong Kong. Field experimental results verified the technical feasibility of the ADC solution in terms of supplying data for concreting productivity analysis and operations simulation modeling.

The reminder of this paper is organized as follows: First, we describe the technical design and system components of the ADC solution. We then elaborate on data capture, data transform, and data analysis based on our ADC solution. In the following sections, truck-tracking experiment results from field trials are presented to demonstrate the usefulness of ADC data, with respect to: (1) analyzing truck-waiting time versus truck-unloading time on site; and (2) predicting truck’s plant-to-site travel time. Conclusions are drawn and future research recommendations made in the end.

Automated Collection of Mixer Truck Operations Data

Fig. 1 gives a depiction of our ADC solution extended from a construction vehicle positioning system tailored for highly dense urban areas, showing: (1) main components; (2) the functioning scope of each component; and (3) the wireless channels for data communication between system components. Note the vehicle inertial navigation technology of DR automatically supplants GPS when GPS signals become unavailable or unreliable. The drift error of DR over a long time period or a long travel distance is corrected automatically by a road-side Bluetooth beacon (BB), which is placed in a location with well-defined coordinates. The beacon resembles the RFID tag in functionality but operates on
Bluetooth for establishing communication links with the in-vehicle navigation unit. In addition, real-time data as of location and status of a mixer truck are transmitted to the control center by short message service (SMS) over commercial mobile phone networks. The control center PC is connected with: (1) a database that archives historical productivity data; and (2) a concrete plant operations simulation platform (HKCONSIM). Readers may refer to Lu et al. (2007) for technical specifications of the integrated construction-vehicle positioning system.

The cyclic process of concrete production and delivery between a concrete batch plant and a construction site consists of six main activities, namely: (1) parking a mixer truck at plant and waiting for dispatch; (2) batching and loading concrete into truck after delivery order being assigned; (3) truck traveling to a specified site; (4) truck queuing and waiting for unloading on site; (5) truck unloading concrete by a particular concrete-placing method; and (6) empty mixer truck returning to the plant. In short, to derive time duration of major activities describing a concrete delivery cycle entails the recording of five key event times, namely: (1) leaving plant; (2) arriving site; (3) start unloading; (4) departing site; and (5) arriving plant. Those events are mostly geography associated. For instance, the event times of “leaving plant,” “arriving plant,” “arriving site,” and “departing site” can be readily identified by matching the location of a mixer truck to the boundaries of the plant or the site in a digital map, by applying the same principle of geometrical association as employed in Navon and Shpatnitsky (2005).

An example is given in order to demonstrate how location matching works: tracking results for the mixer truck “NU001” of a Hong Kong ready mixed concrete plant on April 22, 2006 are shown in Fig. 2. Key relevant locations are marked in the map, including: (1) the mixer truck parking yard; (2) the concrete plant; (3) the two construction sites involved; and (4) the washing pool. Precise coordinates of those locations and travel distances were entered in a geometrical database for location matching analysis, as listed in Table 1. After associating the truck’s positioning records with specified event locations, the complete operations of the mixer truck were traced accurately (as shown in Fig. 2). The truck “NU001” departed from the parking yard at 0816 h (T1 from park to plant; note T is short for point-to-point trip), then underwent three rounds of concrete delivery to construction site 01 (Round 1: T2 and T3; Round 2: T4 and T5; Round 3: T6 and T7), and one round to construction site 02 (T8 and T9). At the end of the working day, the mixer truck finished by cleaning at a washing pool (T9 from Site 02 to washing pool) and then returned.

### Table 1. Key Location Coordinates and Travel Distances in Concrete Delivery Operations

<table>
<thead>
<tr>
<th>Key point</th>
<th>Location</th>
<th>Coordinate</th>
<th>Effective travel distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lat/Long</td>
<td>Park</td>
</tr>
<tr>
<td>Park</td>
<td>Cha Kwo Ling Road</td>
<td>N22.2986/E114.2329</td>
<td>/</td>
</tr>
<tr>
<td>Plant</td>
<td>Pak Shing Kok</td>
<td>N22.3024/E114.2579</td>
<td>—</td>
</tr>
<tr>
<td>Site 01</td>
<td>Tsui Ping North Estate</td>
<td>N22.3166/E114.2339</td>
<td>—</td>
</tr>
<tr>
<td>Site 02</td>
<td>Wing On Plaza</td>
<td>N22.2967/E114.1762</td>
<td>—</td>
</tr>
<tr>
<td>Washing pool</td>
<td>Koi Fai Road</td>
<td>N22.2962/E114.2355</td>
<td>1.1</td>
</tr>
</tbody>
</table>

*Not available.

### Table 2. Detailed ADC Data on Ten Concrete Delivery Trips Tracked in 1 Day

<table>
<thead>
<tr>
<th>Round number</th>
<th>Trip code</th>
<th>Trip description</th>
<th>Distance (km)</th>
<th>Key time collection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T1</td>
<td>Park to Plant</td>
<td>8.6</td>
<td>0816:43 0833:49</td>
</tr>
<tr>
<td></td>
<td>T2</td>
<td>Plant to Site 01</td>
<td>7.5</td>
<td>0918:59 0934:44</td>
</tr>
<tr>
<td></td>
<td>T3</td>
<td>Site 01 to Plant</td>
<td>7.5</td>
<td>1011:13 102:17</td>
</tr>
<tr>
<td></td>
<td>T4</td>
<td>Plant to Site 01</td>
<td>7.5</td>
<td>1154:47 1207:51</td>
</tr>
<tr>
<td></td>
<td>T5</td>
<td>Site 01 to Plant</td>
<td>7.5</td>
<td>1246:02 1258:05</td>
</tr>
<tr>
<td></td>
<td>T6</td>
<td>Plant to Site 01</td>
<td>7.5</td>
<td>1328:14 1341:18</td>
</tr>
<tr>
<td></td>
<td>T7</td>
<td>Site 01 to Plant</td>
<td>7.5</td>
<td>1418:19 1432:25</td>
</tr>
<tr>
<td></td>
<td>T8</td>
<td>Plant to Site 02</td>
<td>15.6</td>
<td>1546:54 1629:09</td>
</tr>
<tr>
<td></td>
<td>T9</td>
<td>Site 02 to Washing pool</td>
<td>10.3</td>
<td>1705:20 1722:25</td>
</tr>
<tr>
<td></td>
<td>T10</td>
<td>Washing pool to Park</td>
<td>1.1</td>
<td>1744:31 1746:32</td>
</tr>
</tbody>
</table>
to park at the plant at 1746 h (T10 from washing pool to park). Detailed event times collected in the total of ten trips and time elapsed in each trip are shown in Table 2. Note that despite relatively short distances (about 10 km), the traveling time (or speed) of a mixer truck between the concrete plant and a construction site in a highly dense urban area could fluctuate, under the influence of truck load and uncertain traffic conditions (e.g., traffic jams, red light stops, or accidents). In this case, T2, T4, and T6 were plant-to-site, fully loaded mixer truck trips, with an average travel speed of 32.9 km/h; T3, T5, and T7 were site-to-plant, empty mixer truck trips registering an average travel speed of 37.5 km/h; it is also observed that the highest average travel speed of 45 km/h occurred on T3.

Start-Unloading Event Recording

As a mixer truck enters a construction site, its on-site unloading process is generally classified as “active state,” while the waiting prior to unloading is regarded “passive state.” Therefore, recording the event time of “start unloading” is vital to separating the two consecutive states and making the truck tracking data useful for productivity study or simulation modeling. Yet, the “start unloading” event can be one exceptional case that does not lend itself to location matching at some sites featuring congested site layout and employing particular concreting methods. For instance, at a bored pile site, a temporary platform with ramp was set up to facilitate the unloading of concrete from the mixer truck to the tremie pipe. The moment that the truck moved onto the platform can be reasonably taken as the “start unloading” event. The above case exemplifies location matching. In the case of a congested building site situated in a downtown, the truck arrived and parked along the street to unload concrete into a concrete pump. The “start unloading” event occurred at the same location as “arriving site.” Thus, the location matching approach would fail due to two events overlapping in space.

In order to consistently record the “start unloading” event, we augmented the truck tracking system with additional wiring design that allows the collection of electrical pulses generated from pressing the concrete-unloading button in the dashboard of the cab (the top left two pictures in Fig. 3). On the moment the button is pressed (i.e., time t1), the voltage measurement increases from 0 to +12 V. The voltage then returns to 0 V after the button is released at time t2. The analog electrical pulse is converted into a digital signal in the format of 0/1 by an analog to digital conversion process (middle in Fig. 3). To remove any signal noise and avoid repeat pressing, a photoelectric isolating circuit and a time delay processing algorithm were employed in our wiring design. As such, as soon as the in-vehicle tracking unit (as shown in the top right of Fig. 3) receives the effective start-unloading signal, a time-stamped short message is generated and immediately sent to the control center via the mobile phone network. In this way, the “start unloading” event is recorded. A glimpse of the records collected in the database before and after unloading button being pressed is shown in the bottom of Fig. 3.

Data Transform and Processing

With the added wiring design, our truck positioning and tracking system was augmented into an ADC system capable of supplying data for productivity study or simulation modeling. The raw data contain: (1) time-stamped truck location coordinates; (2) time-stamped “start-unloading” signals; and (3) the corresponding truck ID. Data transform and processing starts with converting raw data into event time data by location matching. With truck event times available, time duration for concrete delivery activi-
ties can be determined conveniently. Such activity time data can be accumulated to update corresponding statistical distributions of activity duration underlying the HKCONSIM simulation model. The data transform and processing in our ADC system is illustrated with examples in Fig. 4. In the ensuing section, truck-tracking experiment results based on field trials are presented and analyzed.

Analysis of Automatically Collected Data

The ADC system was assembled in house and mounted on a mixer truck to undergo 10-month field trials from September 2005 to June 2006 in Hong Kong. A total of 32,747 time-stamped location points and 106 effective unloading signals were collected and 14 different construction sites were covered. Positioning errors of less than 10 m were recorded on more than 96% of the truck tracking points. Considering that the testing environment was either highly dense urban areas or partially covered building sites, the accuracy and reliability of our ADC solution were deemed satisfactory. Time data for activities “unloading mixer truck” and “mixer truck traveling-to-site” were of particular importance due to the fact that the two activities demonstrated relatively high variability in the real system. Next, we carried out straightforward statistical analysis on the tracking data in two cases. One case was to contrast waiting time versus unloading time experienced by the mixer truck in serving one particular site. The other case was to analyze the travel-to-site duration as for particular road sections during various time periods of a working day.

Case 1: Truck Waiting Time versus Unloading Time

The mixer truck served a building site near the Kwun Tong district of Hong Kong from September 2005 to May 2006. In this case, data for 35 concrete delivery trips were chosen for analysis of a truck’s waiting and unloading times on site. Fig. 5 shows the histogram for the unloading time, with 30 of all 35 observations falling in the leftmost subrange of [6, 15.3 min]. The resultant histogram could be fit into a right-skewed statistical distribution as a simulation input model that represents the time distribution of truck unloading activity. Moreover, decomposition of the truck on-site residence time in each delivery trip is shown in Fig. 6, with the waiting time portion and the unloading time portion distinguished in grey and dark patterns.

In addition, by checking concrete delivery slips obtained from the truck driver, we ascertained concrete placing methods as associated with 23 delivery trips tracked by our ADC system. Averaged waiting versus unloading times for “direct tip,” “mobile pump,” and “crane & skip” are contrasted in Fig. 7. Although the small sample size does not guarantee statistical significance of the results, Fig. 7 helps us gain some insight into the effect of concreting methods on truck waiting and unloading times:

1. As “mobile pump” and “crane & skip” unload concrete into either a hopper or a skip in repetitive concrete-placing cycles, the two methods require comparable time duration to unload the mixer truck (16.7 min vs. 18 min); in contrast, unloading time for “direct tip” is much shorter (9.2 min); and
2. Truck waiting time as for “direct tip” (11.2 min) is appreciably longer than “mobile pump” (5.3 min) or “crane & skip” (6.7 min). This can be accounted for by the fact that “direct tip” was mostly associated with foundation sites (such as
bored pile construction); those site clients normally required the concrete plant to bunch a couple of trucks at their site during the concrete pour to ensure an uninterrupted concrete supply that guarantees a continuous placing operation.

It is noteworthy that our previous related research utilized concrete quality control (QC) records, routinely accumulated on site, for establishing the concrete placing rates of various concreting methods (Lu and Anson 2004). Nonetheless, the scope of the analysis was limited by the extent and nature of the available data, as QC records only tracked the times for the “mixer truck arrival” and “mixer truck departure” events. In contrast, the ADC solution resulting from this research not only allows more sophisticated analysis of site productivity, but also provides input data for enabling simulation modeling of concrete plant operations.

**Case 2: Travel-to-Site Duration on Particular Road Sections**

Truck travel-to-site time duration can be an uncertain variable in the case of Hong Kong’s congested roads and heavy traffic. In order to shed light on variations in the travel-to-site time duration for particular road sections, truck tracking data representing 25 trips from the concrete plant to a Kowloon City building site were analyzed. Note the road sections traveled by the truck driver in each trip were identical and the traveling distance was 7.9 km. The histogram of 25 travel time samples is shown in Fig. 8 with the overall average being 16.96 min and the standard deviation being 2.86 min. In connection with simulation modeling, the travel-to-site activity time can be modeled with one statistical distribution fitted onto the histogram as shown in Fig. 8. In addition, given a particular plant-to-site travel path, variation patterns in travel-to-site time duration are revealed in Fig. 9. For convenience of analysis, we divided daily working time (from 0800 to 2100 h) into five periods. The average travel time duration in different time periods was calculated and is shown in Fig. 10. It is found that during the time period of “1100–1400 h” it took the mixer truck on average 21.5 min to travel from plant to site, which was 7.5 min longer than during the “1900–2100 h” period (14 min). Given more data collected by the ADC system, it would be more accurate to model the travel time for a particular plant-to-site travel path with specific statistical distributions fitted to different time periods of the day.

**Conclusions**

The absence of up to date information on construction projects exacerbates the variability in construction operations, severely hampering effective control and management. In the meantime, data acquisition has constituted the bottleneck in state-of-the-art productivity studies employing “data-thirsty” simulation methods. Research into ADC in construction engineering has advanced rapidly in the past decade, enabling the tracking and monitoring of construction resources, including material, labor, tool and equipment.

This research has investigated the feasibility of sourcing autonomous operations data directly from a GPS-DR integrated construction-vehicle positioning system tailored for highly dense urban areas, in the practical context of ready mixed concrete production and delivery. In order to distinguish the truck’s waiting and unloading states on site in the truck tracking data, we first augmented our truck positioning system into an ADC solution with additional wiring design that allows the collection of electrical pulses from pressing the concrete-unloading button near the dashboard of a mixer truck. Then we assembled the ADC system in house and installed it on a mixer truck of a concrete plant for 10-month field trials in Hong Kong. Field experimental results
verified the technical feasibility of the ADC solution to supplying
data for concreting productivity analysis and operations simulation
modeling. The resultant ADC solution would permit quantitative
analysis based on updated operations data and directly benefit the operators of concrete plants in terms of improving mixer truck resource utilization and raising service standards in concrete delivery. Not limited to tracking concrete mixer trucks, our ADC solution can be readily adapted to other construction logistics applications involving the use of a fleet of vehicles to deliver materials to various sites situated in highly dense urban areas.

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