Feasibility of Automated Monitoring of Lifting Equipment in Support of Project Control

R. Sacks[1]; R. Navon[2]; I. Brodetskaia[3]; and A. Shapira[4]

Abstract: One of the differences between industrial manufacturing or processing plants and construction sites is the temporary nature of the construction site, which has traditionally precluded installation of sophisticated production monitoring systems. Monitoring of production progress, cost, and quality is performed almost exclusively manually, with the result that it is expensive and approximate, and is commonly delivered with a time lag that does not allow for an effectively closed control loop. Automated monitoring of construction lifting equipment to provide useful feedback information for project management is a strong potential candidate; almost all components and materials must be transported by machines, and monitoring of machines is relatively straightforward. A system concept, employing a "black box" monitor and an electronic building information model, was developed. A field study was conducted to test the feasibility of the concept. The results indicate that the system is technically feasible, and offers the potential to deliver real-time, accurate project control information at very low cost.

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Introduction

In most construction projects, effective management is severely handicapped by a lack of timely and accurate feedback information describing actual performance and progress on the construction site (Futcher 2001; Saidi et al. 2003). Quantities of work performed and hours invested by labor and equipment are commonly assessed manually, which incurs costs, and is error prone. Manual data collection also limits the frequency of monitoring; data are accumulated and reported at time intervals that are greater than the typical durations of the construction activities themselves. The result is that corrective intervention is often impossible as the activities have been completed by the time the feedback information reaches the decision makers. In response to this situation, researchers have proposed that automatic data collection on construction sites can provide low-cost, accurate, and timely information (Echeverry and Beltran 1997; Cheng and Chen 2002; Navon and Goldschmidt 2003b).

We note that almost all construction materials and components must be lifted into place using machinery. From a technological point of view, monitoring lifting equipment is relatively straightforward. These two factors suggest that monitoring lifting equipment is a potentially significant source of information useful for construction project control.

Currently, lifting equipment is only monitored for safe operation, for maintenance, and in rare cases for improving operation of the equipment itself. This paper presents and develops the concept of monitoring equipment for project control purposes, and reports the results of a field study that was conducted to test the technical feasibility of the idea. After a brief review of the principles of automated data collection in construction, and of the role of main lifting equipment on construction sites, the paper describes the monitoring equipment used in the field study and the significant aspects of the construction project on which it was tested. Crane cycles were monitored for a selection of different basic construction activities. Based on these measurements, a method was developed for identifying the activities performed using the crane. The method involves isolation and identification of each individual transport operation, for which it requires detailed project information in specific electronic formats. The penultimate section of the paper presents the results of the observations and discusses their implications.

Automated Data Collection for Construction Management

Project performance control broadly refers to the activities taken by the project (or company) management in order to ascertain that

[1]Senior Lecturer, Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel. E-mail: cvsacks@technion.ac.il

[2]Associate Professor, Head, Construction Engineering & Management; Head, Construction Automation Laboratory; Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel. E-mail: ronie@techunix.technion.ac.il

[3]Graduate Student, Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel. E-mail: cvirina@techunix.technion.ac.il

[4]Associate Professor, Vice-Dean for Teaching and Undergraduate Studies, Faculty of Civil and Environmental Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel. E-mail: avishap@techunix.technion.ac.il

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the performance of the project is as close as possible to a set of desirable values. Performance is measured in terms of project performance indicators, such as cost, schedule, labor productivity, and material consumption or waste. The indicators are calculated from data collected at the construction site or in the construction supply chain. The fact that the data are costly to measure and collect using existing manual methods is an obstacle to effective control. There is a severe lack of up to date "as-built" information on construction projects (Saidi et al. 2003). The absence of real time (or near real-time) and appropriate information exacerbates the variability common in construction operations; variability severely hampers effective management (Hopp and Spearman 1996; Howell 1999 Howell and Koskela 2000).

In this context, the term "automated" refers to the notion that the performance indicators can be measured and interpreted automatically, as they are in process industries and in many manufacturing industries. The fact that monitoring and reporting cycles in current practice are longer than most construction activities leads to the conclusion that automating control of on-site construction performance is essential in order to enable management to take corrective measures in real-time. Advanced technologies that can be used for real-time on-site measurement of performance indicators are rapidly emerging, and their costs are declining (Ciesielski 2000; Greeman 2002).

The most advanced present-day methods do not yet exploit automation fully. The COMPASS-ID measurement technique (Chysostomou 2003), employs one or more human observers who patrol the site at regular time intervals and record the tasks being undertaken on a hand-held computer. This is a commendable achievement because it enables real-time labor control, although it still requires full time observers. Localized applications of more technologically sophisticated concepts have been suggested in the academic research literature. Jaselskis and others proposed a conceptual model using radio frequency identification (RFID) technology, which is one step beyond barcode technology (Jaselskis et al. 1995; Jaselskis and El-Misalami 2003). According to their concept, the worker's arrival on site and movement between tasks are recorded automatically using RFID technology, but the worker has to record the cost code of the various activities in which she/he was engaged, using a hand-held computer.

Navon and Goldschmidt (2003a) hypothesized that performance indicators can be deduced by monitoring indirect indicators of construction activity, such as the location and movement of skilled laborers through the work day, and consumption of materials. They tested the hypothesis in an experiment in which workers' locations were monitored through execution of 12 different activities. The same principle served as the basis for another model, which was implemented in a prototype system for controlling earthmoving operations in road construction and tested on site (Navon et al. 2004; Navon and Shpatnitsky 2005). This model was realized in a prototype system and tested in a road construction site, using a global positioning system (GPS) antenna mounted on each of the pieces of equipment performing the controlled activities.

Conceptually, this approach to automated project performance control calls for developing monitoring systems that can measure indirect parameters automatically, in such a way that the monitored data streams can be translated into information that estimates actual project progress. Both of the latter efforts made use of the "work envelope" concept; a "work envelope" describes a volume in space around a building element in which it is assumed that a worker or piece of equipment must be physically present in order to perform a basic construction activity on that element. Sacks et al. (2003b) demonstrated incorporation of a work envelope abstract object class and two specialized work envelope object subclasses in an object-oriented building project model.

Lifting Equipment in Building Construction

Almost every component and material used in construction is transported on site by mechanized lifting or hauling equipment of one kind or another. The types of lifting equipment that may be monitored include cranes (top-slewing and bottom-slewing tower cranes, crawler, and truck-mounted mobile cranes), hoists, concrete pumps, and material handlers. Cranes were selected for the current field study because:

1. they are capable of lifting the full range of construction components and materials, and
2. (partly as a result) they are ubiquitous, being the primary means of material transportation on most construction sites. The number of operational tower cranes alone is estimated at 400,000 units worldwide (Crane Equipment 2001).

The concept of measuring project progress through monitoring equipment, as introduced here, applies to buildings rather than to civil infrastructure projects. In Europe, the lifting solution for almost any building construction project is the tower crane, while in the United States the culture of mobile cranes prevails (Shapira and Glascock 1996). Due to its dense population and the scarcity of real estate, high-rise construction is common in Israel, and contractors traditionally favor European-style solutions (Shapiro et al. 2000). For this reason only, a tower crane was selected for the purposes of the current study; the project control monitoring concept applies equally to mobile cranes.

The range of existing technical solutions for monitoring construction lifting equipment includes "black boxes" mounted on engines, winches and booms, GPS monitors, and RFID tags (Greeman 2002). The monitored data are recorded on data loggers and downloaded periodically, or they can be transmitted to a control station by radio or through cellular phone networks.

Monitoring Equipment and Construction Project

A field study was planned and executed to test the technical feasibility of monitoring construction lifting equipment to provide real-time (or near real-time) project progress information for management. The point of departure was the assumption demonstrated in the research described in the previous section; that construction activities could be identified through the locations of the equipment used in their execution. The location alone is apparently insufficient for conclusive identification, and so additional data was sought. The proposed crane monitoring model is therefore based on automated measuring and recording through the working day of the following parameters: $W(t)$ = gross weight of the load on the hook, measured continuously through time and $L(t)$ = hook location, measured continuously through time in local coordinates.

Two distinct technological solutions were considered for automated weight and location measurement: separate measurement of each parameter using load and location monitors that would be attached to the hook, or use of the "built-in" proprietary monitors that are supplied with many modern cranes for maintenance purposes.

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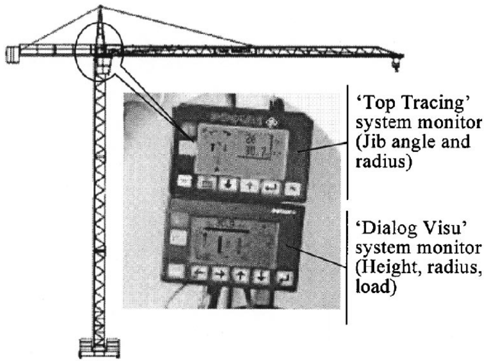

Fig. 1. "Dialog-Visu" and "Top-tracing" monitoring systems mounted on Potain MD 345 crane (data from Potain 2003)

Separate Load and Location Measurement

A variety of tensile links, crane scales, load measuring pins, load cells, and other equipment is available for measuring the gross load weight. These kits allow measurements in a standard range from 500 kg to 100 t and have cable or telemetry connections to a central interface block; with transmission error, accuracy is about ±1% of actual readout. For location monitoring in this combination, the GPS may be used. The GPS is a space-based positioning system that can provide three-dimensional position data anywhere on the earth to those with the proper receivers. To avoid transmission interference and to get submetric accuracy, a pair of receivers may be used and operated in differential mode. Global positioning coordinates can be translated into local coordinates for any particular area, such as a construction site (Peyret et al. 2000, Navon and Goldschmidt 2003b).

Built-In Monitors Supplied by Equipment Manufacturer ("Black Boxes")

Some manufacturers of lifting equipment offer crane monitoring systems that provide real time monitoring of weight and position parameters. For example, Potain's "Dialog Visu" and "Top tracing" control systems (Potain 2003)—see Fig. 1—enable real-time monitoring and collection of the gross load weight, radius, distance of the trolley from the tower, length traveled (jib-to-hook distance) and jib-slewing angle. The hook position definition about the crane axis can be considered a "crane polar coordinate system." A crane equipped with this system was used in the construction site experiments reported in this paper. Independently supplied systems intended for mounting on existing cranes are also available (Guardian 2003).

These advanced control systems are intended mainly to enhance site safety, for more accurate crane operation in zones with reduced visibility, and for operation with remote control. They can be programmed to give warning against overload or to prevent travel into dangerous zones. There appear to have been no previous attempts, neither in research nor in practice, to exploit these monitors to provide construction project managerial information.

In order to evaluate the feasibility of using data collected by crane monitoring "black boxes" to provide managerial information, an extensive series of readings were taken at a construction site on a Potain MD 345 tower crane. Measurements were recorded through a number of typical working days as the crane was observed performing distinct construction basic activities. The slewing angle of the jib, the distance of the trolley from the tower, and the cable length were monitored, thus providing the location of the hook in a cylindrical coordinate system around the crane's tower. These locations were transformed into the building's local Cartesian coordinate system. The load on the hook was also monitored through time.

Table 1 provides a sampling of the data collected. The volume of data generated by the five data streams when measured at short time intervals (in the order of 5 s) makes it impractical to archive the data in its raw form. This problem was overcome by filtering the data and storing only those data points from each stream at which the values changed. In parallel, the actual crane operations were also recorded on videotape.

The observations were performed during construction of the structural frame from the fourth to the seventh floors of the 22 story office building shown in Fig. 2. The structure is a hybrid

Table 1. Sample Results of Crane Hook Location and Load Monitoring, During Installation of Precast Concrete Hollow-Core Plank

	"Dialog Visu"			"Top tracing"		Location in the building's local coordinate system (m)		
Time (h:min:s)	Load (t)	Cable length (m)	Trolley radius[a] (m)	Trolley radius[a] (m)	Jib angle (deg)	*X*	*Y*	*Z*
16:41:13	0.2	64.4	42.5	42.5	83	8.9	39.4	1.6
16:41:18	0.4	64.3	42.5	42.5	83	8.9	39.4	1.7
16:41:23	1.3	64.3	42.4	42.3	83	8.9	39.2	1.7
16:41:28	2.0	63.1	42.2	42.3	83	8.9	39.2	2.9
16:41:33	1.8	58.9	42.0	42.1	83	8.9	39.0	7.2
16:41:38	1.6	52.3	42.0	42.0	83	8.9	38.9	13.7
16:41:43	1.8	45.7	42.0	42.0	83	8.9	38.9	20.3
16:41:48	1.6	39.3	42.0	42.0	84	8.2	39.0	26.7
16:41:53	1.8	37.1	38.8	38.8	84	8.1	35.8	28.9
16:41:58	1.7	37.0	35.3	35.3	87	6.1	32.3	29.0
16:42:03	1.8	36.8	32.0	32.1	87	6.1	29.1	29.2
16:42:08	1.8	36.7	32.0	32.1	87	6.1	29.1	29.3
16:42:13	1.7	36.8	32.0	32.1	87	6.1	29.1	29.2

[a]The trolley radius is measured by two independent systems.

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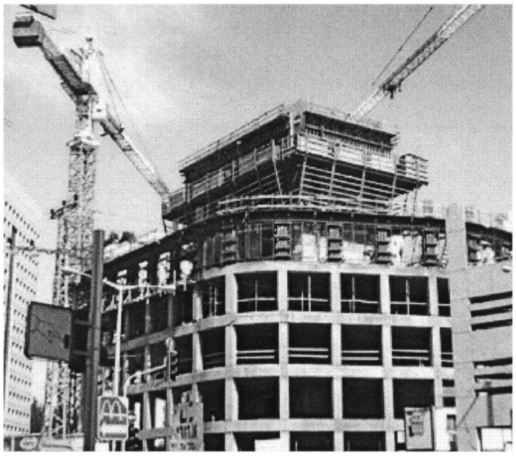

Fig. 2. Construction project on which measurements were recorded

cast-in-place and precast concrete high-rise office building. It consists of a reinforced concrete core, a column and beam perimeter frame, and slabs built with hollow-core precast planks. The basic activities performed using the tower crane in this project were placing and stripping of formwork, placing reinforcement cages, placing concrete, placing hollow-core deck planks, and delivery of miscellaneous tools and materials. The building's core was formed using an industrialized hydraulic self-raising formwork system, with only the reinforcing and concrete placing performed by the tower crane. The beam and column frame was formed using custom-made steel shutters, which could only be handled using the crane. Construction of the core preceded construction of the perimeter frame and slabs by three stories. All of the concrete was placed using two tower cranes.

Identifying Construction Activities from Crane Operations

Construction is planned and controlled in terms of activities or tasks. Regardless of the level of detail of planning and/or of control, the monitoring function must be able to provide information describing what has taken place in terms of the activities. The ability to associate measured equipment actions with predefined construction activities is therefore essential for producing useful management information from equipment monitoring. We define this link, in the context of an object-oriented representation of the information and knowledge about building construction projects, as existing between individual crane operations and element work envelopes. The following sections define the information context and explain how occurrences of the link can be tested for and established.

Knowledge and Information Requirements

For the automated monitoring system, all of the data required for associating equipment actions with specific construction activities must be available in an electronic format that can be readily accessed by the interpretation software. Parametric three-dimensional (3D) information-rich building project models, commonly termed building information models (BIM) (Laiserin 2002), can provide all of the information necessary (Sacks et al. 2003a). The concept of object-oriented building product models is not new (Eastman 1999). The basic idea is to represent the building, its spaces, and its components as software objects, each with distinct identity and geometry, capable of representing form, function, and behavior. The structural steel industry already relies on 3D models for fabrication, and has an effective product model for data exchange among a variety of applications (CIMSteel Integration Standards–CIS/2). The North American precast concrete industry is not far behind (Eastman et al. 2003). The leading construction-oriented computer-aided design software vendors either offer, or are in the process of developing, new software products to support the BIM paradigm for architecture and other building design professions (Laiserin 2002). Thus it is reasonable to assume that information-rich building project models will become commonplace in most construction projects, as they are already in structural steel, and will soon be in precast concrete.

In the short term, for buildings such as the one presented in this research where the design process does not provide the machine-readable project data that is prerequisite for automated monitoring, the project must be modeled as part of the system setup and calibration effort. This building was modeled using a prototypical object-oriented building modeling system developed at the Technion (Sacks 1998). The model was subsequently extended to support automated labor monitoring (Sacks et al. 2003b), through addition of the "Basic work envelope" class and its two object subclasses, "Element work envelope" and "Temporary work space," and other object classes. The central idea behind this extension was the notion that workers must be within a certain distance of an element in order to perform a basic activity on it (Navon and Goldschmidt 2003b). The physical proximity is defined as a bounding volume whose location and dimensions are fixed parametrically in relation to the volume and location of the element, and is called an element work envelope (EWE). A temporary work envelope (TWE) defines a volume in space in which work is performed that cannot be associated geometrically to any specific instance of a building element (such as tying rebar cages at a temporary work station).

In this work, we apply the concept of requisite proximity to an element for working on it to construction equipment. Two new object classes are added: an "Equipment cycle" and an "Equipment operation." An equipment cycle represents a continuous period of time during which the equipment performs an action. Its attributes are measurements through time of its monitored parameters (for example, load and location in the case of the tower crane). An equipment operation is defined to represent a single action performed by the equipment on a single building element. More than one equipment operation, potentially from more than one equipment cycle, may be required to complete a basic construction activity on one element. On the other hand, by definition, an equipment operation can operate on one and only one building element. An equipment cycle may contain a single equipment operation (such as lifting a concrete formwork shutter into place), or a series of multiple operations (such as placing concrete from the same bucket load into multiple columns).

Thus the association between equipment activity and construction activities is made at the level of equipment operations and element work envelopes. In the case of the tower crane, a "Crane cycle" subclass of "Equipment cycle" and a "Crane operation" subclass of "Equipment operation" are defined. To be able to make the association between a crane operation and a construction activity, the following steps are necessary:

1. Monitor the crane and identify crane cycles from the continuous monitored data streams;
2. Isolate individual crane operations within crane cycles;
3. Evaluate the parameter values of each crane operation;

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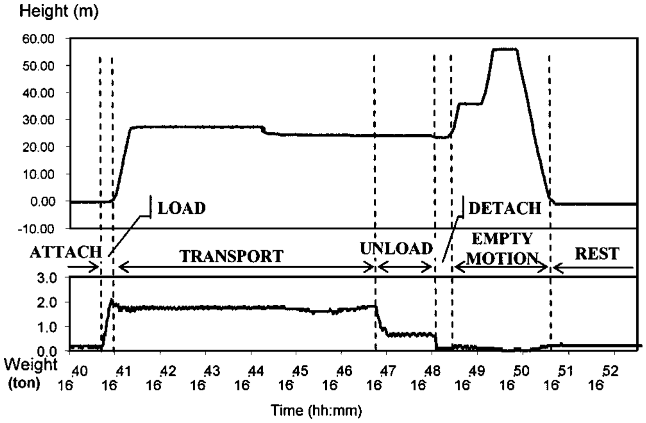

Fig. 3. Typical monitoring data series as function of time

4. Establish the parameter values for all crane-related EWEs and TWEs; and
5. Associate each crane operation with an EWE.

The following sections focus on these five steps. Note that at this point, we implicitly assume that each crane operation can be associated with one and only one EWE. This cannot be taken for granted, but must be explicitly designed for and checked in the calibration of the monitoring system for each and every building. Each project has its unique set of EWEs, which are dependent upon the construction methods employed and on the building geometry. This aspect is beyond the scope of this paper, and will be dealt with in future publications.

Monitoring and Identifying Crane Cycles

Crane monitoring provides two data streams: $W(t)$, the gross weight on the hook measured through time, and $L(t)$, its' 3D location measured through time. Fig. 3 shows a sample of the data monitored in this study: the lower curve describes the change in weight (vertical axis) on the crane hook through time (horizontal axis), while the upper curve shows the height of the hook above the datum 0.0 level. The figure does not show the location in the plan, which was also monitored, as can be seen in the Appendix.

The crane cycles can be identified by dividing the continuous readings into distinct intervals according to unique combinations of the distinguishing qualitative feature of the curves (zero, increasing, static nonzero or decreasing weight, and stationary or changing location). The intervals are as follows:

1. Attaching, detaching, or rest: intervals during which the weight on the hook is zero and the hook is stationary;
2. Loading: increasing weight as the load is picked up, while the location is essentially static;
3. Transportation: static nonzero weight with location changing;
4. Motionless: static nonzero weight with the hook location static; and
5. Unloading: decreasing weight, while the location is essentially static. There may be more than one unloading interval in any cycle, for example when concrete is placed from a single bucket-load into more than one structural element;
6. Empty motion: zero weight with location changing. When auxiliary lifting equipment is used (e.g., a concrete bucket) the weight does not reduce to zero between cycles. In such cases, empty motion intervals can be identified if the following intervals are attaching and loading. Ideally, the presence of auxiliary lifting equipment could be definitively detected by using a RFID on the equipment and a reader mounted on the hook. Since the weight of each piece of auxiliary equipment is known, this would have the added benefit of allowing periodic calibration of the load measurement monitor.

The intervals are marked in Fig. 3, and the feature combinations are summarized in Table 2.

Rest intervals—where the load is set down temporarily before being picked up and moved again—can be distinguished from detaching intervals by observing that the weight immediately after the ensuing loading interval is equal to the weight before the preceding unloading interval. An attaching interval is distinguished from a detaching interval because it is always followed by a loading interval. Finally, a single crane cycle is defined as the period from one attachment interval to the next; thus crane cycles can be identified from continuous data streams.

Isolating Individual Crane Operations

We define a crane operation to be a single unloading interval with its associated loading interval. Interpretation of the monitored data requires isolation and characterization of the crane operations from within the crane cycles. There are two basic cases for crane cycles—single cycles and compound cycles (with multiple unloading intervals).

Single cycles are common for lifting of distinct bodies, where the load is lifted, transported, and released entirely in a single unloading location. This is typical for loads like precast concrete elements, reinforcement cages, sections of formwork, or palettes of packaged materials. During the field study, single cycles that included periods of complete or partial relaxation of the load on the cable were observed, for example, when fine maneuvering was necessary to bring the load to an exact location. A similar result is obtained when an element is set in place, and then lifted out again to allow correction of the bearings (common for precast elements). This behavior seemingly gives rise to "false unloading" intervals, although they are easily identified by noting that the reduction in weight is equal to the immediately subsequent increase in weight at the same location. They are identified as "rest" intervals, and the true unloading event occurs when the load is released entirely and empty motion follows. Thus single cycles each result in a single crane operation.

Compound cycles only occur for lifting of bulk materials, where any part of the load can be released at any location. These are typical for placing concrete, delivering mortar from a bucket, etc. During compound cycles, the weight does not return to zero, because the materials require a container, which shows up as a residual load between unloading and loading intervals. Each distinct unloading interval is considered a distinct crane operation,

Table 2. Summary of Crane Operation Intervals

Crane interval	Hook location L (t)	Weight on hook W (t)
Rest, attaching/detaching	Stationary	~Zero
Loading	Stationary	Increasing
Transportation	Changing	~static nonzero
Motionless	Stationary	~Static nonzero
Unloading	Stationary	Decreasing
Empty motion	Changing	~Zero or equal to weight of auxiliary equipment

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Table 3. Standard Form for Crane Operation Data

Operation number	Loading		Unloading		Weight released	Residual weight from the previous cycle
	Time	Location	Time	Location		
1	t_{L1}	X_{L1},Y_{L1},Z_{L1}	t_{U1}	X_{U1},Y_{U1},Z_{U1}	W_1	W_{P1}
2	t_{L2}	X_{L2},Y_{L2},Z_{L2}	t_{U2}	X_{U2},Y_{U2},Z_{U2}	W_2	W_{P2}
…						
i	t_{Li}	X_{Li},Y_{Li},Z_{Li}	t_{Ui}	X_{Ui},Y_{Ui},Z_{Ui}	W_i	W_{Pi}
$i+1$	t_{Li}	X_{Li},Y_{Li},Z_{Li}	t_{Ui+1}	$X_{Ui+1},Y_{Ui+1},Z_{Ui+1}$	W_{i+1}	W_{Pi+1}
…						
	t_{Ln}	X_{Ln},Y_{Ln},Z_{Ln}	t_{Un}	X_{Un},Y_{Un},Z_{Un}	W_n	W_{Pn}

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which is reported with the data describing its associated loading intervals. According to this definition, a compound cycle may result in more than one crane operation; since each crane cycle has one loading interval, multiple crane operations may share a common loading interval.

Table 3 shows the standard format for reporting crane operation data to the next step in the interpretation process. Note that operations i and $i+1$ represent two operations from the same cycle, and therefore share the same loading time and location data.

Evaluating Element Work Envelope and Temporary Work Envelope Parameters

In the context of monitoring of crane operations, EWEs and TWEs are used to identify both loading and unloading locations. These are defined as follows:

1. A loading station is a volume in space from which materials, building parts or equipment are collected by the crane. These are mainly TWEs, such as a loading bay where concrete mixers discharge their loads, or a temporary storage and cleaning area for industrialized concrete formwork. They may also be EWEs, such as a reinforced concrete element from which a section of formwork is stripped.
2. An unloading station is a volume in which the crane hook is located while its load is released. This volume is most commonly an EWE. It may also be a TWE, as in the case of the formwork storage area mentioned above. Note that a single loading station may be associated with more than one unloading station if the load is distributed to more than one destination, as is often the case when concrete is placed.

The shape and size of the envelopes depend on the nature of the activity, the type of element, and the construction technology. In cast in situ reinforced concrete construction, tower cranes may be employed in performance of any or all of the following basic activities: formwork, installation of reinforcement cages, placing concrete, stripping formwork, and, if necessary, erection of precast concrete elements. The core of the approach to defining envelope geometries is to determine expected hook positions over specific building elements during the execution of specific building activities. Each envelope is a volume defined by a core geometry bounded in each direction by an offset large enough to account for the measurement accuracy of the monitoring system. The control geometry may be a node (e.g., the lifting point of a precast element), a flat rectangle (e.g., the top perimeter of the formwork for a rectangular reinforced concrete column) or some other arbitrary volume. For the project experiments, the envelopes

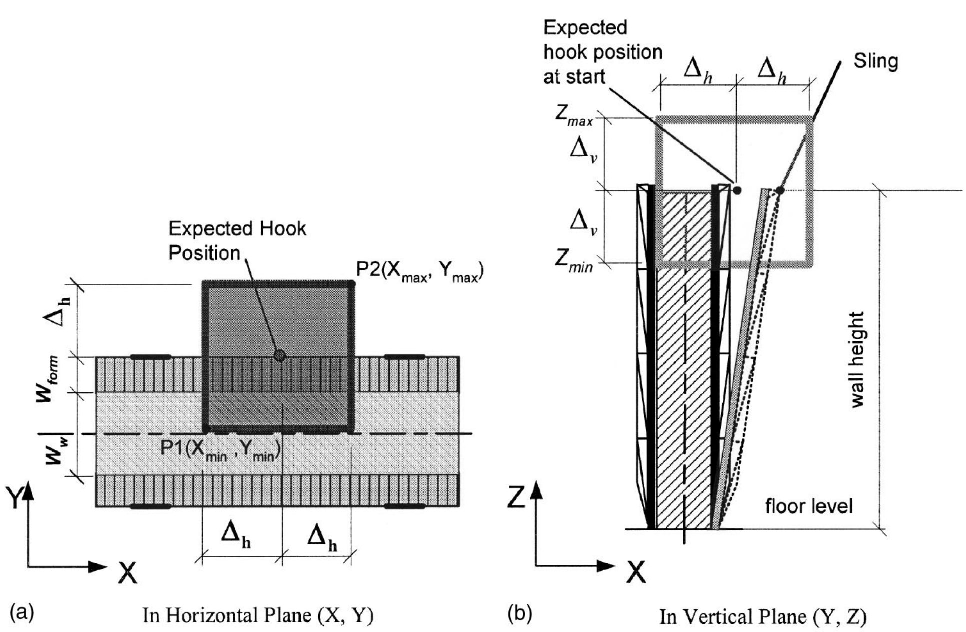

Fig. 4. Element work envelope for stripping formwork from reinforced concrete wall

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were simply defined as boxes with minimum and maximum coordinates along three main axes ($X_{min}-X_{max}$, $Y_{min}-Y_{max}$, $Z_{min}-Z_{max}$), bounding the core geometry. Fig. 4 shows a typical EWE, and the Appendix provides additional EWE definitions, with values for maxima and minima, for envelope parameters for the basic activities and elements in the building on which the field study was conducted.

Associating Crane Operations with Work Envelopes

Once the crane operation parameters have been calculated, the project database is first searched for all EWEs that contain the unloading location or the loading location of each operation. Unambiguous interpretation demands that each crane operation be associated with a single EWE. This would be straightforward if not for the fact that in some cases EWEs have overlapping volumes.

The set of EWEs in the search set can be narrowed using the current project execution status. The EWEs associated through their basic activities with activities that have been completed can be excluded, as can those associated with activities whose technical precedents have not yet begun. The search subset includes only those that are associated to activities whose status is "current" and those that are immediate future candidates for execution. The source for reliable data on project progress is the automated monitoring system itself. If an activity is not commenced on time, takes too long, or any other change is made, the monitoring system should flag the activity and report the problem. The monitoring software module has direct access to the building information model not only to read existing data, but also to update project progress information. Project progress information is stored in the building information model in parallel to the "as-planned" values. For example, start and end dates, resource assignments, and other performance data will have "as-built" fields as well as "as-planned" fields.

Nevertheless, multiple EWEs may still be found for each unloading or loading location. Other distinguishing parameters of the operation, such as the weight released and the residual weight, must then be used to determine which EWE is the correct one. A technique has been developed in which a set of crane operation characteristics is set a priori for each EWE, in such a way that allows unambiguous interpretation; however, this is beyond the scope of this paper.

Field Study Results

Observations

Numerous observations and recordings were made for the full range of activities performed using the tower crane: placing and stripping of formwork, fixing reinforcement cages, delivering reinforcing meshes, placing precast concrete hollow-core planks, placing concrete, and delivery of miscellaneous equipment and tools. For each observation of a basic activity performed on a distinct building element (columns, walls, beams, slab sections) the expected values for the hook location and the load weight were calculated based on the data describing the building elements obtained from the building project model and using appropriate tolerance values for each basic activity type. A detailed example of the results is provided in the Appendix.

In all of these cases, the measured location and weight values fell within the range of expected values. The horizontal and vertical tolerances used were 0.5 and 0.7 m, respectively. These values appear to be large enough to account for inaccuracies in the measuring equipment used. At the same time, they are sufficiently narrow to avoid overlap between envelopes of distinct elements with nodal core geometry—for example, the hollow-core slabs were 1.2 m in width, so that the envelopes of neighboring elements had no overlap.

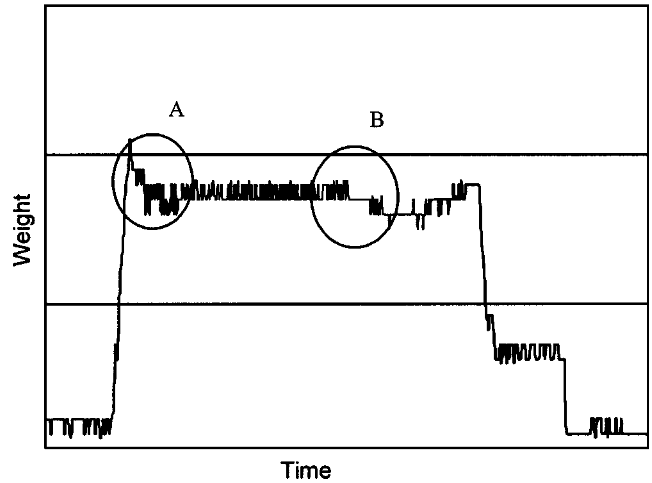

Fig. 5. Typical load measurement through time

For envelopes with larger volume core geometry—such as concrete placing for a beam—these tolerances do result in overlapping volumes. In the field study, the target elements of each crane operation were known, and so the results could be compared with the volumes of predetermined envelopes. Thus while the results are as predicted, they do not guarantee that any crane operation can be uniquely identified.

The tolerance values that define the extent of each envelope beyond its theoretical functional volume should be calibrated to match both the accuracy of the monitoring equipment used and the nature of the building technologies employed. The narrower the tolerances can be made, the fewer overlapping envelopes will occur. However, even if the tolerance could be reduced to zero some EWEs would still overlap, in at least two cases: first, if the building elements themselves overlap (a column sits within the geometric bounds of a floor), and second, where more than one basic activity type is performed on the same element (which is very common). Use of additional characteristics of the crane operation, in addition to the envelope geometry, is therefore required; the technique developed for doing this is beyond the scope of this paper.

Accuracy of Measurement

Two problems arose with regard to measurement accuracy. First, the raw data collected from the monitors displayed fluctuations in the load readings. Second, calibration of the system revealed discrepancies between the actual coordinates of the hook location (measured with the hook and load at predetermined known locations on the site) and the coordinates calculated by transforming the raw cylindrical coordinates (jib angle, hook height, and the distance of the trolley from the tower) into the building's local Cartesian coordinate system.

The load readings fluctuate whenever the hook is accelerated or decelerated vertically, as can be seen clearly at Points A (acceleration) and B (deceleration) in Fig. 5. To avoid this potential

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source of error, the load value is taken as the average over the middle half of the transportation interval, during which the velocity is roughly constant (constant vertical speed—measured as the rate of change of the Z location coordinate—is the most important factor here).

The deviations in location readings were expected. As a crane operates and goes through its motions, it simultaneously generates forces and responds to them. Additional loads might include effects imposed by wind, acceleration/deceleration of the crane motions; they might also include effects of jarring moments, side pulls, or out-of-level setup (Shapiro et al. 2000). These forces and their reactions, steady state and time varying, cause bending of the crane's jib and tower, and stretching of the cable, thus affecting monitoring readout accuracy. Fortunately, the characteristics require determination of the hook location at the time of loading and the time of load release, when the hook is stationary, so that dynamic effects can be ignored. The effects of static bending of the crane and stretching of the cable were dealt with in two ways:

1. By applying a geometric correction to the raw data. The measurement of the distance of the trolley and hook from the base of the tower is adjusted by the distance that the tower and jib are calculated to bend (Δd in Fig. 6). The height of the hook is similarly adjusted by Δh. This correction is straightforward, since the deflections under a range of loadings can be determined empirically by measurement during system calibration; during regular activity, the load at each point in time is also known.
2. By ensuring that the offset dimensions of the basic work envelopes were bigger than the inaccuracies introduced by the crane's deformation.

Limitations

As presently conceived, the tower crane monitoring system can provide quantitative information directly (for example, measurements of the total weight of concrete delivered) and time-related information indirectly (for example, gross durations of construction activities). It cannot provide any indication of the quality of work performed. It also cannot provide independent measures of productivity for any resource other than the crane itself or equipment that is handled exclusively by it (such as industrialized formwork); the timing information it provides can support calculations of labor productivity.

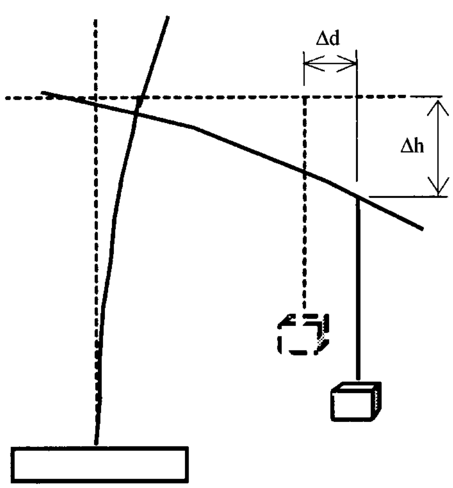

Fig. 6. Correction for tower crane deformation

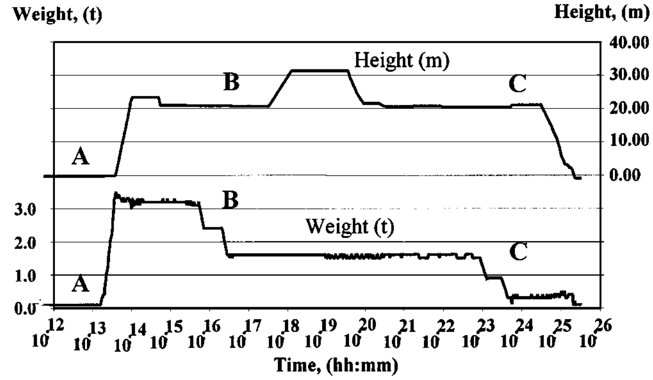

Fig. 7. Weight and height measured for perimeter column and beam–concrete placement

The field study was carried out using a top-slewing tower crane. Monitoring tower cranes is simpler than monitoring crawler cranes or other mobile cranes because their position is static; the principles developed are equally applicable for other types of cranes, although the specific technology used to monitor the location of the hook may need to be different. For example, mounting a GPS antenna on the cable above the hook (or on the hook assembly itself) and monitoring its location using a differential GPS, could provide sufficiently accurate location data.

Discussion

Monitoring a tower crane's motion and the load on its hook using the built-in monitors supplied by the manufacturers is straightforward. Each of the crane's working cycles can be isolated from the continuous stream of location and load data by identifying points in the data stream at which sharp changes occur in terms of motion or of load. Each crane cycle can be divided into, and defined in terms of, six interval types: attaching, loading, transport, unloading, detaching, and empty motion. Where auxiliary lifting equipment is used (such as a concrete bucket or a rigid sling for a precast element), the weight after the last unloading in each cycle

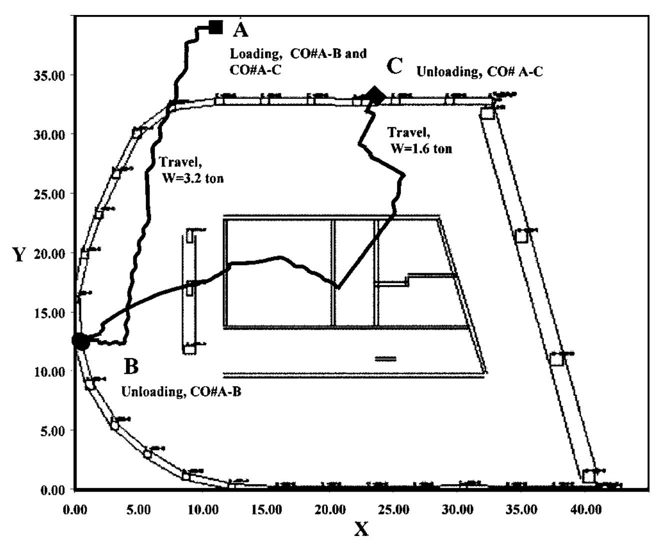

Fig. 8. Horizontal location measured for perimeter column and beam–concrete placement

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Table 4. Predicted Element Work Envelope Parameter Values for "Concrete Placing" of Column C–412–4: C Two-Dimentional Location Coordinates $(X_m, Y_m) = (0.14, 12.4)$; Floor Number $n=4$; Column Dimensions $(a,\ b) = (0.6, 0.6)$

Expected hook location (x,y,z)		$x = X_m$; $y = Y_m$; $z = (n+1)H_f + H_b$	(0.1;12.4;19.5)
Work envelope	Min $(x_{\min}, y_{\min}, z_{\min})$	$x_{\min} = x - a/2 - L_s - \Delta h$; $y_{\min} = y - b/2 - L_s - \Delta h$; $z_{\min} = z - \Delta v$	(−1.7;10.6;18.8)
	Max $(x_{\max}, y_{\max}, z_{\max})$	$x_{\max} = x + a/2 + L_s + \Delta h$; $y_{\max} = y + b/2 + L_s + \Delta h$; $z_{\max} = z + L_s + \Delta v$	(1.9;14.2;21.2)
Weight	$W_{\exp}$	$W_{\exp} = a \times b \times$ column height (2.75 m) $\times$ 2.4 t/m^3	2.38 t

Table 5. Predicted Element Work Envelope Parameter Values for "Concrete Placing" of Beam B–401–402: Two-Dimensional Support Coordinates $(X_{m1}, Y_{m1}) = (25.25; 32.75)$; $(X_{m2}, Y_{m2}) = (22.23; 32.65)$; Floor Number $n=4$; Beam Dimensions $(a,\ b) = (0.5, 0.8)$

Expected hook location (x,y,z)		$x = (X_{m1} + X_{m2})/2$; $y = (Y_{m1} + Y_{m2})/2$; $z = (n+1)H_f + H_b$	(23.7;32.6;19.5)
Work envelope	Min $(x_{\min}, y_{\min}, z_{\min})$	$x_{\min} = \min(X_{m1}, X_{m2}) - a/2 - L_s - \Delta h$; $y_{\min} = \min(Y_{m1}, Y_{m2}) - b/2 - L_s - \Delta h$; $z_{\min} = z - \Delta v$	(20.5;30.9;18.8)
	Max $(x_{\max}, y_{\max}, z_{\max})$	$x_{\max} = \max(X_{m1}, X_{m2}) + a/2 + L_s + \Delta h$; $y_{\max} = \max(Y_{m1}, Y_{m2}) + b/2 + L_s + \Delta h$; $z_{\max} = z + L_s + \Delta v$	(27.0;34.5;21.2)
Weight	$W_{\exp}$	$W_{\exp} = a \times b \times$ beam length (3.1 m) $\times$ 2.4 t/m^3	2.98 t

Table 6. Measured Parameters of Crane Operations CO # A—B and CO # A—C

	Loading		Unloading			
CO #	Time	Location	Time	Location	Weight released, (t)	Residual weight from previous cycle (t)
A–B	10:13:12	(11.11;38.97;−0.30)	10:16:28	(0.41;12.58;20.90)	0.6	>0.3
A–C	10:13:12	(11.11;38.97;−0.30)	10:23:40	(23.60;33.25;20.40)	1.3	>0.3

Table 7. Validation of Unloading Weight and Location Parameters

			Predicted value			
CO #	Parameter	Measured value	Minimum	expected	Maximum	Conclusion
A–B	W	1.6	—	2.38	—	Within expected range
	X	0.41	−1.7	0.1	1.9	Within expected range
	Y	12.58	10.6	12.4	14.2	Within expected range
	Z	20.90	18.8	19.5	21.2	Within range, but close to maximum
A–C	W	1.3	—	2.98	—	Within expected range
	X	23.60	20.5	23.7	27.0	With in expected range
	Y	33.25	30.9	32.6	34.5	Within expected range
	Z	20.40	18.8	19.5	21.2	Within range, but close to maximum

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does not reduce to zero, and the residual weight can be used to identify the auxiliary equipment. From the crane cycles, it is possible to extract the distinct transport operations (defined as a single loading interval with a corresponding single unloading interval). Once these are isolated, the weight released, the loading location and the unloading location of each operation can be reported. If the geometry of the building under construction, and of any temporary facilities on site, is provided in an information-rich building model, then it is possible to generate work envelopes for each combination of building element and basic activity type. The geometry of the work envelopes is calculated based on the core geometry of the expected position of the crane hook during execution of each specific basic activity, and takes into account the tolerance required for inaccuracies in the load and location measuring system. The set of EWEs/TWEs can be searched in order to associate individual crane operations with work envelopes.

Unique identification of each crane operation on the basis of the unloading location or the loading location alone is not practical if overlapping envelopes exist. By definition, multiple activities are performed on each building element, which results in overlapping work envelope volumes. Similarly, the geometry of some elements, such as slabs, leads to overlap between their envelopes and those of other elements to which they are connected. Knowledge of the construction sequence, and of the status of execution of the construction activities, enables the search for enclosing work envelopes for each crane operation to be narrowed to those activities which are in progress or are candidates for execution. Nevertheless, situations of overlap still remain. In these cases, additional characteristics of the crane operations must be used in order to distinguish between the operations. A technique is required in which unique sets of characteristic values can be set for each EWE a priori, and then rapidly tested against the characteristic values of each crane operation. Such a technique, using five characteristics, is the subject of ongoing research, and will be reported in later publications.

The values for the tolerance settings for each work envelope type are dependent on the construction technology employed and on the accuracy of the monitoring equipment. It would therefore be necessary to calibrate a production system for each situation in which it would be applied. In the case of the field study, all of the observed crane operations yielded monitored values that fell within their expected range. For operations that cannot be associated with any specific building element, it is not possible to prepare an EWE, which precludes any possibility of identifying them with construction activities using the method developed here.

Conclusions

This research represents a first step in proving the feasibility of providing useful construction management control information using monitors mounted on lifting equipment. Given the widespread use of cranes the worldwide, the concept may hold great potential for the improvement of project control.

The field study has shown that if an information-rich building model is available, then crane operations can be associated with the basic activities performed on a building's elements. Additional work is necessary to prove that the association can be made uniquely in every case. Naturally, not all construction activities require the use of lifting equipment from start to end, and so monitoring lifting equipment alone cannot provide a complete picture of project progress. Ideally, other technologies could be used to monitor other project progress indicators. Data from multiple sources could then be integrated to provide a complete and accurate account of what has taken place, the rate at which it was performed, and the quantity of resources consumed. As more technologies are adapted for automated construction site data collection, the focus in automated project performance control research is likely to shift to the problem of integration of multiple sources describing the same activities.

The potential benefits are considerable. Providing information describing the start and end time of each crane operation for each basic construction activity will allow software to identify the first and last occurrences for each basic activity, and then to report the start time, gross duration, and the end time of each construction activity. Once a system was installed and operational, collection and interpretation of the data would be more economical than the manual methods available in current construction control practice. The information is also reliable and can be reported in real time. This means, for example, that a project schedule could be updated with actual "as-made" information entirely automatically. In this way automated monitoring can enable true closed-loop control for construction project management, which would be a fundamental improvement in the way the industry is managed.

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Appendix. Representative Field Study Results

Perimeter Column and Beam—Concrete Placement (see Figs. 7 and 8)

The parameter definitions and values are as follows: floor height $H_f = 3.6$ m; concrete bucket: height $H_b = 1.5$ m; sleeve length $L_s = 1.0$ m; offsets: horizontal $\Delta h = 0.5$ m; vertical $\Delta v = 0.7$ m (see Tables 4–7).

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