Monitoring Lifting Equipment for Automated Progress Control: A Feasibility Study

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ABSTRACT: Reliable and timely information describing up-to-date performance is a prerequisite for effective management of construction. Existing methods for on-site data collection are labor-intensive, subjective, and the data are frequently available only after activities have been completed. Monitoring of the main lifting equipment on construction sites can provide real-time, low-cost and objective data for interpretation within an APPC system. This paper reports on a field study conducted monitoring a tower crane employed in construction of a hybrid cast-in-place and precast concrete structure. Data describing the load weight, the hook height and the position of the hook in the building have been collected for multiple occurrences of different activity/building element combinations (including column formwork, slab formwork, pouring concrete beams, pouring concrete slabs, and reinforcing columns). A set of distinguishing characteristics of crane operations has been identified for computer-automated identification of the construction activities performed using the crane. A rigorous comparison of the potential values of each characteristic, for each activity type, has led to the conclusion that the characteristic values alone are insufficient for distinguishing between different activities. However, when the activity location is considered in the context of the building's geometry and construction schedule, the activity can be identified almost all of the time. The geometry and schedule are provided in the format of an electronic Building Project Model. In this way, a set of interpretation rules capable of interpreting the data monitored in real time can be compiled. Useful information concerning the construction process can be reported, including the overall actual start and finish times of an activity, its duration, and the net time that the crane was employed for it.

KEYWORDS: Automated data collection; Building project model; Construction cranes; Project control.

1. INTRODUCTION

Reliable and timely information describing up-to-date performance is a prerequisite for effective management of construction. Existing methods for on-site data collection are labor-intensive, subjective, and the data are frequently available only after activities have been completed. Given this state of affairs, automation of on-site monitoring holds the potential to significantly improve the degree of managerial control that can be applied in construction. A general framework has been proposed for automating both

- on-site monitoring of construction activities, and
- interpretation of the data collected.

The framework is called Automated Project Performance Control (APPC). The principles for APPC were set out by Navon and Goldschmidt [Navon 2003a]. Field experiments were conducted in automated monitoring of construction workers [Navon 2003a] and earthmoving equipment [Navon 2003b].

Following these precedents, Sacks et al. recently proposed that monitoring building construction equipment holds the potential to provide significant data for APPC [Sacks et al. 2002]. The proposal is based on two observations: firstly, nearly all of the materials and components for a building are lifted into place by equipment, such as tower and mobile cranes, concrete pumps, hoists, etc. and secondly, collecting the raw data by tracking and recording the activity of construction cranes is technologically straightforward. The primary challenge in implementing a system is to automatically interpret the raw monitoring data to identify the activities that the equipment has performed. This paper reports on the results of research conducted with the goal of proving the feasibility of building knowledge-based software capable of performing the necessary interpretation. The following sections describe the conceptual approach and the proposed system process flow. Next, the characteristics of crane operations, as observed in a field study on construction of a reinforced concrete office tower, are identified. The relationship between specific value sets for the characteristics and the construction activities performed using the crane form the key to distinguishing between the different activities. The feasibility of interpretation using software is demonstrated through an analytical process in which distinct characteristic property filters are assembled for each distinct activity. Lastly, the potential for such a system to support automated reporting of activity resource consumption, durations, etc., is explored.

2. PROJECT ACTIVITY MONITORING SYSTEM

The monitoring system architecture is shown in figure 1. Apart from the raw data feed from the construction equipment, the system relies on project information stored in a building project model [Sacks et al. 2003, Sacks] and a knowledge-base.

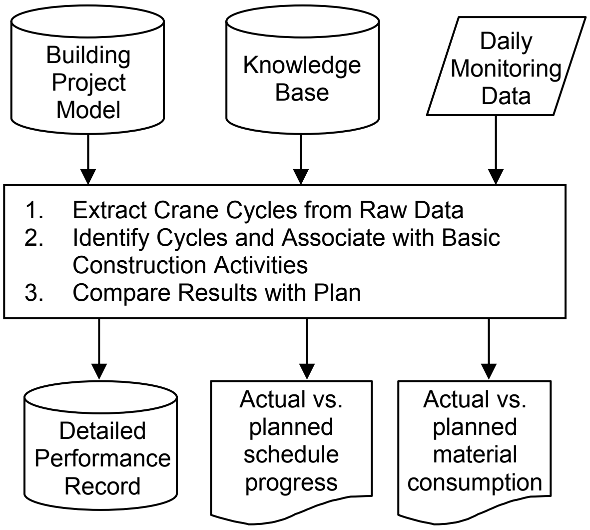

Figure 1. System overview.

The knowledge base includes data for calibration of the system for auxiliary equipment such as concrete buckets, lifting straps, etc., whose height and weight must be considered in interpreting the raw data. It also encapsulates the knowledge about typical characteristics of crane operations for different building activities. For example, in pouring concrete, the crane motion while loaded always originates outside of the building perimeter and ends within the building perimeter; when stripping forms, the direction is opposite. One component of this knowledge is a set of typical parametric ‘work-envelopes’, which define the possible locations of the crane hook during execution of the respective basic activities for each building element type. The element-basic activity (EBA) envelopes and their use are described in section 5.2 below. Volumetric envelopes are also defined for well-defined loading zones on the site, such as a delivery bay for concrete mixers, storage areas, etc.

The building project model comprises a full object based definition of the building project, including 3D geometry, a schedule of planned construction activities and details of the resources (equipment, materials and labor).

The interpretation module functions in three distinct stages. The first task is to distinguish between the different cycles of crane operation, which is done by identifying load changes on the hook. These occur at loading stations and at release stations. Typically, there is no motion at the stations. Some activities, such as concrete pouring, may have multiple release stations in each cycle. If auxiliary equipment (such as a concrete bucket) is attached over a series of cycles, the load on the hook during travel after the last release point of each cycle does not reduce to zero (in these cases, the activity can sometimes be identified by associating the minimum load at the end of each cycle with the weight of a piece of auxiliary equipment). Next, each cycle, with one or multiple release stations, is identified and associated with a specific basic construction activity performed on a specific building element. The feasibility of this step is the subject of the following sections. Lastly, the results are compiled and summed to a level of detail appropriate for comparison with the planned values for activity durations and labor and material consumption rates.

The outputs – activity durations, project progress, equipment usage rates and material consumption data, etc. – are detailed in section 5 below.

3. FIELD STUDY

A field study was conducted during the construction of a hybrid cast-in-place and precast concrete high-rise office building. A tower crane fitted with the proprietary ‘Dialog-Visu’ and ‘Top

Tracing' monitoring systems was used, which provides hook height and load weight, the angle of the boom and the distance of the carriage from the mast [Potain]. The building consists of a reinforced concrete core formed using a self-climbing formwork system, a column and beam perimeter frame formed using purpose made steel shutters, and slabs built with hollow-core precast planks (figure 2). All of the concrete was poured using two tower cranes.

Figure 2. Field study building.

Two specific technical problems had to be overcome in collecting the raw data: accuracy and storage volume. An approximation algorithm was developed to correct the location data for bending of the crane mast, thus improving the location accuracy. The problem of data storage was addressed by identifying significant operating characteristics, including points of loading and unloading in real time, thus obviating the need to record all of the interim data at short time intervals.

From a technological point of view, the equipment necessary for collecting the data automatically is available (sensors and data loggers). In the field study, records of hook weight and location through time were collected for all of the typical basic activity types. The data were translated from the cranes monitoring system's native form into the building's local Cartesian coordinate system. The basic activities are listed in Table 1 together with the list of building elements on each floor. The sequentially numbered cells indicate element specific basic activities that occurred in the project (the gray cells did not occur).

4. INTERPRETATION FEASIBILITY

Two possible approaches were considered for identifying specific element activities executed using a crane (step 2 in figure 1). The first is to assemble a broad set of knowledge rules with if-then format, and then process any given reading through an inference engine. The drawbacks of this approach are that each activity reading must be processed in a single computation, and the rule-base is difficult to elicit and maintain.

The second approach, adopted and developed in this work, consists of the following steps:

1. Establish a standard set of characteristics that can describe any given crane activity.
2. For each possible element specific basic activity, set the range of values that can conceivably occur for each characteristic. This forms a 'filter' of possible characteristic values for each activity type.
3. Process each reading by comparing its individual set of characteristic values with each filter. If the reading matches the filter, then the activity performed is of the type associated with the filter.

This approach offers a number of advantages. Each reading can be preprocessed and characterized in a standard format in real-time, thus reducing data storage requirements. The filter values are relatively easy to set. It also allows for rigorous validation: all that is required in order to demonstrate the feasibility of using the system to distinguish between crane activities is to prove that one and only one filter can match any given individual crane cycle reading. For this to be the case, any given pair of activity filters must have at least one distinguishing characteristic. In other words, a sufficient condition for proving uniqueness of any two activity filters is to show that the value ranges for at least one characteristic are mutually exclusive.

4.1 Crane activity characteristics

Five independent characteristics of crane cycles (or sub-cycles), that could be determined algorithmically from the raw data, were identified for use in matching crane cycles to specific element basic activities. They are:

1. The **relative locations of the loading and unloading stations**. The four possible values are from outside the building into the building, from inside to outside, from outside

to another point outside, and from inside to inside.

2. The **location of the loading station**. The possible values are the loading work envelopes set for the project. The list can be updated at any time.
3. The **location(s) of the load release station(s)** within a cycle. The data collected in the field study show that for some activities the load is not released in one single action. Observation of the same activities reveals that these are activities such as concrete pouring and placement of precast elements (precast elements are commonly set in place but not released from the crane until they have been set in place by the erection crew).
4. The magnitude of the **weight released at each release station.** The possible values are the set of distinct weight ranges appropriate for each activity type**.**
5. The **weight on the hook during motion after the last release point in the cycle.** If non-zero, this represents the weight of auxiliary lifting equipment attached to the hook during the cycle. The possible values are the distinct weights of each piece of auxiliary equipment, which are calibrated for the system at the start of the project.

4.2 Element Basic Activity Envelopes

The location value of characteristic #3 for each reading is replaced with the unique identifier (ID) of a specific element-basic activity work envelope (an EBA envelope). The full set of work envelope IDs for the building is the range of possible values for this characteristic. The volumes of the EBA envelopes are pre-calculated for each element in a building using the knowledge base and the building project model. Figure 3 shows an example of an EBA envelope for stripping the steel formwork from a reinforced concrete wall.

In some cases, the crane is used for activities that cannot be directly related to any work envelope. For these, characteristic #3 is null. In the present work, a generic material delivery activity filter was defined for these cases. In other cases, the release location may fall in more than one EBA envelope (where envelopes overlap). Hypothetically, if one considers the full set of EBA envelopes for a building, there could be many such overlapping envelopes. However, in reality, the size of the set of EBA envelopes that form the range of values for any particular data reading can be greatly reduced by considering the status of the activities with which each is associated. At any given point in time as construction progresses, a limited number of element basic activities can be candidates for execution. The candidate EBA envelope set is therefore recalculated in accordance with the logic of the technological dependencies between activities, as reflected in the construction schedule.

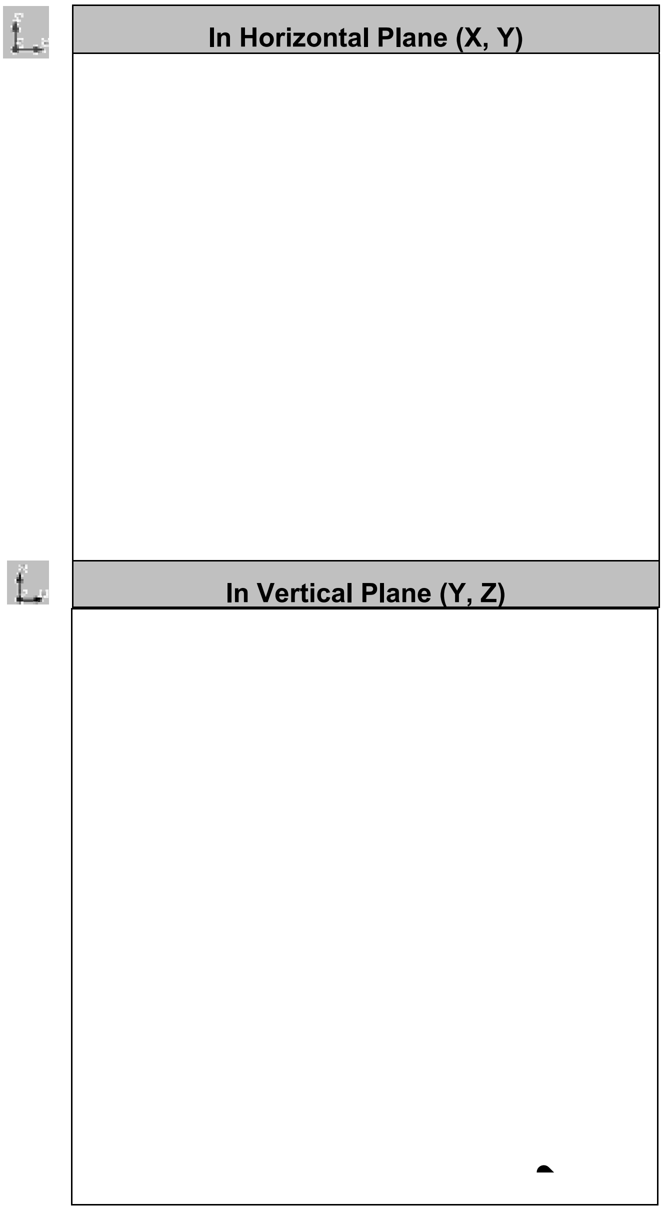

Figure 3. Typical crane hook location envelope for stripping formwork from a concrete wall.

Any remaining overlap between EBA envelopes within the same execution phase implies that the system will not be able to distinguish between the associated activities based on this characteristic alone. In these cases, the necessary condition for establishing feasibility is that there must be a pair of mutually exclusive filters for at least one other characteristic (#1, #2, #4, or #5), i.e. other than the EBA envelope ID (which is derived from characteristic #3).

4.3 Feasibility for the Field Study Building

In the case of the building used in the field study, 25 distinct element basic activity types were identified (numbered #1 to #25 in Table 1). Comparison of the characteristic value filters without consideration of the EBA envelope ID yielded unique identification for only five of the element basic activities. Thus use of the envelopes is crucial for interpretation of the data.

When all EBA envelopes were considered, only 3 of the activity types had envelopes that occupied unique volumes in space (i.e. no overlap with any other envelope). Applying the logic of the construction phase sequence increased the number of unique envelopes to 14 of the 25, with eight distinct instances of overlap among the 11 remaining envelopes. For each instance of overlap, the mutually exclusive filter values test was applied, and brought the number of identifiable element activities to 18. Only two groups of activities remained indistinguishable from one another; a) steel-fixing (#3 in Table 1), installation of opening frames (#7) and formwork for interior walls (#10), and b) bundled rebar deliveries (#22-24) and miscellaneous material deliveries (#25). The first set can be dealt with by uniting the activities into a single ‘interior wall preparation’ activity, which can be uniquely identified. This reduces the level of detail at which interior wall activity can be reported, but it is still effective for determining the status of the higher-level construction activities (e.g. ‘build interior walls’). The second set be can be dealt with similarly (united into one generic ‘miscellaneous materials delivery’ activity), although in fact it does not contribute to determining the status of the higher-level activities.

If the second set is ignored, the final result is that 19 typical element basic activities can be isolated. For each floor of the field study building, there are numerous elements of each type. When the full complement of individual element specific activities is considered, fully 353 out of a total of the original 378 (93%) can be uniquely identified.

5. PROJECT CONTROL INFORMATION

The field study results also shed light on the nature of the benefits that could be obtained from an operational system. The success of managers at both the project and company management levels in effectively controlling construction projects is dependent on information. Given appropriate software, the information that can be produced inexpensively and in real-time by the proposed system (possibly in conjunction with other measurement technologies) includes:

- Project activity progress reports – construction activity start and finish times,
- Materials consumption data (such as concrete quantities delivered),
- Net equipment hours per activity,
- Equipment usage patterns.

6. CONCLUSIONS

Analysis of the typical activities in the field study suggests that the raw data can be interpreted to produce reliable information about the timing, duration and material consumption of project activities. Interpretation is not feasible without use of the element basic activity work envelopes to distinguish between crane cycles which have otherwise overlapping set so characteristic values. Furthermore, reduction of the set of envelopes to include only those associated with basic activities that are candidates for execution at any point in time is crucial for success of the system. In the case of the field study building, once the range of potential overlaps was reduced, the test for mutually exclusive characteristic filters revealed that 93% of the activities could be uniquely identified; the remaining 7% were of a type that was unnecessary in determining the status of the higher-level construction activities.

Monitoring lifting equipment such as tower cranes therefore holds the potential to provide reliable, cheap and machine-readable information describing project progress, durations for basic construction activities at the level of individual building elements, and relatively precise consumption quantities for certain materials (such as concrete or rebar cages).

The next stage in this research is to implement the system and apply it to one or more projects for durations longer than was possible in the field study. This includes developing a standard set of EBA envelope definitions and implementing software routines to interpret the data. For each project, a 3D project model and a construction schedule must either be supplied or purpose-built. The goal would be to demonstrate a system that could automatically update the project schedule, report activity durations for calculating resource consumption rates, and report material consumption quantities.

7. REFERENCES

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Table 1. Basic Activities and Building Elements (element specific activities are numbered #1 to #25).

Activities **Elements**	**Fix reinforcing steel cages**	**Set door/ window opening frames**	**Build form-work**	**Pour concrete**	**Strip form-work**	**Install hollow-core planks**	**Deliver rebar in bundles**	**Other**
Perimeter columns	#1	-	#9	#11	#19	-	-	#25
Perimeter beams	#2	-				-	-	
Walls	#3	#7	#10	#12	#20	-	-	
Columns	#4	-	- a	#13	- a	-	-	
Beams	#5	-	- a	#14	- a	-	-	
Floor sections	-	-	- a	#15	- a	#21	#22	
Core walls	#6	#8	- b	#16	- b	-	-	
Core slab sections	-	-	- a	#17	- a	-	#23	
Stairs (core)	-	-	- a	#18	- a	-	#24	

a: These activities were performed using conventional formwork without the crane.
b: These activities were performed using a set of self-propelled climbing forms.