An Overview of Automated Project Performance Control Research at the Technion

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Abstract

Current monitoring and control methods rely on massive manual work. As a result, control information is expensive to produce, or generated irregularly. Additionally, the information is only available infrequently – in many cases after the controlled activity was completed – and its quality and integrity are low. The purpose of our work is to improve monitoring and control information, i.e. to offer it on a daily basis, to improve its quality and integrity and to reduce the cost of generating it. To do all this we started exploring the use of automated data collection (ADC) technologies. We developed models for automated labor and equipment control, materials management and control as well as monitoring safety measures – all described in this paper. Materials management and control is currently the most practical application. On the other end of the spectrum is labor control, which currently is the most challenging area.

Keywords: Automation; Data collection; Feedback control; Control methods; Monitoring

I. Introduction

Construction Automation (CA) could be referred to as a generic term whereby manual procedures are replaced by computer-based ones. Thus, Information Technology (IT); the emerging Web-Based techniques; Robotics; Automated Data Collection (ADC); and other technologies are all part of CA. In the early days of CA, Construction Robotics (CR) was the main focus of researchers in this area – the articles at the beginning of the 1980s were very optimistic and enthusiastic – some were even prepared to take a risk and forecast when robots would replace construction workers. Although, this has not happened (yet?), research in this area is still very relevant and valuable, but rapidly becoming a less popular area of research. The reasons for this are beyond the scope of this paper.

The focus of CA research at the Technion has shifted in the same direction. One of the new areas of research that we have focused on in recent years is called Automated Project Performance Control (APPC). This area broadly refers to the activities taken by the project management in order to ascertain that the performance of the project is as close as possible to a desirable value. The performance is measured in terms of project performance indicators (PPI), such as cost, schedule, labor productivity, materials consumption (or waste), etc. The desirable performance is normally considered to be the planned one (at least at the beginning of the control process). Consequently, systems such as cost, schedule, labor, materials, and quality control are examples of the area of project performance control.

This research direction stems from two reasons: (a) the increasing need for feedback and monitoring information, and (b) the rapid technological developments in the ADC area and their declining costs. For more than a decade researchers have been pointing out the deficiencies of the current-practice, manual, data collection and/or the need to automate the collection and the processing of the data to produce useful and up-to-date feedback information without investing too much cost and time (Cheung et al. 2004; Ciesielski 2000; Davidson and Skibniewski 1995; Saidi et al. 2003). Among the major deficiencies of the current practice are:

- They are labor intensive because (a) they rely on manual data collection, and (b) they also require extensive data extraction from drawings, from plans (schedule, budget, etc.) and from databases (standards, historical database, etc.) as well as a lot of calculations.
- The quality of manually collected and extracted data is low, error prone and expensive.
- Projects are, therefore, controlled infrequently and in generic terms, which make analyzing the causes of deviations difficult.
- Projects are not controlled in real-time, thus making it very difficult if not impossible, to

take corrective measures in time.

The main technologies that can contribute to the ADC-based automation of monitoring and control based are:

- Barcode – a technology that consists of a series of parallel, adjacent bars and spaces that allows for real-time data to be collected. The data in the barcode acts as a reference that the computer uses to look up associated records. These records contain the descriptive data and other pertinent information that is needed to complete the identifying process. The data is collected with a barcode reader, or scanner, which is a hand-held or a stationary input device used to capture and read information contained in a bar code. Barcode technology has been mainly proposed for: materials tracking or materials waste reduction; monitoring construction progress; and labor control (Akinci et al. 2002; Chen et al. 2002; Cheng and Chen 2002; Echeverry and Beltran 1997; Oh et al. 2004).
- RFID (Akinci et al. 2002; Jaselskis and El-Misalami 2003; Junichi et al. 2005; Sawyer-Tom 2004). RFID refers to a branch of automatic identification technologies in which radio frequencies are used to capture and transmit data from a tag, or memory chips, embedded or attached to objects. Compared to barcode, RFID is more advantageous, especially for materials tracking, because it has larger data storage capabilities, it is more ragged, it does not require line-of-sight, and it is faster to collect data about batch of components.
- Global Positioning System (GPS) – a position and navigation system that can provide three-dimensional positions anywhere on the earth to those with the proper receivers. For dynamic positioning, the principle of differential GPS can be applied in two ways: (1) the differential mode using range measurements, called DGPS, and (2) the differential mode using phase measurements, called “kinematic GPS”.
  - Differential GPS (DGPS) (Peyret et al. 2000a) is used to measure locations at a metric or sub-metric accuracy. In DGPS two receivers are used; one measures the coordinates of a stationary point, called the base, whose position is perfectly known in the reference geodetic system. The 3D deviation between the measured and actual position of the base, which is roughly equal to the measurement error at a second receiver at the unknown point, is used to correct the position computed by the latter.
  - In kinematic GPS, all raw measurements available, including measurements of the signal carrier phases, from both base and rover receivers are used to compute the 3-D vector between the two antennas. The positions are computed then with a centimetric accuracy. As with DGPS, the kinematic computation can be performed either in post-processing or in real-time, called Real Time Kinematic (RTK) GPS.
  - Being a satellite-based technology, standard GPS needs a line-of-sight between the receiver and the satellite. As such it cannot normally operate indoors. Recent developments enable GPS to operate indoors by adding cellular, laser or other technology (Van-Diggelen 2002). This is an exciting development offering a variety of options for automated monitoring.
- Video and audio technologies. The use of video cameras, or computer vision, has been proposed for construction management, or control/monitoring purposes e.g. Deng et al. (2001), Abeid et al. (2003), and Wu and Kim (2004). Video cameras can photograph the site in real-time from various angles. Manual/human analysis, or advanced pattern recognition algorithms, can provide invaluable data, which could be converted into information regarding progress, or the location of key materials on site. The automated option needs more research in various areas, such as pattern recognition, interpretation of the raw data into meaningful construction management information, integration with other automated data collection methods (e.g. RFID), filtering (of the pictures to neutralize varying lighting conditions, or dirt and dust), etc.
- Laser Detection and Ranging (LADAR). Due to its declining costs and the increasing reliability LADARs have become very attractive for construction management and control purposes (Cheok and Stone 2004). The authors list the following as potential applications: object recognition, tracking terrain changes at a construction site, terrain characterization, and others.

This paper gives brief theoretical background of APPC, describes the APPC research at the Technion, and some of the related work elsewhere. Due to space limitation, whenever needed, the paper refers the reader to other papers, describing the related work.

II. Construction Management and Control

II.a. Project Management

Success, from the project management's viewpoint, is when the project is completed with the lowest possible budget, as quickly as can be achieved, with the highest quality, with no accidents, etc. In other words, the desired values of PPI must be optimal, even though the objectives are normally conflicting. Consequently, the management decides where it is prepared to compromise, and sets the targets accordingly. These targets are called 'Desired Performance' in Figure 1.

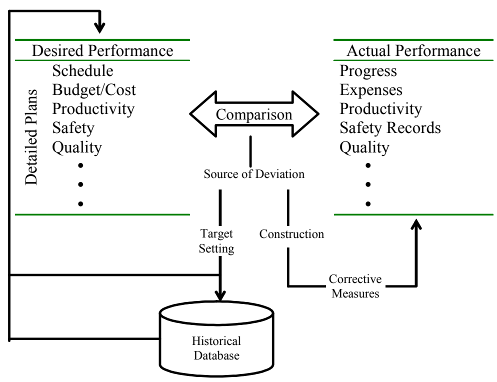

Figure 1: The Control Loop

Desired performance is translated to instructions in the form of detailed plans. If the latter could be performed exactly as planned, the construction management's only role would be to set the best targets, juggling among the conflicting objectives. But normally there are numerous reasons why the achievements deviate from the targets, such as (McKim et al. 2000): unforeseen site conditions; scope changes by owner; design changes; procurement problems; and design coordination. This is where the control function steps in – it has to alert the construction management about deviations between the planned and the actual performances.

II.b. Performance Control

The comparison between desired and actual performances is the beginning of the control function. When a deviation is detected, the construction management analyses the reasons for it. The description in Figure 1 roughly divides these reasons into two groups: (a) target setting (i.e. planning), or (b) causes originating from the actual construction. (In many cases the causes for deviation originate from both sources.) If the deviation is caused by the construction, the construction manager analyzes the reasons for it and takes corrective measures that will bring the actual performance as close as possible to the desired one. Consequently, the definition of the desired performance is very important. Normally the tendency is to equate the desired performance with the planned one because it increases predictability and reduces uncertainty.

When the deviation is caused by unrealistic target setting (plans), the latter and the historical database have to be updated. This approach, where initially the desired performance is the planned one but as the project progresses, after analyzing the actual performance, the desired performance changes accordingly, is called Adaptive Control.

The performance control has to identify discrepancies between the planned and the actual performances. Effective control needs two types of information in real-time: (a) a list of the activities to be performed on the given day, broken down in terms of PPI. (b) Measurement of the actual performance in the same terms. The first type of information is automatically extracted from the Project Model – PM, which has up-to-date project planning and design data (Sacks et al. 2003). The best way to measure actual performance in real-time economically is by automating it (Navon and Goldschmidt 2003a).

II.c. Automated Project Performance Control

The main challenge today in automating the control process is automated measurement of the performance indicators. In many instances measuring devices evaluate the parameter in question indirectly, e.g. GPS systems measure time-of-flight of a signal from known reference stations and calculate positions. The same approach is used for automated PPI measurement – the values of some indirect parameters is measured automatically and converted into the sought value of the PPI by special algorithms. Examples for this approach are described in the following Section.

III. Automated Project Performance Monitoring and Control at the Technion

Our group has been involved with the development of automated models whereby an indirect parameter is measured with ADC technologies and converted into the controlled parameter by special algorithms. This approach was used to develop labor control model (Navon and Goldschmidt 2003a; Navon and Goldschmidt 2003b), earthmoving operations in road construction (Navon and Shpatnitsky 2005) and tower crane monitoring (Sacks et al. 2005). Additional research was done to develop a model which monitors preventive measures against falls from heights (Navon and Kolton 2005), and a materials management and control model (Navon and Berkovich 2005). The ongoing research continues some of the research mentioned above (which will be described together with the previous research) and an attempt to use Daily Site Reports (DSR) to collect field data, which will be described separately.

III.a. Labor Control

III.a.1. Introduction

The objective of this research, which was the first of the APPC initiative (Goldschmidt and Navon 1996), was twofold: (a) to investigate the concept of measuring indirect parameters and converting them into the controlled parameter. (b) To conduct a feasibility study to check if this concept can lead to an automated model. This investigation was conducted for a case study of labor control. More specifically the following questions had to be answered: (i) is there an indirect parameter, which can be measured automatically, in real-time, and be converted into labor inputs? (ii) If such an indirect parameter exists, how can it be measured? (iii) Once measured, how can it be converted into labor inputs?

III.a.2. The Idea and the Model

To process a building element (erect formwork, paint a wall, etc.), the worker has to be close to it (within human reach). Consequently, by knowing the worker's location at a given time together with additional information (e.g. worker's trade and candidate activities for the given day), the activity s/he is working on can be determined. Therefore, the selected indirect parameter is the worker's location.

To check this idea, a preliminary model that converts the locations into labor inputs was developed (Navon and Goldschmidt 2003a). The model uses two sources of data (Figure 2): (i) the Project Model (PM), which provides data referring to the planned inputs, the schedule and the physical design of the building; and (ii) data relating to the actual performance, as measured by the ADC module, which uses remote sensing technology to measure the location of each worker at regular time intervals. The model uses these locations to covert them into actual inputs/productivity, compare the latter to the planned ones and produce the output. The feasibility of developing the ADC and the PM was checked and demonstrated (Navon and Goldschmidt 2003b; Sacks et al. 2003).

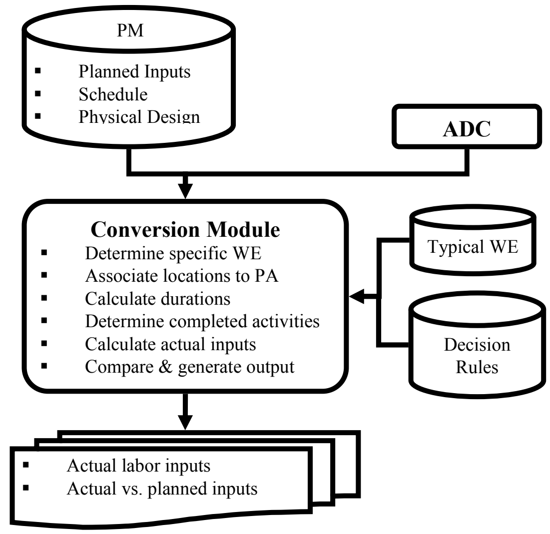

Figure 2: Labor Control Model

The model calculates the time workers spend being involved with each activity and associates it with the amount of work performed by the worker, or the crew, using the work envelope (WE) concept. A WE describes a volume in space, within the proximity of the building element to be installed, in which it is assumed that a worker, or a piece of equipment, must be physically present in order to perform a construction activity on that element. After determining the Pending Activities (PA) – all the activities whose predecessors are completed, which means that they can be active on the given day – the model determines specific WE for each PA. By associating the locations, measured by the ADC Module, to WE (each related to a different PA), the model links the times the workers spent in a WE to the activity. The association is done using different sets of decision rules (DR). Based on the location to activity association, the model calculates the duration of time workers spent performing each activity. After determining the completed activities, the model calculates the actual inputs/productivity, compares them to the planned ones and generates the output.

III.a.3. Model Verification

Site experiments were conducted in three construction sites, which included a location "measurement" and simultaneous manual measurement of the same activities. The manual location measurement simulated the ADC by "measuring" relative locations at regular time intervals. These locations were converted into inputs/productivity by the model and compared to the results of the manual measurements.

In one of the sites, twelve activities were monitored during the experiment. In ten of the 12 activities the difference between the time measured manually and that calculated by the model was less than ± 12%. In the two other activities the deviation was ± 22%. The experiment was conducted with different sets of decision rules (DR). It is important to note that in all the activities where the deviations exceed ±10% using one set of DR, the deviation using another was meaningfully smaller. This probably means that it is possible to develop activity-dependent algorithms that will choose the right set of DR according to the type of the activity (short vs. long; single vs. multiple activities performed by a crew during the entire day; etc.). Consequently, the experiments indicated that an activity-dependent algorithm may enable an accuracy of ±10%.

More details about the model, the site experiments and the project model can be found in Navon and Goldschmidt (2003a), Navon and Goldschmidt (2003b) and Sacks et al. (2003).

III.a.4. Status of the Ongoing Research

The conclusions of the previous stage of the research were that the location is a good indirect parameter and that it can be measured and converted into labor inputs/productivity. Therefore the present stage will attempt to answer two research questions: (i) what are the expected accuracies of the model? (ii) What factors affect these accuracies (e.g. shape, or size of WE; predefined vs. dynamic WE; ADC measurement frequency; PA characteristics)?

Because suitable off-the-shelf ADC technologies are not yet available, the previous stage of the research was based on manually simulated location measurement. Currently we are conducting experiments using standard GPS technology in frame-construction activities, assuming that a building frame is a relatively open environment, whereby the GPS receiver can maintain a clear line-of-sight with the satellites – the success was limited.

Currently we are also trying to go a step farther and improve our location measurement methods. We are now considering other options, such as more accurate and structured manual measurement, or video (or time laps) technology. Once we find the right measurement technique, we will conduct extensive site experiments to answer the research questions mentioned above.

III.b. Earthmoving Equipment Control

III.b.1. Introduction

Earthwork project management is experiencing impressive advancements, which improve the quality of its output, by increasing the accuracy and quality of the product; increase the efficiency of operations and save costs. These advancements include measuring various parameters relating to the health and maintenance of the earthmoving equipment – such as valves pressure, weight of bucket, etc. (Kannan and Vorster 2000; Maio et al. 2000) – as well as continuously monitoring the location of the equipment during its operation (Caterpillar 2005; Ligier et al. 2001; Minchin and Thomas 2003; Oloufa et al. 2003; Peyret et al. 2000b; Peyret and Tasky 2004; Taylor and Tometich 2003; Trimble 2005).

The above impressive achievements deal mainly with issues such as the automation of quality assurance (e.g. asphalt compaction), or the reduction of the surveying costs during earthmoving operations. Very little attention has been given to automate the measurement of managerial parameters such as progress and productivity. This Section describes a model that uses GPS technology for automated data collection to produce information needed for efficient monitoring of road construction. The model uses algorithms that convert the collected data into control information and presents it in terms of duration (or progress), productivity, and quantities.

III.b.2. The Model

The principles used for labor control served as the basis for another model, which was implemented in a prototype system for controlling earthmoving operations in road construction (Navon and Shpatnitsky 2005). The model (Figure 3) compares between the planned and the actual values of progress and productivity variables. The model has two main sources of data: (1) The Project Model (PM), containing the planned schedule, the productivity, and all the data regarding the physical design of the road (layout, cross-sections, etc.). (2) The Location Measurement Module (LMM), using GPS. This module measures the location for each member of the fleet at regular time intervals. The module records the time of measurement, the identification of the equipment and its location.

The PM interface begins the process by

extracting all the pending activities, the geometrical values of the road, the planned quantities of work and the planned productivity. Specific Work Envelopes are calculated for each pending activity, based on information in the Knowledge Base, which includes a typical work envelope database, and on the geometrical information extracted by the PM interface. The WEs correspond with planned work sections, as represented in the schedule. Next, a geometrical calculation associates each of the locations to these specific work envelopes, by checking if the measured location is included within the WE. This, together with DR from the KB, enables the model to determine which activities are actually being performed. Once the model identifies that a new activity has started, it also determines which of the activities are completed. The cycle ends by determining the actual time spent performing each activity, and the productivity, which is based on this time and the completed quantities, extracted by the PM interface. These data serve as a basis for the output of the model.

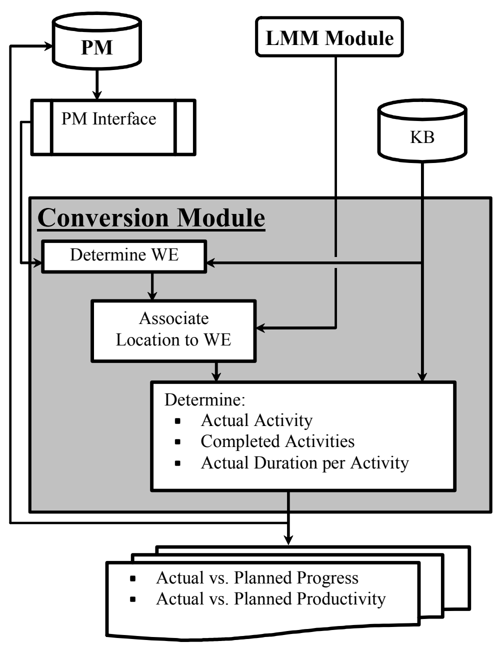

Figure 3: Earthmoving Control Model

The output of the model compares the actual performance, as measured and calculated by the model, to the planned one. It includes:

- A comparison between the actual productivity and the planned one, extracted by the PM Interface.
- A comparison between the actual progress and the planned one according to the updated schedule, also extracted by the PM Interface.

III.b.3. Model Verification

This model was realized in a prototype system and tested in the field for three weeks on a road construction site, using GPS mounted on each of the pieces of equipment performing the controlled activities. The productivity of four activities was measured with the prototype system and, at the same time, it was recorded manually so that the accuracy of the model could be assessed. The comparison shows that the deviation between the actual productivity and the one calculated by the prototype is -2.2% to +4.4%. These results are very encouraging, indicating that automated productivity measurement of earthmoving equipment in road construction is possible. Moreover, the measurement technology (GPS) is available off-the-shelf and affordable.

III.b.4. Ongoing Research: Dynamic WE

The previous stage applied the principles of the labor control model, namely that the road is divided into *predefined* work sections (WS). While this assumption is logical in building construction (e.g. a slab, or a wall, are well defined hence they can serve as a good basis for WS determination), it is often not the case in road construction. What we discovered during the field tests was that at the end of each working day we had to manually define the WS. This lead to the current stage, whereby a new concept for WE and WS is being considered.

Instead of associating locations to activities in a two stage association procedure – as explained in Navon and Shpatnitsky (2005) – by predetermining WS and correspondingly WE, the algorithm will determine the WE dynamically during its operation, according to the measured locations. Various algorithms were considered for the dynamic work envelope (DWE) algorithm. The first is called Minimum Convex Polygon (MCP). This algorithm determines the area of the smallest (minimal) convex polygon which encompasses all the measured locations. The advantage of this algorithm is its simplicity. The problem with it, on the other hand, is that the calculated area includes the entire area encompassing all the measured locations (Seaman et al. 1999), which means that even areas where work was not performed, are included. The latter are demonstrated by the hatched areas in Figure 4a (the dots in the figure represent equipment location measurement and the line represents the resulting DWE). Even an incidental measurement (marked A in the figure) expands the resulting WE. Hence this algorithm might be inaccurate in cases where work pattern is not continuous.

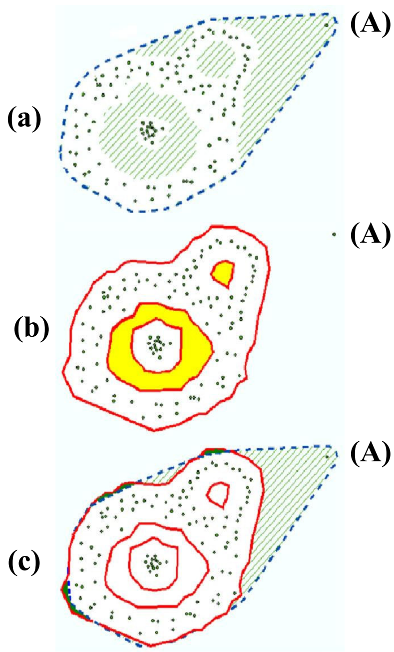

Figure 4: Dynamic Work Envelopes Algorithms

The Kernel Density Estimation (KDE) algorithm is more sophisticated – it is based on statistical principles and hence is more accurate (Silverman 1986). This algorithm is capable of identifying and subtracting areas where there is no concentration of locations (shaded between the encompassing lines in Figure 4b). Moreover, the algorithm is capable of ignoring incidental readings such as A. A comparison between the two algorithms is shown in Figure 4c (the MCP algorithm is in a broken line and the KDE in a continuous line). The comparison shows that not only the KDE algorithm excludes the areas without dots in the middle (shaded in Figure 4b), but it is also more accurate in the perimeter – the differences are marked in Figure 4c with hatched and shaded areas).

We are planning a feasibility study of these algorithms, which will be based on field data collected with GPS from earthmoving equipment in a major road construction project.

III.c. Tower Crane Monitoring

The idea of monitoring construction lifting equipment to provide useful feedback information for project management stems from the fact that almost all construction components and materials must be transported by machines, and monitoring them is becoming increasingly easy. A model, employing a 'black box' monitor and a PM, was developed. The 'black box' is based on crane monitoring systems that provide real-time monitoring of weight and position parameters, which some manufacturers of lifting equipment provide. For example, Potain's 'Dialog Visu' and 'Top tracing' control systems (Potain 2005) 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. 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.

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. The results indicate that the system is technically feasible, but a sophisticated algorithm and additional monitoring sources are required in order to interpret the monitoring results unequivocally. More about this research can be found in Sacks et al. (2005).

III.d. Materials Management and Control

III.d.1. Introduction

The problem with materials management is the lack of up-to-date relevant information, hence the importance of monitoring the flow of materials and the data associated with them (Chai and Yitzchakov 1995). Currently materials tracking is still a very big problem on construction jobsites and even in manufacturing plants related to construction (Barriga et al. 2005; Saidi et al. 2003). The main benefits of an efficient Materials Management and Control System are (Akintoye 1995; Choo et al. 1998; Formoso and Revelo 1999; Formoso et al. 2002; Poon et al. 2004; Thomas and Sanvido 2000): Increased productivity and avoidance of delays, mainly due to the availability of the right materials prior to work commencement; Reduction in man-hours needed for materials management – craft foremen can spend up to 20% of their time hunting for materials, and another 10% tracking purchase orders (PO) and expediting (Bell and Stukhart 1987); and Reduction in the cost of materials due to reduction in waste caused by manual and inefficient materials management and control (Li et al. 2003; Poon et al. 2004).

III.d.2. The Model

The aim of our research was to develop a model based on ADC technologies for materials management and control. The model manages and initiates ordering of materials automatically, based on project plans, the actual flow of materials and the stocks at the construction site. The model permits real-time control enabling corrective actions to be taken on time.

The Model deals with materials purchasing, their delivery to the site and their dispatching for use in the building. The model uses Decision Rules (DR) to determine which materials to order and when. The rules relate to: (1) lead times for supply. (2) Minimal inventory for the various types of materials. (3) Minimal quantity per PO to avoid ordering small batches, which can increase transportation costs. (4) Maximal time between arrival of the material to the site and its dispatch for use – this rule is used to determine Dead Inventory.

The model (Figure 5) has five Units: Input, Purchasing, Analysis, Tracking and Alerts and Reports. The model follows up the progress as reflected in the up-to-date Schedule, which is part of the PM. Based on this, the model determines the PA. The Input Unit also calculates, for each PA, the quantities of the required materials.

These data are transferred to the Purchasing Unit, which determines the materials needed to be ordered and a purchase order (PO) is issued. The purchase order is manually approved by the project management. Once a PO is approved and sent to a supplier, the model awaits a confirmation from the supplier. This confirmation means that the supplier has received the PO, understood it and is able to supply the order in time. If the supplier does not confirm, the reason for not confirming is verified with the supplier, as a result of which the PO may be re-issued.

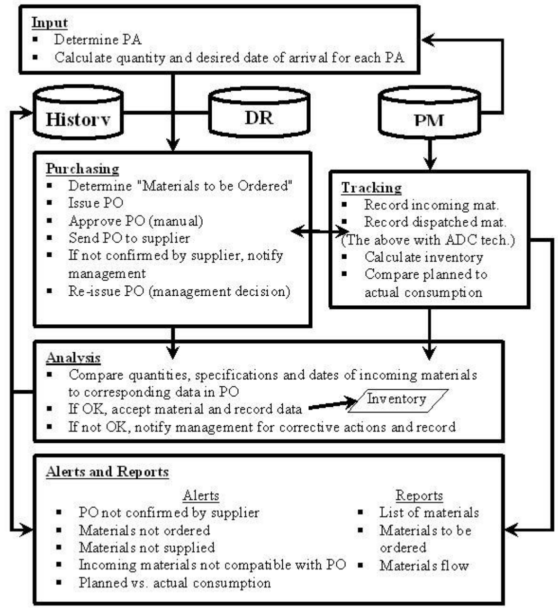

Figure 5: Schematic Materials Control Model

The model records the incoming materials and the ones which are dispatched for use in the building. Thus the model follows up the rolling and the dead inventories. As soon as materials arrive to the site, their quantity, specification and planned date of arrival, are compared to the relevant data in the PO. If all of these meet the specifications in the PO, the materials are accepted and the data are recorded. Otherwise, the construction management is notified and corrective actions are taken. All accepted materials are added to the Inventory file. The Model logs problems arising from the above, such as late supply, mismatch between specifications in the PO and the ones of the actually supplied materials – these problems are logged in the Historical Database.

The model generates reports and alerts. The reports include a comprehensive list of all the materials needed in the project, a list of materials to be ordered, and a cumulative list of materials flow. The alerts include PO not confirmed by supplier, a list of materials that should have been ordered, but were not, a list of materials that were expected and did not arrive, materials arriving to the site which are incompatible with the PO, and the deviation between planned and actual quantities.

III.d.3. Model Verification

Most of the components of the model were implemented in a prototype system. The databases and the algorithms were built with Microsoft Access© and for the ADC the prototype used a handheld computer (IPAQ). The prototype was tested in an ongoing project and its performance was compared to customary materials management and control procedures. After building all the project specific databases in the office, the research team stayed on the site for three days during which they accompanied all the activities relating to materials ordering, their arrival to the site and their dispatching for use in the building. The data regarding the incoming materials were collected using the IPAQ.

The experience gained in this field test indicated that the main benefits of using the model are: materials availability, which minimizes the probability of missing materials; reduced delays, due to the availability of materials; meaningfully reduced time spent searching for materials, assessing inventory levels and tracking purchase orders; suppliers' timeliness, as the model alerts when suppliers have not confirmed the PO; materials receipt problems due to the availability of up-to-date information in real-time; reduced occurrence of forgetting to order materials because the model initiates the issuance of the PO; inventory accuracy as it is continuously calculated; reduction in total surplus; and availability of actual vs. planned quantities comparison in real-time.

On the other hand, the model assumes that the design and planning database (PM) has to be updated frequently and data regarding incoming and dispatched materials has to be collected continuously. Although the use of PDA yielded real benefits, we believe that more automated data collection technologies (e.g. bar-code, RFID) can enhance the efficiency and accuracy of the model.

III.e. Control of Preventive Measures Against Falls from Heights

III.e.1. Introduction

Falling from heights is the number one risk factor in lethal accidents in construction – about a third of the accidents in US construction are caused by falls from height (Hinze et al. 2005; OSHA 1990; OSHA 2002). Many of the fall accidents could have been prevented if the right preventive measures had been taken in time. These measures are guardrails – the most common and the best measure. All other measures do not prevent the fall, but rather intercept the fallen worker and prevent injury – they include: safety nets, personal measures, protective partitions, or surfaces, and others.

The aim of our research was to develop an automated model that monitors guardrails in buildings under construction. The model identifies the activities associated with risk of falling from heights and the areas where these activities are scheduled to be performed. Accordingly, the model plans the protective measures, namely the guardrails. The model follows up the existing guardrails and constantly compares their locations and lengths to the planned ones. Based on this comparison, the model issues warnings whenever guardrails are missing, or temporarily removed.

III.e.2. The Model

The model identifies activities which expose workers to fall hazards and the areas of work where these activities are scheduled to take place. The model alerts the construction management, in real time, when and where these hazards are not treated by appropriate protective measures – continuous guardrails.

The input to the model includes five databases (Figure 6), as follows:

- The PM provides the model with data relating to the building elements, schedule related data, and the required inputs needed to construct the guardrails.
- The Risk Factors database is needed to define the level of hazard such as the height the activity is performed at, type of construction, period of the year, day of the week, etc.
- The Safety Regulations database holds the safety regulations relevant to the model.
- The Activity Characteristics database classifies the activities according to predefined characteristics which permit the model to identify them as dangerous (e.g. type of activity, the constructed building element and the location of the building element).
- The Risk Assessment database is built once by the project management. It includes general characteristics of the project such as the construction method, number of floors, height of a typical floor, and the type of construction.

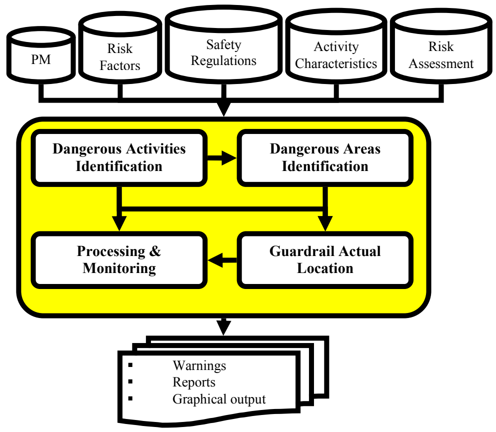

Figure 6: Schematic Safety Model

The model is divided into four modules:

- Dangerous Activities Identification, which identifies activities creating fall hazards, or ones performed where a fall hazard exists; classifies them; and identifies the types and the level of the hazards.
- Dangerous Areas Identification, which identifies dangerous areas, determines where and when protective measures have to be taken and designs the guardrails.
- Guardrail Actual Location, dynamically determines where the guardrails are actually installed and whether they are continuous. This is done in order to compare the planned guardrails' locations to the ones actually installed and used, at all times.
- Processing and Monitoring, which handles the data processing to generate the reports, and compares the planned timing and location of guardrails to the actual location of currently installed guardrails. It also checks if all the guardrails are continuous and ascertains that none of their elements have been removed.

There are three types of outputs:

- Warnings – issued to alert about deviations between planned and actual timings and locations of guardrails.
- Written reports regarding all aspects of fall hazards and the protective measures.
- Graphical outputs. The latter are used to illustrate the warnings and reports, and as a general means for monitoring and managing fall hazard safety.

III.f.Daily Site Report Tool

III.f.1. Introduction

The daily site report (DSR), or daily log, is one of the most important records during construction (Liu et al. 1995). The DSR normally holds a vast amount of data, such as (Abdelsayed and Navon 1999; Liu et al. 1995; Russell 1993): number of workers broken down to trades; materials arriving to the site; number and type of equipment; receipt of drawings and plans; weather conditions; contractors/subcontractors; work accomplished; major events (e.g. concrete poring); problems; etc. – all these on a daily basis, which means that it is very detailed. Additionally, these data should be accurate and reliable, as it is legally signed by representatives of the two stakeholders of the construction process (e.g. contractor and owner).

Unfortunately, such a valuable source of reliable and detailed data is not normally used for management and control of the ongoing project – it is mainly used for litigation: claims and disputes – (Liu et al. 1995; Russell 1993) and sometimes for billing purposes. Written reports have their limitations because their quality and clarity depend on the writing skills of the writer (Liu et al. 1995). As a result, many important details are left out and they can never be recovered. This is because in many cases the handwritten document is illegible and search possibilities are either limited, or labor intensive. Because of all the above, even the litigation purposes are sometimes only partially achieved.

Professor Russell from University of British Columbia has lead an impressive initiative to computerize and use the DSR to monitor progress and problems (Russell 1993; Russell 1995; Russell and Fayek 1994). While updating the schedule the user of the model also fills in the reasons for delays (when relevant) from a database called "Problem Source". The model proposes corrective measures taken from another database called "Corrective Actions". This model is a decision support system for progress control and it relies on manual data collection.

III.f.2. Research Hypothesis and Objective

A computerized DSR will serve as a data collection tool to build a database which contains data regarding the *actual* performance of the project (Abdelsayed and Navon 1999). These data, which are collected anyhow for other purposes, will be used by algorithms developed for this purpose to generate managerial information regarding the actual events occurring in the project. This information will be used to control the project in real time on a daily basis and generate warnings when deviations occur. Additionally, because the database includes variables such as the number of workers for each trade, the materials arriving to the site (type, quantity, date), the user will be able to easily analyze the reasons for the deviation and, thus, be much more informed to take corrective measures.

We believe that the computerized DSR will also vastly improve its use as a litigation tool because it will be much more legible and searchable. Additionally, we believe that algorithms that identify conflicts as they occur can be developed, enabling to solve the conflict earlier than customary today. Moreover, this tool will also enable the development of algorithms that will help to avoid some of the conflicts, such as late arrival of plans, or drawings, forgetting to perform quality control tests which are on the critical path, and others.

III.f.3. Initial Model

We are currently developing the model and its user interface – both are internet based, which means that both the filling of the DSR and the use of the information generated from it are accessible from the site, as well as the main office.

All The manual data is entered through the user interface (UI) which is based on ASP.NET internet pages (Figure 7), filled using standard features such as lists and Combo boxes, forms, checklists, dropdown menus, etc. The data is stored in an Access© database, where it is also processed and compared to the plans to generate the output. Apart from the data entered via the UI, the model uses data from other computerized sources (if and when available) such as: time and attendance, materials management system, schedule, budget, accounting, and purchasing.

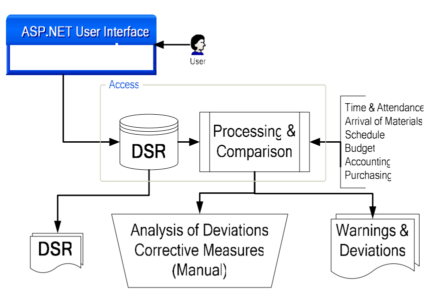

Figure 7: DSR Model

The output includes a conventional DSR for each day, the deviations from plans and warnings when these deviations exceed a predefined value. The user can also generate customized and ad-hoc information to analyze the causes for deviation and thus take corrective measures.

We are currently engaged in the development of the UI. We have not decided yet what control information the model will generate and, hence, which additional computerized systems it will use. This is quite an initial stage, but we are convinced the potential is great.

IV. Conclusions

The increasing need for feedback information regarding the performance of the project (e.g. progress, cost and resource consumption) on one hand, and the developments in ADC technologies, on the other, have stemmed our current research initiative. The developments in ADC technologies are: (a) a number of promising technologies are offered (e.g. RFID, LADAR), (b) their costs are rapidly decreasing and (c) their performance in terms of accuracy and reliability is constantly improving. Our initiative attempts to achieve better control to improve the performance of the projects by automating both the data collection and its processing.

We have embarked on an attempt to automate the control of labor because this is the most important and sensitive resource. The initial results were promising, but current research demonstrates the difficulties of research in this area – the prime difficulty is the lack of off-the-shelf location measurement technology suitable for labor control, especially for interior finishing tasks. Hence, labor control is still the most challenging APPC research area.

The notion that the above mentioned difficulty should be much less of a problem with earthmoving operations lead us to the next step, namely to apply the same principles to control earthmoving equipment in road construction. Here, too, we had promising results in the first stage, but we discovered that the concept of predefined WE, which is suitable for a building because it is structured, is probably less suitable for road construction. The current stage investigates the possibilities of using dynamic WE, which means that the WE is defined automatically, according to the measured locations, by the control algorithm itself.

The principle underlying the labor and earthmoving control research was extended to monitoring tower cranes in building construction. A multi-characteristic algorithm to interpret the crane monitoring data into useful construction management information was developed. The results of this study showed that it is feasible to develop such a system, but additional monitoring data is needed from other sources, such as materials management and control.

The most promising automated control area is materials management, as we discovered with the development of a prototype system for this purpose. While the algorithms of this system are complex, the technologies needed for the ADC module are available off-the-shelf – these are barcode and RFID, for engineered-to-order, or other components of materials, and LADAR for bulk materials. Handheld computers, such as the one we used for our prototype, is suitable for all types of materials.

Due to the high incident of fatal accidents in construction, we decided to extend our automated control activities into accident prevention. We chose the subject of falls from heights as our first focus because this is where most of the fatal accidents occur. The model developed in this research identifies and manages fall hazards among scheduled activities. The model proposes activities, to erect protective measures, which precede the dangerous activity. Additionally, the model identifies the dangerous areas associated with the dangerous activities and presents them graphically on the project's drawings. The model includes a component that continuously monitors the existing protective measures in real time.

Finally, we recently started developing the DSR module of our information sharing, internet-based, prototype. Future research will focus on using additional technologies to automate the data collection, such as video – we believe that there is a great potential for this direction, although the algorithms will probably be quite complex.

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