A CONCEPTUAL PROGRESS MEASUREMENT FRAMEWORK FOR AUTOMATIC WORK-PACKAGING AND ASSESSMENT WITH COMPUTER VISION

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ABSTRACT: The challenges associated with collecting accurate data on the progress of construction have long been recognised. Traditional methods often involve human judgement, high costs, and are too infrequent to provide managers with timely and accurate control data. The aim of this study is to propose a prototype system that employs Computer Vision (CV) techniques to report on progress automatically. Significant changes on site can be determined by assessing digital images compared against geometric and material properties of components supplied from an integrated building information model. This model stores and relates this feedback to a representation of the work breakdown structure (WBS) which assigns components to work packages. The structure can be formed in a number of ways based on various criteria, as revealed by the recent results of an industry survey investigating existing practices. We present this proposed theoretical framework and discuss the challenges associated with any practical implementation for the automated assignment and assessment of work packages.

KEYWORDS: progress measurement, work breakdown, change detection, computer vision.

1 INTRODUCTION

Construction project managers continue to face great challenges in delivering projects on time, within budget and to the required quality standards. A key concern with the traditional project control systems is that they rely on manual data collection and this has been shown to be costly, ineffective and too infrequent to allow for prompt control action (Navon, 2007). The most economical way to measure performance, according to Navon and Sacks (2006), is to automate the process. This entails automating not only assessment but also, as much as possible, the planning assignment aspect of the project, since this will ensure the optimum benefits of using a computer integrated system.

One problem that must be addressed in automating planning is the level of detail at which actual progress data on performance criteria will be collected and maintained. This has a direct impact on the two most objective project performance criteria commonly used in the field of construction management (i.e. time and cost). Traditional approaches to project control treat these variables individually, with schedule control being performed at a more detailed level than cost control. Collecting and analysing data on these highly interrelated variables independently has been shown to be costly and inefficient (Abudayyeh and Rasdorf, 1991). Long recognising this, various efforts have called for the integration of both time and cost into a more holistic model (e.g. Jung and Woo, 2004; Jung and Kang, 2007). However, monitoring and control in an integrated fashion requires collecting data for both variables at the same level of detail. One way to achieve this is for the entire project to be broken down in a hierarchical fashion into unique, measurable units or work packages that can be assigned to one individual or organisation. Such a structuring, generally referred to as the work breakdown structure (WBS), can then form the basis for planning, scheduling, responsibility assignment, information management, and project control.

This motivates us in this work to describe an integrated system that aims to provide much more responsive and "closed loop" feedback for progress monitoring based on the WBS. We enable this in two ways: firstly by integrating a means of modeling and assigning components to work packages based on given criteria. Secondly, to automatically interpret and report the completion of components, as captured in images of the site, and so estimate the progress of those work packages. In this approach, we thus build on the recent industry trends for expanding on Building Information Models (BIM) beyond the design phase of the project, especially the ability to provide nD modeling that reflects the state of the project at any given time. Given the importance of the WBS in project control, we incorporate a framework for the semi-automatic generation of work packages into the proposed progress measurement system. This framework is built on our earlier work (Trucco and Kaka, 2004), (Lukins et al, 2007) and (Ibrahim et al, 2007).

2 FRAMEWORK OVERVIEW

Our proposed system focuses on the interaction between the project planning phase and the physical reality of what has actually been performed to date. Key to this idea is the use of a work breakdown structure to represent the grouping of components into more meaningful blocks. A work package can then be said to be completed if it is possible to confirm that all of its constituent components are themselves finished.

The framework (Figure 1) is built as a natural extension to existing Building Information Models. At its core is a database, comprising instances of building components (such as columns, walls, beams, etc.). In addition to basic planning information relating to scheduling and cost estimates, these components are populated with additional attributes by the WBS assignment module to define what package they belong to. The project manager can easily update this information based on generated progress reports, or whenever the need arises.

The visual assessment module can then interface with the BIM and provide, for a particular view and set of images, its assessment of completed components, and the dates at which they underwent a significant change. From this, additional attributes can be used to infer the status of other components, even if not visible. Finally, this collated information can be used to generate on-demand progress reports as to the current status of the project, as feedback to the project manager.

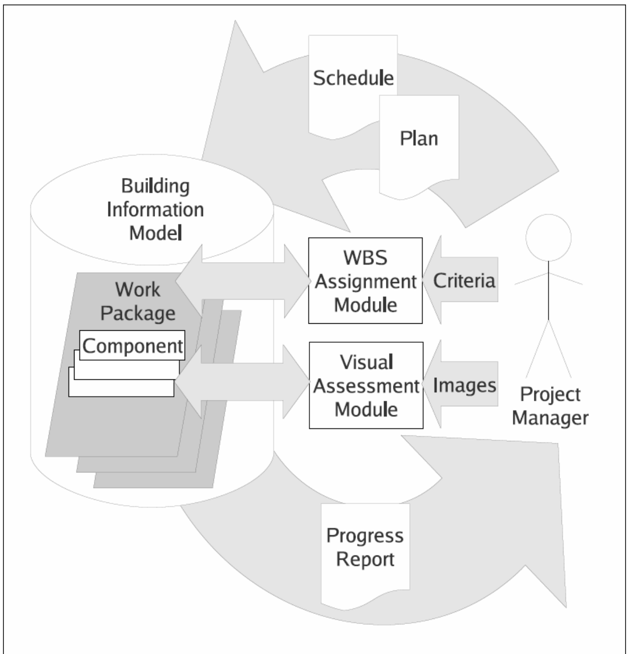

Figure 1. The automated progress measurement framework.

3 AUTOMATICWORK PACKAGING

It is indeed daunting, and perhaps impossible, to effectively manage a project without breaking it down into smaller more manageable units. This is especially true for large complex construction projects. Breaking down the entire work serves to ensure better scoping of the project and hence, more accurate scheduling and cost estimating. Not only does this ensure more accurate planning, it also ensures tighter project control. It is essential, therefore, that the entire project is broken down in a hierarchical fashion into unique, measurable units of work that can be assigned to one individual or organisation. Such a hierarchical subdivision is generally referred to as the Work Breakdown Structure, and the importance of using it as a tool for effective project control has been stressed by many researchers (Globerson, 1994, Rad 1999, Colenso 2000, Charoenngam and Sriprasert 2001).

However, as Wideman (1989) states: building up effective work packages is perhaps the most difficult and challenging task in project management. One issue that is crucial to the formulation of an effective WBS is the choice of appropriate decomposition criteria by which the project can be subdivided. The decomposition criteria reflects the facets of information that can be used as the basis for subdividing the work at various levels of the WBS. However, the identification of these criteria presents a particular challenge, given that various classifications of construction information which may be used. For example, the International Organisation for Standardisation identified eight facets which include facility, space, element, work section, construction product, construction aid, attributes, and management. In addition to these, Chang and Tsai (2003) proposed lifecycle, function and tasks while Kang and Paulson (1997) identified operation and resource.

In order to address the problem, a survey was conducted, aimed at identifying the most frequently used criteria in the formulation of the WBS. First, various criteria for the classification of construction information were identified from the literature. Respondents were then asked to indicate those criteria they actually use in developing a WBS. This was achieved through postal questionnaires sent to the top 100 UK contractors and 80 randomly selected additional contractors. A total of 40 (22%) useful responses were received and analyzed. Respondents included planners, bidders, project managers, quantity surveyors and estimators. Although the sample size is relatively low, 82% of the respondents have at least ten years of experience in developing WBS. To be eligible for use in our framework, a criterion must be used by at least 50% of the respondents and its usage must not be peculiar to a particular profession, kind, or size of organisation. This is important as it will serve to ensure wider applicability of the framework amongst contractors. Table 1 shows the criteria and their frequency of usage. The results suggest that the most frequently used criteria (used by at least 50% of respondents) are "Elements", "Work Section", "Construction Aids" and "Physical Location".

Table 1. Decomposition criteria of work packages.

Decomposition Criteria	Frequency of Use	Percentage of Respondents
Elements	38	95.0
Work Section	32	80.0
Construction Aids	30	75.0
Lifecycle Phases	17	42.5
Management	16	40.0
Facility	14	35.0
Construction Product	12	30.0
Attributes	10	25.0
Function	10	25.0
Spaces	7	17.5

We further analyse the usage of each of these criteria by testing their connection to other factors that may influence their adoption within a project. Using the Chi-square statistic, the usage of each was tested for dependencies on the respondents profession, the kind of organisation, and the size of company. None of the criteria was found to be correlated on any of these variables (to within the 5% significance levels). All four of the top criteria are therefore generically useful, and can be exploted by the framework.

Recent developments in the area of Building Information Models have made it feasible to store vast amount of information in computer interpretable format. In addition to basic geometry information, attributes relating to each decomposition criterion can be defined for each instance of every building component in the BIM.The building model is thus made up of a collection of components, and each component can be assigned one of the four decomposition criteria. The actual allocation of a component to a criteria is performed by selecting a pre-defined value that designates the nature of the decomposition. These values are ultimately based on standardised construction classification documents that define each decomposition criterion. For example, for the "Elements" criterion, each component can take only one value from the standard list of elements developed by the Building Cost Information Service (BCIS). For Values relating to "Work Section" criterion would be based on the Standard Method of Measurement (SMM7) classification of work section, while those relating to "Construction Aids" would be based on the table M of UNICLASS classification of construction aids. It should be noted that the authors are not currently aware of any standard classification document based on "Physical Location" of work. For the present study, we simply adopt a classification developed by Blythe et al, (2004) which is based on floor levels (e.g., 1st floor, 2nd floor, etc.).

Once each design object has been allocated based on these criteria, work packages can be generated in a hierarchical fashion, by querying the building model database. Figure 2 shows the process for automatically generating work packages. All design components in the BIM are first grouped based on a chosen criterion. This automatically generates a set of work packages, each of which contains design objects with unique attributes relating to that particular criterion. This is repeated for each resulting WBS element until an appropriate level of detail is attained.

The output of this algorithm (as shown in Figure 3) groups the elements into their respective work packages. In this particular example we show only the decomposition of a sample "Frame" element, which comprises of components that form the building's loadbearing structural framework. This is further decomposed by "Work Section" into two WBS packages at the second level of the hierarchy, and each of these is further divided into packages based on the "Physical Location" of the grouped components. This example can be directly related to the visual assessment (as presented in Section 4) in which the second floor concrete columns form part of work package 2.2.3. By tracking the progress status of the constituent components, the overall completion of the package can be reported on.

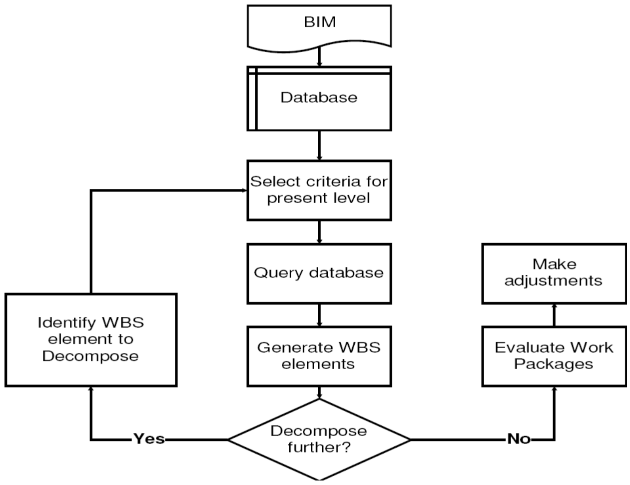

Figure 2. A conceptual process framework for generating work packages.

This simple hierarchical allocation approach can produce useful and realistic groupings of components, yet it still has a number of limitations. In particular the fact that attributes relating to the "Construction Aids" criterion (such as scaffolding, formwork, and tools) are not normally represented in the building model. However, this criterion may be required in the formulation of the WBS since it relates to significant contracted work and costs. This is not currently addressed by the framework, and it also creates particular problems for visual verification since it is much harder to confirm the extent and presence of such aspects on site due to the arbitrary and complex way they can be erected or moved.

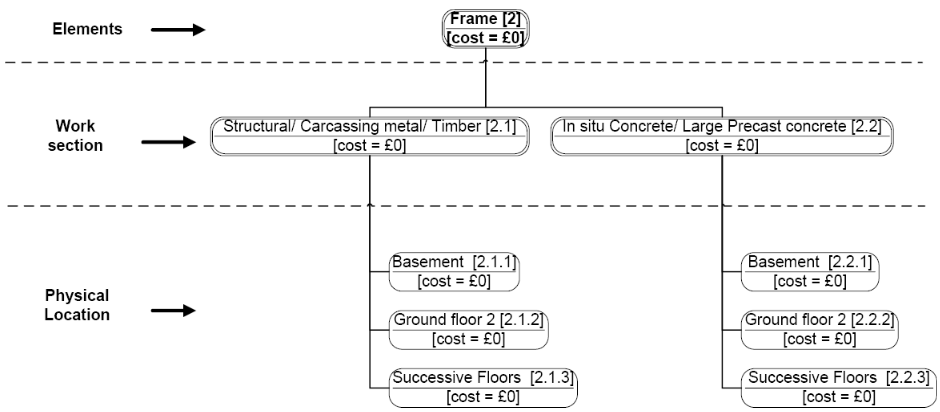

Figure 3. Sample automatically generated package allocation.

Furthermore, the framework assumes that the project manager knows the appropriate level of detail to decompose to. This is unhelpful particularly to the inexperienced manager. In our future work, we hope to investigate factors that affect the decision to further decompose a work package and then develop and incorporate a module that does a trade-off between the benefits of keeping to a given level of detail and the administrative costs of decomposing to more detailed levels. Apart from aiding the inexperienced user, this will clear the way for standardising work packages and ultimately lead to continuous improvement since performance of standardised work packages could then be compared across projects.

4 VISUAL ASSESSMENT

Images form a naturally quick and easy way to capture information on a construction site. However, the interpretation of those images (what the site actually represents) is a particularly difficult problem. This is especially true in the case of images of construction, which are unfortunately rife with clutter and ambiguity. The task can be made harder if the location of the components within the site is not known a priori, as this then involves exploiting the contextual and geometric aspects of the scene to try and estimate the location of the camera. This approach is similar to rectification techniques applied in photogrammetry, but applied to the task of verifying if matching component structure is present in the scene.

One alternative however is to exploit images that are captured from a known fixed position. While this has implications for inflexibility in response to occlusions caused by changing structures, the benefits of always "on-demand" images provides the possibility for fast and responsive assessment. Such a system can also be easily integrated with existing security infrastructure, as the same issues apply in selecting suitable locations for cameras. Furthermore, multiple fixed cameras could conceivably be combined with other digital and measurement tools (Navon, 2007), to at least confirm the presence of components on the site. The more information available (combined views, RFID tags, or human feedback) the better the system can expect to observe particular areas of progress, and focus where to confirm activity.

In this paper we assume that this position is known, or at least aligned. This frees us to determine the question of change detection within the image, and what that means in terms of completion of components, and consequently the status of work packages. Intuitively, we conceive of an image as an ever changing array of values, across which are observed changes for each local pixel neighbourhood (Radke et al, 2005). Some of these changes can be assigned to lighting and other variable conditions. Small variations can be accounted for by various transient events, such as equipment or scaffolding being moved. However, more fundamentally, there should also be larger, localized changes related to events of greater significance, represented by a consistent change mask.

Key to identifying this consistency, and relating it to a particular component, is the simple idea of first segmenting the image into a set of discrete component masks. These represent prior knowledge of the shape of each component and its occupancy within the scene, derived from the initial alignment of the camera viewpoint (Figure 4). This enables individual regions of the image to be analysed when they undergo significant transition, for example when initial construction occurs, or if there is a sudden texture or colour change indicating additional work. It is the combination of the component mask and change mask that allows us to infer the timings of significant changes within the regions of any given component.

However, the greatest concern with this combined approach is that the component masks of later constructed components may occlude or overlap with regions shared by previous activity. It is therefore important to maintain the relationship by which observed changes must correspond to the same location, size, and shape of the component in question. Furthermore, in most of construction a great deal of preparatory work occurs both around and within the area of the final component, yet the actual change can occur very quickly (i.e., an entire column lowered into place). Variations in the shape of the structure do not actually occur very frequently, rather it is often the effects of exterior modification - such as painting, casting or rendering - that give visible indication of change. The challenge is to relate particular types of events to the completion of the component.

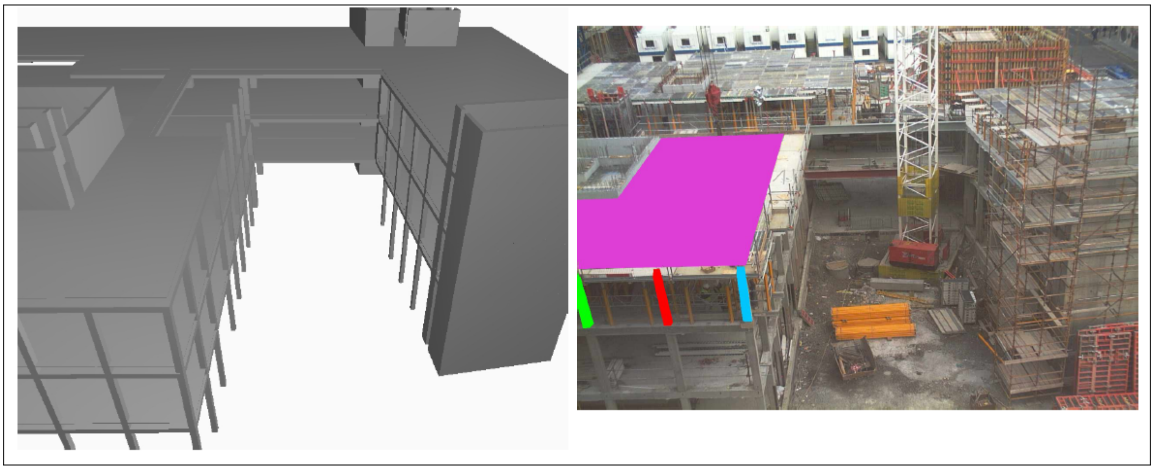

Figure 4. Alignment of camera and resulting component masks.

To highlight the validity and practicalities of this approach, we consider a simple example for detecting the completion of some columns in the work package 2.2.3. Our image data comes from the construction of the new Informatics Forum at the University of Edinburgh. We only focus on a subsection of the aligned model - in the area which is actual visible to one of the fixed cameras capturing at 15 minute periods, from 09:00 to 15:00. Figure 4 shows the results of a basic change detection algorithm, where the images are first partitioned into blocks and pre-processed to normalise the intensity distributions (Xiaolong and Khorram, 1998). This acts to remove a great deal of the localised shadows and lighting effects. Following this we apply a spatial-temporal derivative filter to smooth out noise and locate significant alteration with respect to time (Simoncelli, 1994). The amount of mean change is then computed for each respective component mask, relative to the mean change observed for the other components. The graph shows these values, per component, occurring for 5 days, with the highest detected for the times of insertion of the three columns. Later on, the concluding slab work, a component in a different work package is also detected, representing a measure of progress in that work package

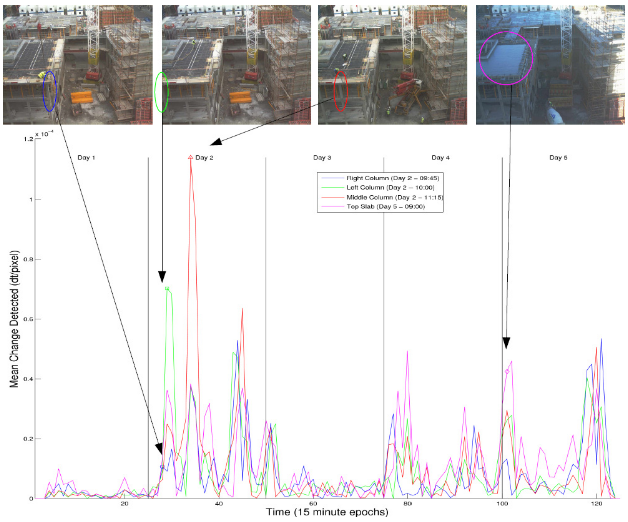

Figure 5. Analysis of change detection for work package components.

Ultimately, the spatial resolution and temporal frequency with which the images of construction are captured defines the accuracy of this approach. Given that components that are farther from the camera will be compared less reliably, a certain amount of error may occur. It should also be stressed that this approach could still be confused by longer term changes in the scene, for example if a large piece of equipment is placed in front of the structure for a prolonged period. Similarly, if a particularly large component was only moved or constructed over a number of days, it will lack definition as a region of consistent change. A possible solution would analyse the type of change, and to allow activity to accumulate over time.

The further issue of coverage is certainly the biggest concern with using a fixed camera approach. It is simply not feasible to confirm for any given moment absolutely every component. Particularly as the construction progresses and components that were once visible can disappear from the scene. This could be addressed by applying additional knowledge of the building to infer that components are probably complete. However, it must be acknowledged that this approach will not be totally reliable, since the only way to truly gain confidence that a component is finished is to visually verify it. The ideal solution must combine multiple sources of image and additional information to increase the overall reliability.

5 CONCLUSIONS

We have reported on a conceptual framework based on an expanded BIM, which is capable of managing and automatically assessing work packages. We have focused on the two main components of the system: the work breakdown assignment module and the visual assessment module. Our work breakdown approach is based on the results of an industry wide survey which provides us with a useful set of criteria to group components by. For visual assessment we apply the concept of change detection to determine when components are visibly in situ. By illustrating how these aspects can be implemented we hope to have also shown the feasibility of this approach, and potential benefits.

In future work, we will look to further provide these management functions to meet the needs of identifiable users. We also seek to properly proceed with integrating work breakdown criteria within the BIM database. This will allow us to experiment with different management strategies for given scenarios, and to verify the accuracy of the assessment, particularly in light of when progress is actually finished. Fundamentally, we also need to verify the limits of visual assessment, given that images of construction offer some of the most challenging problems facing interpretation with Computer Vision. Being able to incorporate both fixed and mobile cameras in assessment could offer improved coverage and performance. Furthermore, modeling within the system, the ordering and types of change that could occur within a components life-cycle would make events easier to spot and relate towards the question of final completion.

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