Automation in Construction 18 (2009) 294–301

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Automating progress measurement of construction projects

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ARTICLE INFO

Article history:
Accepted 15 September 2008

Keywords:
Progress measurement
Computer vision
Work breakdown structure (WBS)

ABSTRACT

The accurate and up to date measurement of work in progress on construction sites is vital for project management functions like schedule and cost control. Currently, it takes place using traditional building surveying techniques and visual inspections. The usually monthly measurements are error prone and not frequent enough for reliable and effective project controls. This paper explores the potential of using computer vision technology in assisting the project management task. In particular, it examines the development of an integrated building information system that aims to determine the progress of construction from digital images captured on site in order to semi-automate the work in progress measurement and calculation of interim payments as well as function as an early warning system of potential delays. The study focuses on the quantity rather than quality aspect of work and is limited to the superstructure of buildings.

1. Introduction

Many construction companies consider the measurement of work in progress to be one of the most challenging problems faced by project management [1]. In construction projects, site managers normally spend a significant amount of time measuring, recording and analysing the progress of work. This is essential for many business and project management functions such as cost and schedule control, financial reporting, claims and productivity measurement. In order for these functions to be reliable and effective, regular and accurate measurement is required. However, there is often lack of accurate and up-to-date as-built information due to the time consuming and expensive practice of manual data collection [2–4]. In building construction, the average duration of activities is typically in the range of days. However, the average frequency of manual data collection and reporting is monthly. The absence of accurate and real-time as-built information handicaps the managers' ability to monitor schedule, cost and other performance indicators. This in turn reduces their ability to detect or manage the variability and uncertainty inherent in project activities [5].

Several construction companies have started exploiting the use of digital imaging in supporting the visual inspection task [4]. Regularly captured images on the construction site are used in examining the progress of work, minimizing the need for site visiting. The main use of digital imaging however has so far been limited to supporting the visual inspection task, with the managers having to examine the images and determine progress. There have been some attempts to link the captured images with bar charts in order to highlight the difference between schedule and actual progress [6]. The interpretation of the images however is still left to the user.

Computer vision, a technology that focuses on providing computers with the functions typical of human vision and can be used in deriving 3D objects from 2D images, provides the opportunity for automatically analysing the captured images and measuring the work in progress. While the application of computer vision might be limited to certain stages of construction where the progress of construction is more visually evident (e.g. development of superstructure) and while it might not be possible to fully automate the work in progress measurement task (e.g. some activities might be too complex to analyse or not directly related to the construction of individual building components), the use of computer vision provides the opportunity for assisting the project management task to certain extent. For example, a computer vision system that constantly monitors construction progress might function as an early warning system of potential delays. Additionally, the measurement of the work in progress and calculation of interim payments can be semi-automated increasing efficiency. This paper presents the development of such a system aiming to assist in the construction of the superstructure of buildings.

The outline of the paper is as follows. First, computer vision technology is introduced along with its application in construction. Second, the importance of progress measurement is highlighted and the main methods in measuring progress are introduced. Third, the concepts of data integration and work breakdown structure (WBS) are

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doi:10.1016/j.autcon.2008.09.004

presented. A flexible approach to creating a WBS is described. Fourth, the architecture of the developed system is outlined. Evaluation results and feedback from the two workshops are also summarized. Finally, conclusions are drawn and potential future work is discussed.

2. Computer vision

Computer vision is concerned with modelling and replicating human vision using computer software and hardware. It is a fast evolving discipline that studies how to reconstruct, interpret and understand a 3D scene from its 2D images [7] and [8]. The typical tasks for computer vision are:

- Recognition: determining whether the image data contain some specific object, feature or activity;
- Motion: estimating velocity either at each point in the image or in the 3D scene;
- Scene reconstruction: creating a 3D model of the scene;
- Image restoration: removing noise (sensor noise, motion blur, etc.) from images.

Computer vision has found applications in a large number of areas, including automatic face recognition and interpretation of expression; automated medical image analysis, interpretation and diagnosis; recognition of printed or handwritten characters and words. In the construction area, there have been some efforts to extract data from construction site images. Dick *et al.* [9] present a framework in which a dictionary of common building elements and their learned distribution are fitted to observed geometry. Cantzler *et al.* [10] describe an algorithm exploiting geometric constraints to improve the quality of automatically reconstructed building models from images. However, all these efforts are concerned with building model reconstruction, not with measuring progress. In addition, the reconstructed models do not generally have the level of detail required in measuring the progress of construction of building components.

Some studies have also touched the issue of quality assurance, e.g., tolerance verification [11]. This approach to detecting defects can visually highlight the differences between the "as-built" state and original model. Scanning technology implies that the results can be very accurate. However there are issues related to the sheer volume of data to be interpreted. Some research exists on the observation and verification of buildings using remote, long-distance imagery, including LIDAR and visible-spectrum images. For example, Huertas and Nevatia [12] report a system for detecting specific changes in the overall structure of buildings. They exploit linear structure and seek to discard false edges created by shadows. Generalised 3D models are fitted to the result and discrepancies are used to verify the identified changes.

2.1. Use of computer vision in progress measurement

Progress measurement is based on identifying changes either as departure from an a-priori model or as difference between images taken at different times [12] and [13]. If changes to the structure of building components can be identified from a series of images captured on site, it is possible to confirm the completion date for the components and therefore determine the progress of work on site.

Retrieving data on structure from images however is a hard problem, especially in cases where the images are incomplete and noisy, such as images taken from construction sites [14]. The key problem is that construction sites offer some of the worst instances of cluttered scenes. Furthermore, changes to the true structure over time, which indicate the real progress, may be surrounded by a large number of additional spurious events. These can broadly be classified as noise and include effects that are environmental (light and shadows, rain, snow, etc), partial (longer cumulative periods of work such as pouring concrete) and occasional (people and equipment moving or staying still for a period of time).

3. Progress measurement

3.1. Linking construction progress to schedule information

Retrieving data on the construction of building components from digital images represents the first step in measuring the progress of work. This is because project managers usually define the activities in the schedule at a different level of detail, i.e. the work package rather than the individual building component level (e.g. 'formwork', 'reinforcement', 'concreting', etc, instead of 'build wall'). A work package may refer to several building components and the construction of a building component may involve several work packages. An inherent problem in integrating the extracted construction progress data from the images with schedule information is enabling the computer to maintain the relationships between building components and work packages.

Some commercial 4D softwares, e.g. 4D Suite, JetStream, allow users to specify the relationships between building components and work packages manually [15]. However, for complex projects with a large number of building components, the linking process could become time consuming and error prone.

There have been some attempts to automate the process by generating a schedule from a 3D CAD model automatically [16–18]. However, total automation is not possible and human intervention is usually required in establishing the linkages between components and packages. This is because it is not always possible to take into account the multitude of non-explicit or project-specific requirements inherent in construction projects (for example, some of the typical tasks in the construction of a building component might not be required under certain conditions or some of the work packages might relate to the method of construction which might not be known in advance as it depends on many different factors such as the availability of resources, site conditions, time and cost constraints, etc) [19] and [20]. In addition, there might be tasks that cannot be inferred from the design (e.g. tasks referring to temporal works).

3.2. Integrating schedule and cost information

The integration of schedule and cost information requires that cost and schedule share a Work Breakdown Structure (WBS) [21] and [22]. A WBS is defined as "a deliverable-oriented grouping of project elements, which organizes and defines the structure of the entire project. Each descending level represents an increasingly detailed definition of a project component" [23]. It is a straightforward means of relating time and cost information, and in this paper progress information. The significance of WBS in project control is twofold: first it is a classification mechanism that decomposes the project elements into a manageable level; second, it is an integrating mechanism that provides a common perspective to relevant construction business functions [24].

There are two main issues in developing a WBS: the decomposition criteria and the level of detail. The division of work packages could change dramatically based on the criteria used. However the difficulty of integrating schedule and cost information stems primarily from the level of detail required for effective integration [25]. Usually, a single project activity will involve numerous cost account categories and numerous activities might involve expenses associated with particular cost accounts. It is usually a many-to-many relationship between activities and cost accounts.

4. The Integrated Building Information System

In this research, an Integrated Building Information System (IBIS) has been developed to assist the project management task during the construction of the superstructure of buildings. The system semi-automates the work in progress measurement and calculation of

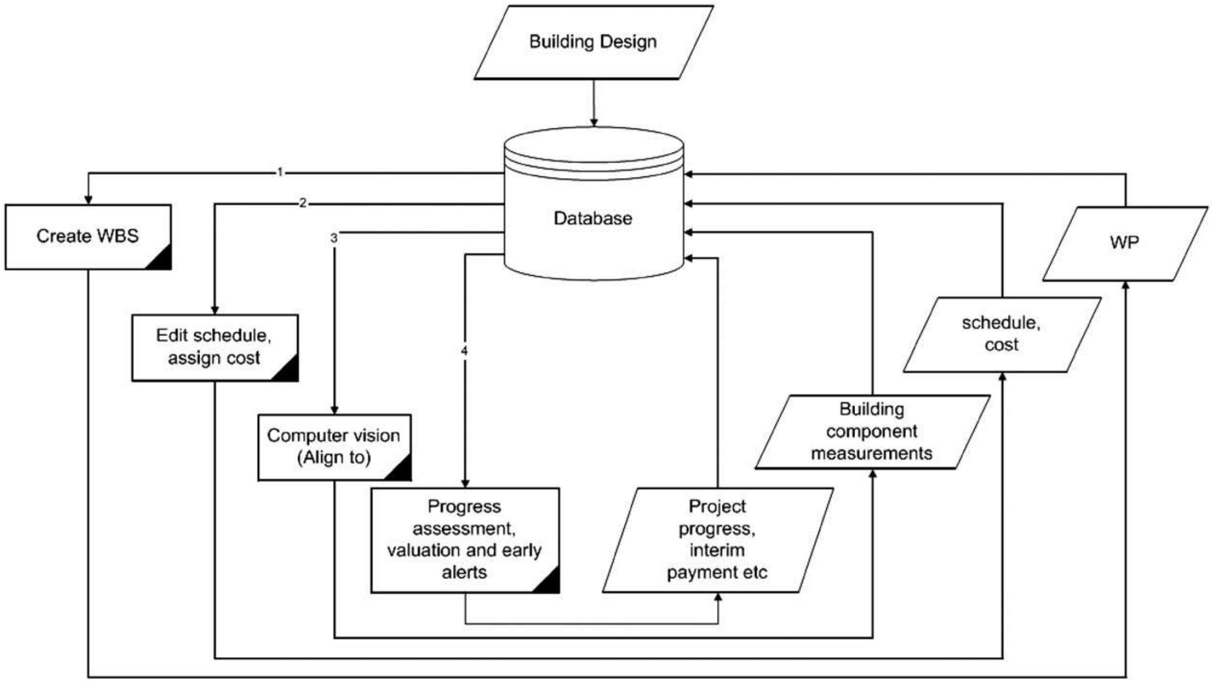

Fig. 1. IBIS System architecture.

interim payments as well as functions as an early warning system of potential delays. It uses computer vision technology to determine the progress of construction from digital images captured on site and a semi-automatic approach in linking construction progress (completion of building components) with schedule and cost information. The developed system consists of four main modules: (i) computer vision; (ii) WBS; (iii) scheduling and budgeting; and (iv) progress measurement, valuation and early alerts (Fig. 1).

4.1. Computer vision module

The computer vision module retrieves the 3D "as-planed" model from the IBIS database (Fig. 2). The model is used to first align a sequence of images taken from a particular position and angle with related building components found within the site. This is effectively a model-based fitting approach that seeks to rectify the reality of the observations to the appearance of planned components. The alignment

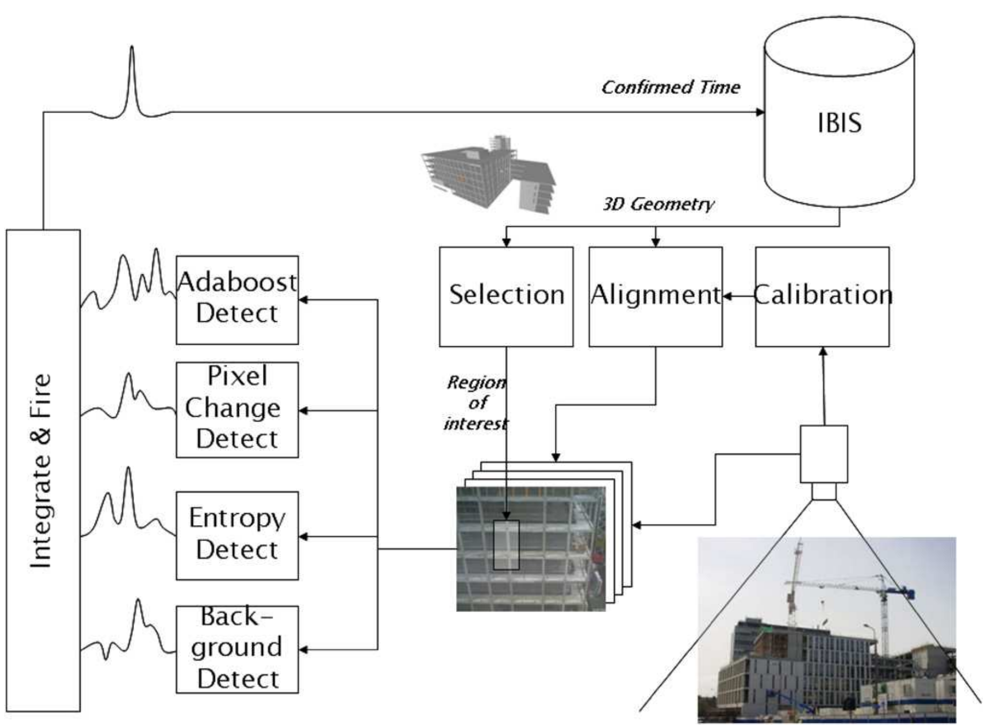

Fig. 2. Computer vision process.

in many cases requires an additional degree of fine tuning to recover a good fit to the intrinsic parameters of the camera, particularly the focal length. This could be performed in advance by a calibration procedure. The output of this process is a set of component regions and template masks created from the projection of the model onto the aligned image. These component regions and template masks guide the computer vision module to spot changes occurring over time by identifying the corresponding building components through those masks.

In identifying the building components, sudden effects of lighting may cause false detection of changes in the image. To remove as much as possible of such variations, the image is first converted to gray scale and the pixels within $n \times n$ sub-blocks are normalised to have zero mean and variance of one. As in this case only a relatively small area (in terms of the overall image) is considered each time, the approach is justified for removing a considerable amount of localised brightness and shadowing [26].

The detected changes in the images are analysed to examine whether they are due to the appearance of scheduled components. Different algorithms, such as Adaboost detect, pixel change detect (Fig. 4), are used in cross checking the changes spotted in order to increase the accuracy of the results. The changes detected are used to calculate the sum and the mean change in the regions of interest determined by the template mask for each component. Significant changes in the region are then considered to indicate that the relevant component is appearing on site. Similarly, if no further changes in the region are detected after a certain time, it is then considered to indicate that the component is complete. Once verified, the completion time of the component is saved to the IBIS database and used for the progress measurement in the later stage. Theoretically the verified changes could also be used to compare with the 3D "as-planed" model in order to calculate the percentage completion of building components. More information on the operation of the computer vision module can be found in Lukins *et al.* [26].

4.2. WBS module

In order for the system to measure the progress of work and calculate interim payments as well as detect any delays based on the progress of construction, the relationships between building components, work packages and cost items need to be maintained. As we saw, one approach in establishing those relationships is for the user to specify them manually. Another approach is to automatically generate the work packages and cost items based on the design information. As it is time consuming and error prone to specify the relationships manually on the one hand and it is not possible to fully automate the generation of the work packages and cost items on the other, a semi-automatic approach has been followed in this research.

The system automatically creates an initial WBS based on the design information and a number of criteria specified by the user as described below. The system also allows the user to make modifications to the WBS and specify any new relationships between building components, work packages and cost items manually.

The initial WBS is automatically generated by the system using a multilevel decomposition process in which the designed construction model (the design is saved in a model based form being created using an object-based design package–Autodesk Revit in our case) is decomposed into detailed work packages based on a number criteria specified by the user (Fig. 3). According to a recent industry survey [27], the three most used criteria in creating a WBS are work section, geographic location (e.g. floor level) and type of components. The system allows the user to select any of these criteria and the more criteria selected, the more work packages at a higher level of detail are created with less number of building components associated with each package. For example, as Fig. 4 illustrates, by choosing the 'work section' criterion, three packages are created (Fig. 4A). By adding the floor section criterion, 27 packages are created (Fig. 4B). Finally, by adding the element criterion, the number of packages increases to 35 (Fig. 4C).

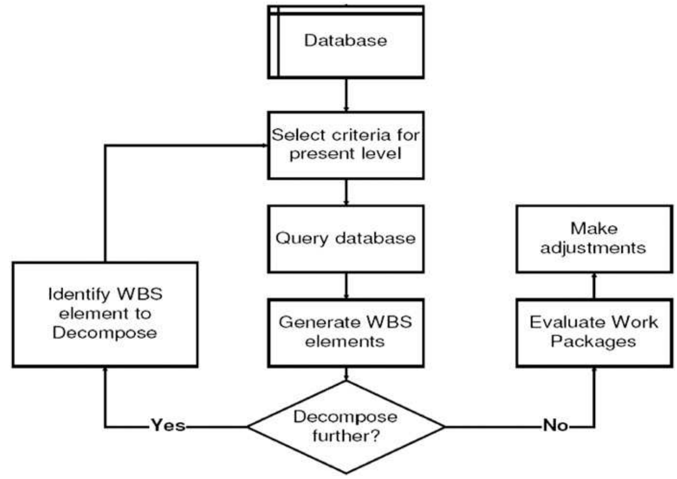

Fig. 3. A flexible approach to generate WBS (modified from: [27]).

It should be noted that the generation of the WBS can be further improved by adding more criteria or associating 'recipes' (typical work packages) with the construction of each object. However, as the focus of this study has not been on the automatic generation of the WBS but rather on measuring the work in progress, further refinements to the model were not attempted. Emphasis was placed instead on maintaining the relationships between building components, work packages and cost items while allowing the user to modify the automatically generated WBS, as explained in the next section.

The generated WBS forms the basis for the integration of design, cost and schedule information, work progress measurement, and calculation of the interim payments and productivity rates. For example, in order to calculate interim payments, the work packages can be used as the middle layer in linking the retrieved construction progress data with the cost information.

4.3. Scheduling and budgeting module

The generated work packages are automatically loaded into MS Project which is used as the scheduling tool. Using the MS Project editing functions, the user can perform any modifications to the packages. An existing work package may be subdivided into a further level of detail (e.g. 'Build Wall 1' may be subdivided into 'Formwork Wall 1', 'Reinforcement Wall 1', 'Concreting Wall 1', etc). While it might not be possible for the system to determine the completion of the individual sub-packages, completion of the parent package assumes completion of the children ones. Existing work packages associated with building components may be also grouped under new parent packages (e.g. 'Build Wall 1' and 'Build Wall 2' may be grouped under 'Build Walls Zone A'). Completion of the children packages assumes completion of the parent ones. By maintaining the parent/child relationships, the system is able to recognise the completion of the parent work packages on the completion of the child ones and vice versa.

The system also allows the user to define new work packages which can be manually associated (through a built-in interface) with any number of building components. By maintaining the relations between components and packages the system is able to detect the packages completed on the completion of the building components. Having defined the work packages, the user can schedule them (define

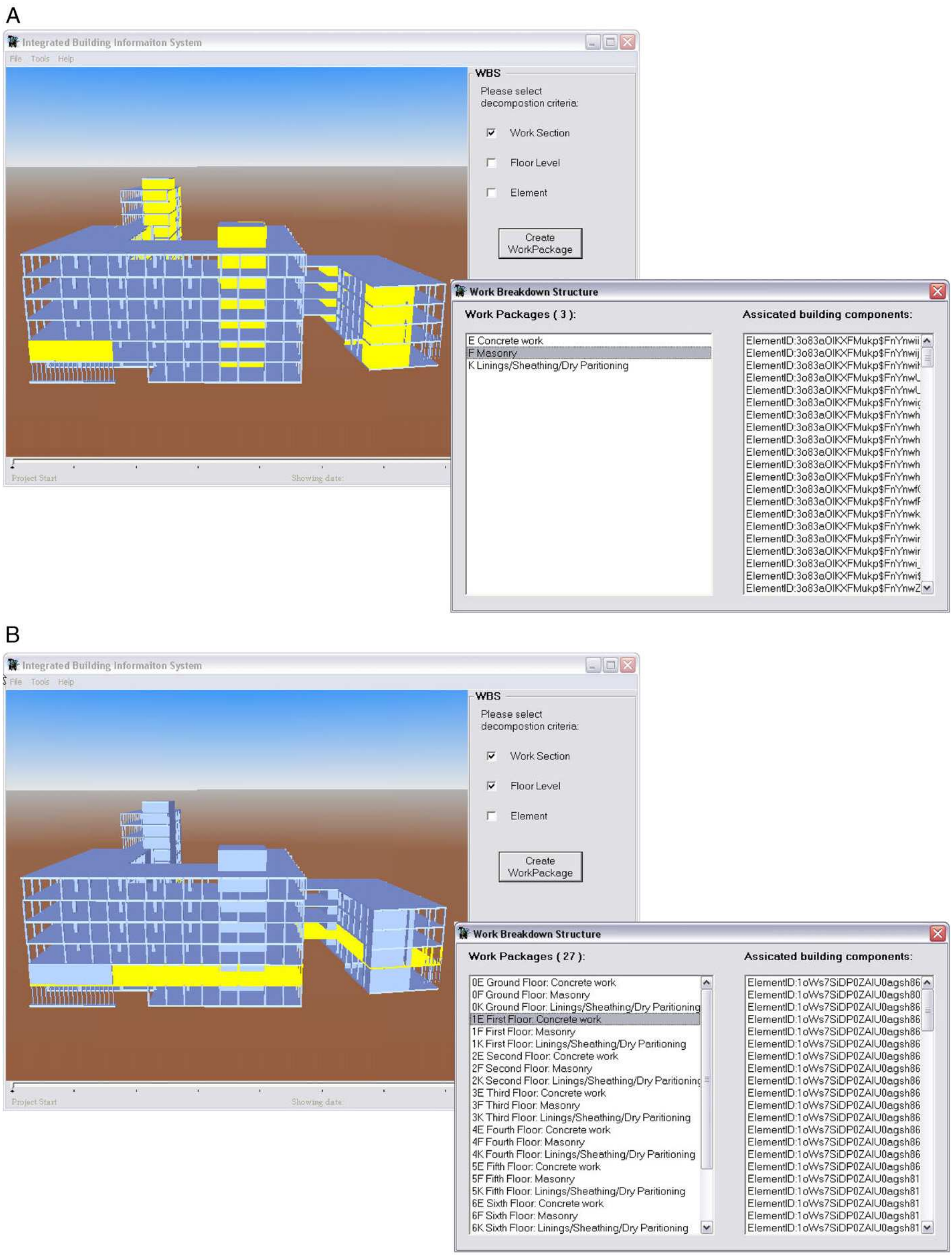

Fig. 4. Work package breakdown: (A) Selecting a single decomposition criterion in creating the WBS; (B) Selecting two decomposition criteria in creating the WBS; (C) Selecting three decomposition criteria in creating the WBS.

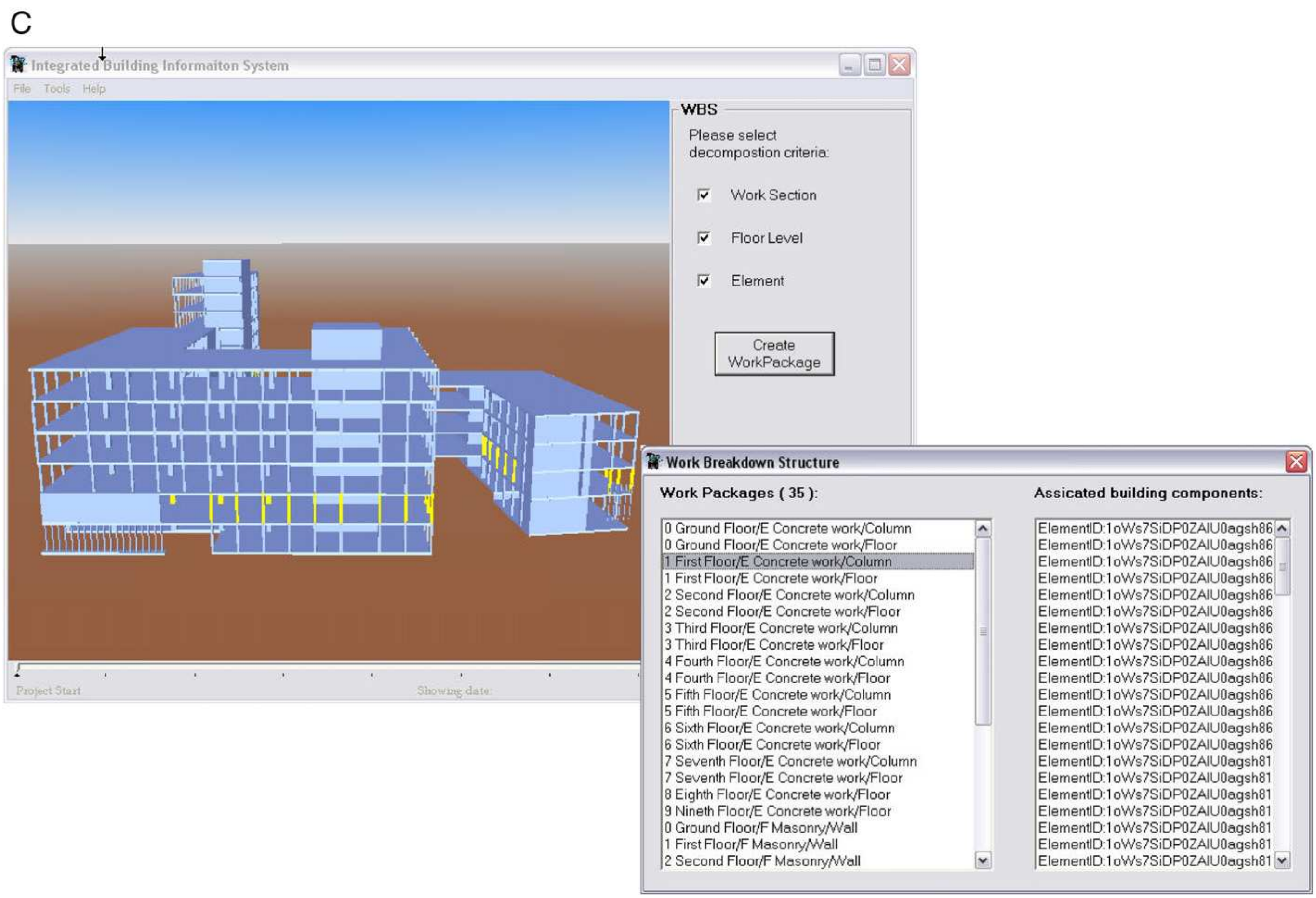

Fig. 4 (*continued*).

start and end dates) as well as specify the costs associated with each package.

4.4. Progress measurement, valuation and early alerts module

The progress measurement, valuation and early alerts module uses the input from the computer vision module on the progress of construction and the relationships between building components, work packages and cost items maintained by the IBIS system to highlight the work packages detected by the system as completed. As it was mentioned, the system might not detect all completed packages so the user has to check the remaining ones.

Based on the completed packages, the module can produce an initial valuation report, including productivity rates, which needs to be completed by the user. Early alerts are also raised, in the form of emails, on detecting any work packages that have not been completed by their scheduled end date.

The sum of the cost of the completed work packages is the estimated interim payment. Productivity rates are estimated by multiplying the percentage completion of activities with the corresponding total quantities divided by the time taken to achieve that level of progress. Performance diagrams can be also created for the project manger to monitor project performance (Fig. 5).

4.5. Evaluation and feedback

A real construction project was used as a case study in evaluating the performance of the computer vision module and two workshops with the participation of industrialists took place in evaluating the overall system operation.

4.5.1. Results from the case study

The performance of the computer vision module was evaluated in the construction of the School of Informatics building at the University of Edinburgh. A 3D building model was provided by Bennetts Associates while digital images were captured from cameras installed on site.

The computer vision module was tested at various stages of the building's superstructure construction. The module was able to detect the construction of building components at 70% of the time. Part of the limited detection rate was due to the images exhibiting heavy clutter and uncontrolled lighting variations. Improvement may be achieved by refining the model based fitting for image alignment and making the detection algorithm more reliable by including texture and colour. Another problem has been the limited coverage of the fixed cameras especially in relation to the internal building. While the installation of more cameras or the use of portable ones might increase coverage, knowledge of the building model could be used in inferring the completion of components in those areas where coverage is limited (e.g., on detecting that the 2nd floor slab has been completed, the system can infer that the columns on the 1st floor have been completed as well).

4.5.2. Feedback from the workshops

The prototype was also evaluated in two workshops. In the first workshop, 12 persons, including four industrialists, one senior Local Council official, one EPSRC member and six academics (excluding the researchers in this project), attended. In the second workshop, eight people, one planner, two project managers, one quantity surveyor and four academics (excluding the researchers in this project), attended.

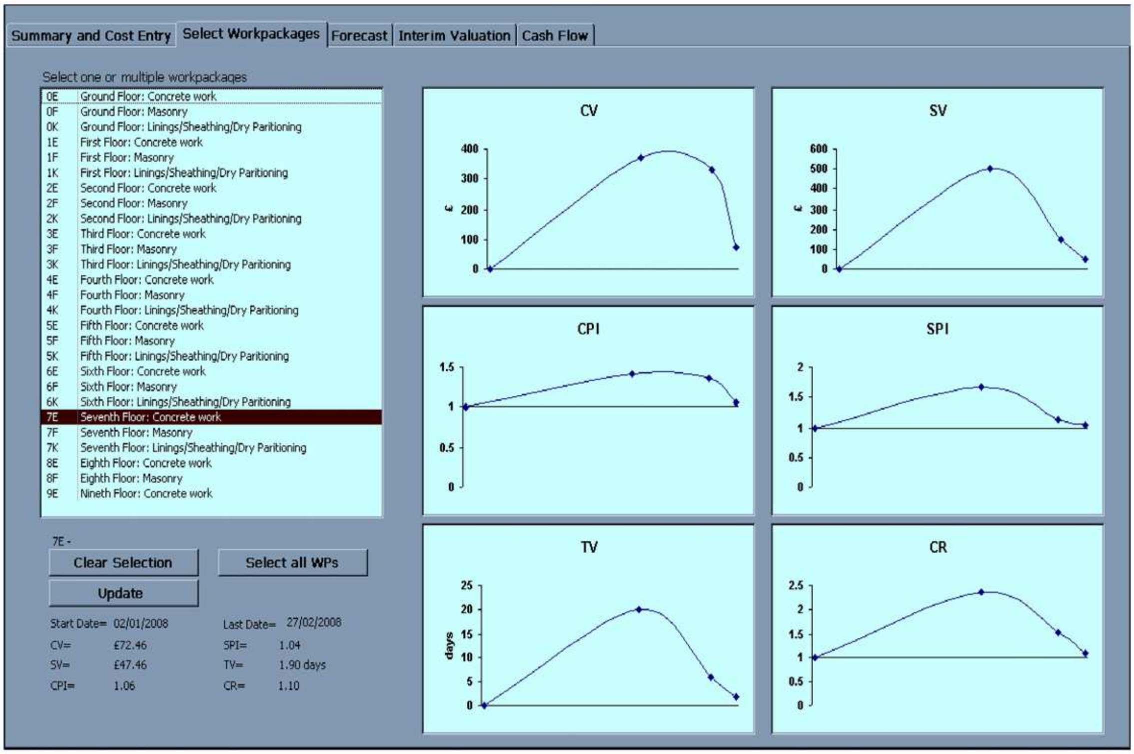

Fig. 5. Project performance diagrams.

The prototype was demonstrated and discussions followed regarding its potential use in construction. A questionnaire was then distributed to collect further feedback. In the questionnaire, participants were asked to specify their jobs and experience of construction project management. One question asked was to evaluate the usability of the prototype from different perspectives e.g. applicability in construction management, practical relevance. Another question was to assess the prototype's potential in different project management functions, e.g. cost and schedule control, progress measurement and calculation of interim payments. There were also some open questions to stimulate discussion. As illustrated in Tables 1 and 2, the system was rated with an average score of at least 3.75 out of a maximum of 5 in all aspects.

Regarding the use of the system in assisting progress measurement and the calculation of interim payments, the participants recognised its potential in reducing human errors and increasing efficiency. Although the system can only provide a partial assessment of the work progress and partially calculate interim payments, the participants still considered it as a valuable aid, especially in large projects where big jobs are normally paid against milestones or over a relatively long period, e.g. every two months. However, as the results from the questionnaires indicate (Table 2), the greatest value of the system was considered to lie in schedule and cost control through the system's ability to constantly monitor progress and provide early alerts on potential delays. By linking digital images with schedule and cost information, the system was also considered to provide not only visual but also quantity information of work progress, something that could be used as an evidence base for potential contractual claims/damage to work.

5. Conclusions and future work

Work in progress measurement is a complex task to be fully automated. However, as this study has demonstrated, the use of computer vision provides the opportunity for assisting it to a certain extent. Using a 3D 'as-planned' model of the building and a model-based fitting approach, the developed computer vision module is able to detect the construction of building components. Based on the progress of construction and knowledge of the work packages in the schedule associated with the construction of each component, the system is able to detect the completion of work packages at a given point in time. The relationship between building components and work packages is established by semi-automating the generation of the WBS on the one hand and allowing users to modify the generated

Table 1
Questionnaire results: usability validation

	1 (Very poor)	2 (Poor)	3 (Average)	4 (Well)	5 (Very well)	Mean score	Standard deviation
Applicability in construction management	0.0%	0.0%	12.5%	62.5%	25%	4.13	.641
Practical relevance to construction management	0.0%	0.0%	12.5%	75%	12.5%	4.00	.535
Comprehensiveness	0.0%	12.5%	12.5%	50%	25.0%	3.88	.991
Clarity	0.0%	0.0%	12.5%	75.0%	12.5%	4.00	.535
Logical structure	0.0%	0.0%	25%	75.0%	0.0%	3.75	.463

Table 2
Questionnaire results: potential to add value

	1 (Very low)	2 (Low)	3 (Average)	4 (High)	5 (Very high)	Mean	Standard deviation
Work package planning and formulation	0.0%	12.5%	12.5%	62.5%	12.5%	3.75	.886
Cost and schedule control	0.0%	12.5%	12.5%	50.0%	25.0%	3.88	.991
Calculation of interim valuations/payments	0.0%	0.0%	37.5%	50.0%	12.5%	3.75	.707
Cash flow analysis	0.0%	0.0%	50.0%	25.0%	25.0%	3.75	.886

packages while maintaining the relationships between components and packages on the other. By allowing users to associate cost items with the work packages, calculation of interim payments is also possible.

The system cannot provide a complete picture of work progress. The computer vision module has a limited success rate in detecting the completion of building components. Further improvement can be achieved by refining the model based fitting for image alignment and using knowledge of the building model in inferring the completion of components. The computer vision module also detects only the completion of components without giving any indication of the percentage completion at a point in time. Such indication can be given by comparing the 3D 'as-planed' model with verified changes between image sequences. Further work is required towards this direction. Based on the percentage completion, the calculation of interim payments can be improved for linear and continuous processes that produce a single output [28]. The operation of the system has also been limited to the superstructure of buildings. Other construction stages may be covered, however, the results will be limited for stages where the progress of construction is not as visually evident (e.g. fixtures and fittings).

While a number of refinements may improve the system's performance in measuring the work in progress, total automation is not possible. This is not only because of the inherent complexity in analysing the digital images as well as the presence of work packages that are not directly related to the construction of building components, but also because of the system's limited ability in interpreting user defined work packages. For example, if the user defines a 'Build foundations for Wall 1' package, the system will not be able to immediately detect the completion of the package unless an algorithm for detecting the construction of foundations is implemented (the system however will be able to detect the completion of the package on detecting the completion of the whole wall). Obviously, there is a limit to the number of cases that can be covered.

Nevertheless, these limitations do not dismiss the system's value as the evaluation workshops indicated. The system can still assist the project management task by semi-automating the work in progress measurement and calculation of interim payments. In addition, it can constantly monitor the construction progress and provide early warnings of potential delays. Finally, while the system has been developed to support building construction, its application to other type of projects is possible. In fact, the system might be more particularly suited to projects where the progress of construction is more clearly evident such as civil engineering ones.

Acknowledgments

This research has been funded by the Engineering and Physical Sciences Research Council (EPSRC) whose support is gratefully acknowledged. We thank the School of Informatics at the University of Edinburgh for the image sequence data and Bennetts Associates (Architects) for the use of the 3D building model.

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