A 4-D Project Control System with Information Visualization Technology

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Abstract
Project control, which entails the management of data concerning cost and schedule, is the fundamental task of project managers. A capable project control system is an essential tool that enables project managers to deliver projects successfully. However, most project control systems summarize a project's status by producing huge datasets of tables and charts with formats predetermined by system analysts. Consequently, project managers must eliminate redundant data in order to diagnose problems and make decisions; all within a very limited time. Despite the great progress that has been made in information technologies in recent years, project control researchers have failed to take advantage of emerging information technologies to improve the usability of project control systems. Among emerging information technologies, information visualization technology is the most promising. It offers better support for project managers' ability to perceive and capture project control data by allowing them to take advantage of visual cognition so that they can readily find deviations and patterns as well as make judicious decisions effectively and efficiently.

Our proposed approach is to create a project information structure (PIS) integrating the data of a project's work breakdown structure (WBS), cost breakdown structure (CBS), and organization breakdown structure (OBS) for a specific moment during construction into a three-dimensional tree. In order to understand the trend of the overall project, the 4-D project control system provides a temporal function, which allows the project manager to view the PIS along a timeline. Many potential problems can be detected early enough to correct if the project manager has the ability to scrutinize a 3-D tree consisting of project control data along a timeline.

Keywords: construction, project control, information visualization, cost, schedule, personnel, work breakdown structure

1 Introduction

Construction projects involve complex relationships among schedules, costs, and personnel. The general practice of construction management in the United States is to prepare a project schedule and a project budget separately during the pre-construction stage of a project. As a result, project control during the construction stage is habitually divided into two parts – schedule control and budget/cost control. However, the separation of schedule and budget/cost controls may not help project managers in understanding the overall status of a project's performance or to adequately control it.

In order to deliver projects on time and within budget, project managers need to manage exceptional cases such as deviations in project control data. Deviations should be under tolerant ranges, otherwise they should be controlled in time. Project managers must agilely find deviations and their root causes before taking necessary corrective actions. Among emerging information technologies, information visualization technology is the most promising to better support project managers' ability to perceive and capture project control data (Songer et al 2004).

1.1 Statement of the Problem

During the construction phase of a project there are considerable challenges to consider, such as bad weather, variability in labor productivity, absenteeism, labor turnover, procurement and delivery delays, design inaccuracies, change orders, contractual disputes, rework, labor disputes, accidents, and vandalism (Gould & Joyce 2008). The size and complexity of construction projects have increased rapidly, making project control even more difficult. Consequently, competent project control systems are essential to project managers.

Most current project control systems are based on summarizing a project's status by tables and charts. These systems, with their limited support to project managers, are hardly acceptable in this era. Construction projects have frequently used computer-based systems to conduct data-processing tasks such as storage and retrieval of data, calculation and comparison, plotting and tabulation, access of databases via query transactions, and preparation of reports. Instead of providing large datasets, project control systems should give more specific information so that project managers can easily conduct exceptional management.

Human limitations, such as working memory and information assimilation, cause cognition to scale poorly as the amount and complexity of information increase. We cope with large-scale cognitive tasks through cognitive artifacts for holding and processing information as needed, such as paper, pencils, abacuses, computers, reading, writing, and arithmetic. Vision typically plays a key role in cognitive artifacts, and visualization is about exploiting the power of human vision for maximizing cognitive performance. Visualization can help create an internal model in the mind of the user, and information visualization can help explore visual representations for a large quantity of data so that the user can grasp the data's meaning easily (Chen 2005).

1.2 Purpose of the Study

The purpose of this study is to design and develop a digital prototype of a 4-D project control system with information visualization technology.

Project control requires a great deal of tacit knowledge. This kind of knowledge is very difficult to be described clearly. The number of actual datasets in a project control system is usually not large (less than 10,000), but these datasets are highly dimensional (10 or more attributes). In addition, the quality of project control data is generally not as good as that collected via sensors or through swiping credit cards (Lee & Rojas 2013). With these unique characteristics, it is believed that artificial intelligence techniques, such as knowledge-based systems, neural networks, and data mining, are not very suitable to project control.

Intelligence augmentation can be achieved by using well-designed cognitive artifacts. Information visualization can help us exploit the power of human vision for maximizing cognitive performance. The 1990s and onwards have witnessed leaps and bounds in the field of information visualization, with the development of increasingly powerful techniques and visually appealing information visualization artifacts (Card et al 1999; Chen 2006; Ware 2012). However, information visualization has not been applied to the design and development of project control systems yet (Lee & Rojas 2013).

1.3 Study Procedures

Step 1: Preparation of project control data

The work breakdown structure (WBS), the cost breakdown structure (CBS), and all daily reports were generated based on a highway bridge project discussed in Construction Project Management (Sears et al 2015). The organization breakdown structure (OBS) and various probable problems encountered during construction were produced by the authors based on their experience.

Step 2: Initialization of the 4-D project control system

After successfully developing a digital prototype of a 4-D project control system, the authors stored the data from the highway bridge project in the 4-D project control system database.

In general, project control includes four tasks: (1) to analyze data in order to determine favorable and unfavorable trends; (2) to identify probable causes for activities with good and poor performance; (3) to select actions for improving performance; and (4) to forecast future performance. In this study, only tasks 1, 2 and 4 were focused on.

2 Literature Review

Visualization of construction project progress has been studied in two approaches: (1) project control data projected onto physical models and (2) project control data exploited and viewed by using information visualization technology. The latter approach explores the semantics of project control data with information visualization systems to help the user find deviations and patterns quickly (Songer et al 2004; Russel et al 2009; Lee & Rojas 2013), and is the focus of this paper.

The concept of 3D visualization of work packages containing project control data was introduced to the construction industry in the early 1980s (Neil, 1983). The approaches to integrating project control data such as cost and schedule together were explored in the early 1990s (Rasdorf & Abudayyeh 1991, 1992; Abudayyeh & Rasdorf 1993). Applying information visualization technology to project control data has been studied since the early 2000s (Songer et al 2004; Russell et al 2009; Lee & Rojas 2013). Visual representations with information visualization for project control data have been proposed. However, no digital prototype based on these proposed ideas has been designed and implemented since it requires programming proficiency, database design expertise, and web-oriented knowledge besides insights into project control and information visualization.

3 Project Information Structure

The purpose of this section is to discuss a data structure called project information structure (PIS), upon which a 4-D project control system with information visualization technology can be built. For a project, we can describe its control data according to their nature by presenting the data onto the leaf-nodes of its cost breakdown structure (CBS), work breakdown structure (WBS), and organization breakdown structure (OBS) in a 3-D Cartesian coordinate system (see Figure 1). Projecting the nodes of these three 2-D tree structures together in the space after carefully considering their constraints and meanings, we can create a 3-D PIS (see Figure 2). A PIS represents a set of project control data at a specific moment during the project construction stage. As the project progresses, the moving loci of a PIS constitute the backbone of a 4-D project control system.

3.1 Relationships among a PIS and its Corresponding CBS, WBS, and OBS

In order to integrate three different kinds of project control data (i.e. cost, schedule and personnel data) together to make a PIS, we ought to first build the project's CBS, WBS and OBS (see Figure 1). Actually, a PIS is a 3-D virtual tree whose nodes contain pointers pointing to the corresponding nodes of the CBS, WBS and OBS. The nodes of these 2-D structures contain the project control data. According to the nature of the project, we can first assume either the CBS or WBS as a major framework of the PIS, and then link the nodes of the other two 2-D tree structures with the nodes of the major framework one. When linking these nodes, there are four kinds of relationships: one-to-one, one-to-many, many-to-one, and many-to-many.

3.2 A Database for Storing the Relevant Data

In order to integrate those three 2-D tree structures together to build a PIS (see Figure 1), we need to first create a database for each tree structure, respectively. It should be noted that all the tree structures involved in this study (i.e. CBS, WBS, OBS and PIS) belong to multi-way trees. Their representative logical data model is shown in Figure 3.

Database modeling and design for this study is based on the approach described in a book entitled Database Solution: A Step-by-Step Guide to Building Databases written by Thomas Connolly and Carolyn Begg (2000). A description for the problem needed to be modeled is first written; a logical data model for the problem is then created by using an entity-relationship diagram; and finally normalized tables with their attributes and various keys are developed.

The root node of a tree structure never has a parent node, and each node except the root node must have a parent node. The number of child nodes for a parent node ranges from 0 to many, which is indicated as 0 .. * in Figure 3. In a tree structure, a node's parent is one but only one, which is indicated as 1 .. 1 in Figure 3. In short, the differences among the WBS, CBS, OBS, and PIS are their attributes only, and their data structures all belong to a multi-way tree (see Figure 3).

When integrating the WBS, CBS and OBS to build a PIS, from the perspective of any node of PIS, we should consider four situations: one-to-one, one-to-many, many-to-one, and many-to-many as discussed in previous section. Theoretically speaking, we can project the WBS, CBS, and OBS of a project to build a PIS tree without a problem. However, in reality, we need to have an extra relational database table called MultiChildCondition (see Figure 4) to ensure that each and every record in the tables has one but only one value. In other words, we must refer to the MultiChildCondition table under the condition that a PIS node is projected from more than one node of WBS, CBS or OBS.

3.3 Algorithms for Displaying a PIS Tree on the Monitor

In the database, each project can store the data of its WBS, CBS and OBS tree nodes. In other words, project control information for several projects can share the same storage space. Before speaking of displaying the project control information in a 3-D tree structure on the monitor, we need to first find out all the PIS nodes and their corresponding levels in the PIS tree structure for a project. For each and every tree in this study, an algorithm called FIND-ALL-NODES as shown in Listing 1 can help organize its relevant data to be a predetermined format so that later processes, such as 2D and 3D tree drawing on the monitor, can be based on it.

This algorithm is recursive because the algorithm name – FIND-ALL-NODES – can be found in the middle of the pseudo code as shown in Listing 1.

There is no software-on-shelf for drawing tree structures on the monitor such as work breakdown structure, cost breakdown structure, and project information structure. Therefore, we have to come up with our own 2-D (e.g. WBS, CBS and OBS) and 3-D (e.g. PIS and a project control tree for the entire project) tree drawing algorithms.

For drawing a 2-D tree on the monitor, we have to first calculate the X and Y coordinates of all tree nodes so that all the nodes can be clearly displayed. For drawing a 3-D tree on the monitor, we can view the parent node of a tree structure as the apex of a pyramid in geometry. We can then determine the diameter size of a tree fragment at a specific tree level so that all the nodes can be shown clearly.

4 A Four-dimensional Project Control System

4.1 Overall Architecture

Data sharing systems have become a trend since the late 1990s. This kind of data processing and monitoring system is usually web-based. These kinds of systems consist of server-side systems and client-side programs.

However, client-side programs require initial installations, occasional upgrades, and regular maintenance by well-trained technical personnel. These tasks make client/server (C/S) architecture systems not very convenient and economical to the user. With the advent of browser/server (B/S) architecture, tasks such as installations, upgrades, and maintenance can be completed remotely by technical personnel working for software service suppliers. Therefore, the browser/server (B/S) architecture system has become prevalent in the software industry since the early 2000s. The 4-D project control system with information visualization technology belongs to a B/S architecture system. In addition, most users are very familiar with internet browser software such as Internet Explorer. This 4-D project control system can increase its usability through B/S architecture.

The 4-D project control system is built based on project information structure (PIS), which requires the 3-D display capability. However, it is very challenging to display a 3-D model inside a web browser with acceptable efficiency. WebGL enables the web browsers to render 3-D models with GPU instead of CPU. In other word, the WebGL technology provides web browsers capabilities to display project information structure (PIS) efficiently (Congote, et al 2011). It is why this project is built based on B/S architecture with WebGL.

The user interface for a 4-D project control system consists of the project control data in a PIS format as well as various control components such as labels, buttons, legends, and dialog boxes. Looking at Figure 5, the PIS is processed by the WebGL library while the control components are handled by the HTML 5 as shown in the client-side devices. The client side and server side can communicate with each other via the Internet and a component called Servlet 3.0. Data storage and retrieval for a PIS tree are completed by using codes written in the JAVA programming language and a MySQL database in the server-side devices.

4.2 Information Visualization Technology

4.2.1 Color Identification

The color, shape and size are the most identifiable characteristics to human vision. Seven predetermined colors are adopted in the 4-D project control system (see Figure 6). The gray means the current activity has not started yet; the green means the current activity is under construction without problems; the red means the current on-going activity has risks of falling "behind schedule"; the yellow means the current on-going activity has risks of going "over budget"; the orange means the current activity has risks of "behind schedule" and "over budget"; the blue means the current activity has been completed without problems; and the purple means the current activity has been completed with problems in its history.

4.2.2 Overall Structure Display

Project managers can view the project control data from the perspective of either a specific part of a project or the entire project tree. The 4-D project control system allows the manager to zoom into a tree fragment of the PIS or zoom out to look at the entire PIS tree (see Figure 6). Project managers can rotate a PIS tree by using the drag-and-drop functions of the mouse, which allows project managers to improve their understanding of the project by changing their viewpoint.

4.2.3 Time Travelling

In order to understand the trend of the overall project, the 4-D project control system provides a time travelling function, which allows project managers to view the PIS along a timeline. Many probable problems can be detected early enough if the project manager has the ability to get project control information along a timeline.

5 Conclusions and Future Work

The 4-D project control system with information visualization technology is the first and only attempt so far at designing and implementing a digital prototype for construction project control. The PIS used in the system has been built by integrating three 2-D tree structures relevant to project control data (i.e. CBS, WBS and OBS) without assuming any tree structure is more detailed or coarse than others. In other words, the PIS can deal with any kind of corresponding relationship among CBS, WBS and OBS (i.e. one-to-one, one-to-many, many-to-one, and many-to-many). In real time, the monitor can present a 3-D PIS for a specific moment during construction and can also display many PISs including both the past and future during construction in a time series. This digital prototype belongs to a browser/server architecture system with WebGL. The codes were written in the JAVA programming language. A MySQL database was employed in the server-side devices.

A usability study is underway to compare the users' performance using the 4-D project control system with information visualization technology vs. using a conventional cost-loaded project control system based on MS Project. In the near future, the results of this usability study will be published.

6 Figures and Algorithms

6.1 Figures

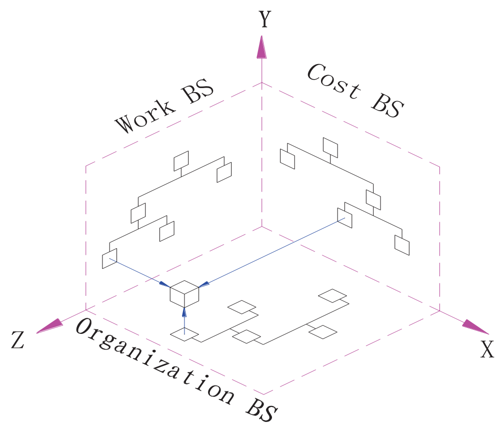

Figure 1 A relationship between a PIS node and its corresponding nodes in WBS, CBS & OBS

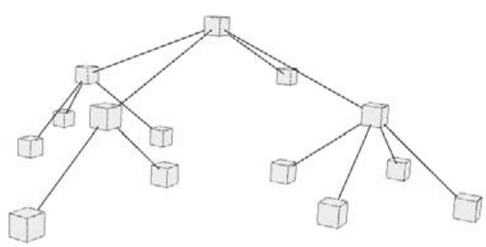

Figure 2 A PIS at a specific moment during construction

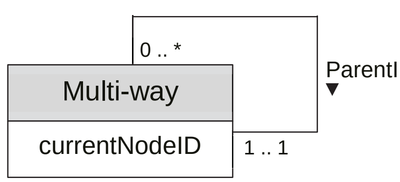

Figure 3 A logical data model for multi-way trees

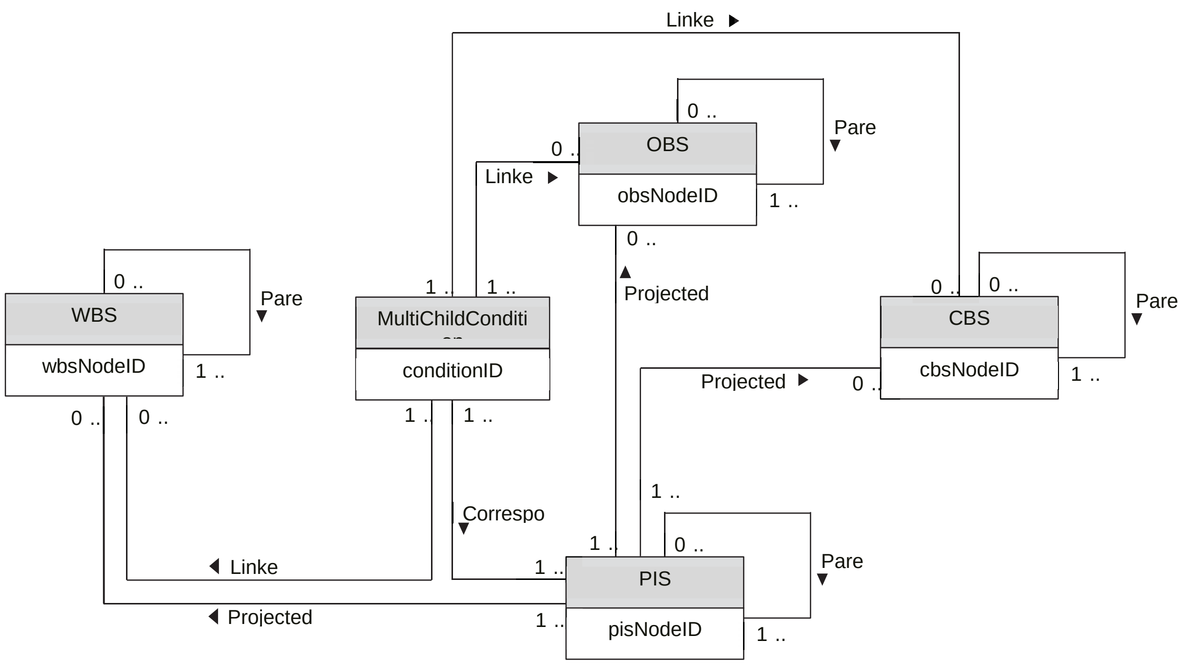

Figure 4 A logical data model for building a PIS tree from WBS, CBS and OBS trees

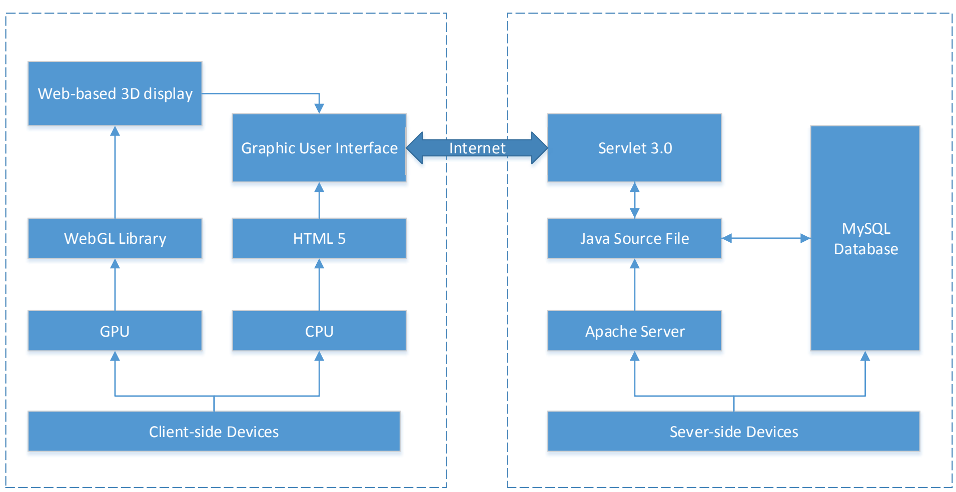

Figure 5 Architecture of the 4-D project control system

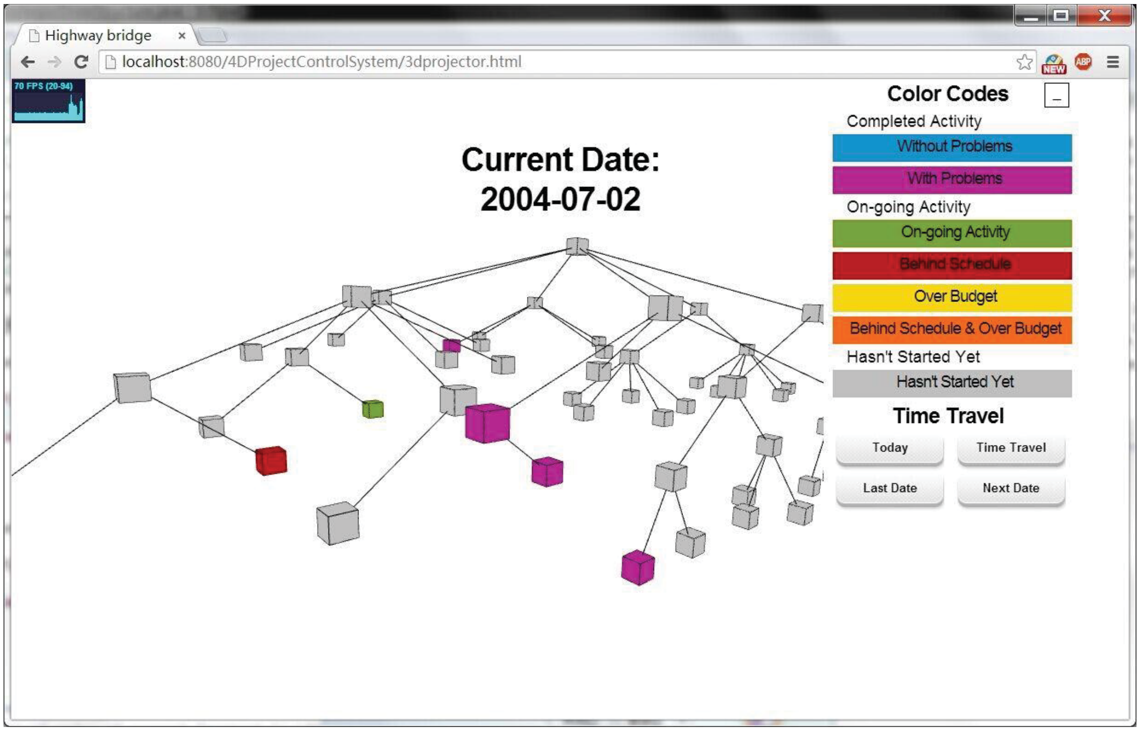

Figure 6 An example of overall structure display

6.2 Listing

Listing 1 FIND-ALL-NODES (id)

```
nodes[ ] ← get-children (id)
if length[nodes] > 0
    for i ← 1 to length[nodes]
        child-id ← get-id(nodes[i])
        FIND-ALL-NODES(child-id)
    for j ← 1 to length[nodes]
        store(nodes[j])
return
```

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