FLEXIBLE DESIGN REPRESENTATION FOR CONSTRUCTION

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Abstract. A high percentage of overall defects in the built environment occurs during the construction period. Some of these relate to design and the others relate to construction. The detection and reasoning of defects requires involvement of multiple expertise. Researchers in the School of Architecture, the Robotics Institute, and the Department of Civil and Environmental Engineering at Carnegie Mellon University are investing ways to integrate suites of emerging evaluation technologies to help find, record, manage, and limit the impact of construction defects. As part of this effort, the researchers have conducted case studies on construction sites near Pittsburgh, Pennsylvania. Each case study serves as a test-bed to measure the feasibility of our approach and to discover problems. In this paper, we discuss the overall project work flow in which we emphasize the importance of a flexible representation for construction, and describe our solution using a concept of representational flexibility named *sorts*.

1. Introduction

Practice in architecture and building involves the participation of various expertise within the lifecycle of a building. According to Gielingh (1988), the building lifecycle is structured around its major transition points; these can be classified by the following six phases: feasibility study, design, construction planning, construction, operation & management, and demolishing planning. Each phase has many activities and involves the participation of actors from different disciplines.

We concentrate on the construction phase. Integrating the different views into a single project model, or supporting information exchange between the alternative representations is far from straightforward as current research into project models shows (Stouffs and Krishnamurti, 2002). Most standard modeling approaches provide a near complete description of product and process models that relate to a single construction project. However, these lack several important representation schemas among which include: (i) a model of the as-built information; and (ii) a flexible decomposition of the product model to incorporate the different views of the specialty trades at any given point in time.

A common and prevalent situation in construction is the occurrence of defects resulting in costly rework and adversely affecting the overall performance of the building environment and building lifecycle. (Burati, 1987)

At Carnegie Mellon University, researchers from the School of Architecture, the Robotics Institute, and the Department of Civil and Environmental Engineering are investigating ways to integrate emerging evaluation technologies to help find, record, manage, and limit the impact of construction deviation (Akinci, 2002). The team employs laser scanners and embedded sensors to assemble as-built information of a construction site into a digital model. This model is compared with a digital as-designed model in order to detect deviations from the properties delineated in the design specification. In such efforts, the project model is referred to a "living" model, since it is continuously updated and maintained to reflect the current conditions at a construction site. The envisioned system for active project control and management uses a core project model composed of a three-dimensional design model with explicit design specifications, a construction process model, an as-built model of the site, and multiple views. As part of this effort, we (the team) have conducted three case studies on construction sites near Pittsburgh, Pennsylvania. These case studies serve to identify challenges in applying a specific design representation to suit the different perspectives from various objectives during the construction deviation identifying process. (Gordon, 2003)

2. Approach

Overall, the process for each case study starts with information gathering in order to build an as-designed model to a level of detail that is useful for comparison with features that are to be extracted from a current condition of construction. In order to compare geometric features that are derived from laser scans, the as-designed model must be three-dimensional and detailed. For non-geometric features, components must be represented with expected performance attributes that will correspond to the gathered data.

The living project model goes beyond geometry both as-designed and as-built, incorporates intelligence corresponding to performance attributes, temporal and sequential information such as the construction process model, and includes data from numerous documents such as the specifications and requirements. This project model is updated during the building construction period.

The entire process follows the following sequence: (i) developing the as-designed model; (ii) developing the living project model; (iii) determining the measurement goals; (iv) planning for embedded sensors and laser scanner; (v) laser scanning; (vi) object recognition; and lastly, (vii) reasoning about deviation. This is an iterative process that continues until construction is completed.

2.1. OVERVIEW OF PROJECT WORK FLOW

From one of the case studies mentioned previously, we briefly examine each phase in order to predict possible views of the different actors.

In determining measurement goals, we need as-designed documents and construction specification. Depending on the nature of the properties to be measured, goals differentiate into specific methods of data collection. For example goals with geometric information require laser scanning in order to compare specific shapes from the as-designed and as-built models. Other properties, such as temperature (inside of concrete), can be measured using embedded sensing technologies. Even when a property has no geometric relevance, locating the sensors requires dealing with the as-designed geometry.

Once measurement goals have been determined, planning for each method of data collection proceeds. For a given construction schedule, as-designed model, and measurement goals, an embedded sensing plan is made by multiple decisions of when, where, what properties, how long, and which sensors are needed. In the case of laser scanner planning, a further goal is to optimize the use of the scanner to achieve a given set of measurement goals within the construction area.

Once the preparation for data gathering is completed, the actual data collection occurs at the construction site. Owing to the dynamics of the site, such as the placement or erection of temporary elements (e.g., scaffolding, formwork, etc), and changes (or differences) to the construction schedule, laser scanner path planning needs to be supported by mobile computing to update for obstacles in found at the construction site at scan time.

Laser scanning produces low data format geometry, namely, a three-dimensional point cloud. Although it is possible to visualize the as-built condition from this point cloud, as a representation, this low data format is computationally cumbersome for reasoning about deviations. Object recognition techniques convert the raw data into a higher-level representation suitable for comparisons with the as-designed model.

Subsequently in the sequence, the as-designed and as-built models are compared to look for discrepancies by overlaying the models, to within allowable tolerances described in the construction specifications. This visual inspection provides a more detailed comparison than the on-site traditional inspection method; additionally, eventually, we intend to automate this process.

Figure 1 illustrates a conceptual flow of project sequence. As can be observed, the flow is iterative and relates the different perspectives to the project model.

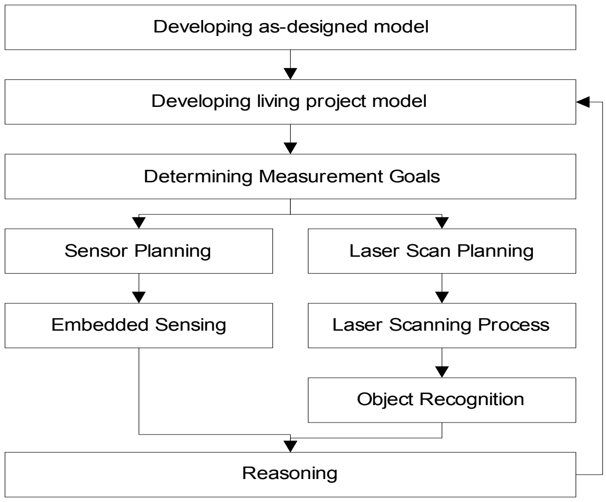

Figure 1. Conceptual Project Flow

2.2. CASE STUDY

For the case study, each individual view was defined in a specific way. In this section, we outline three different views on the living project model, namely, that of the construction inspector, embedded sensor planner, and laser scanning technician. It is important to note that when the as-designed model is incorporated into the building construction process, information reflecting the construction specification, owner and construction contracts, construction process model, and so on, will be accumulated into the living project model.

The construction inspector decides upon measurement goals, in order to reason about deviations. For this, the construction specification, the design specification, a detailed three-dimensional geometric as-designed model and the construction process model are required. The information must be categorized according to the required properties. For instance, geometrical elements need to be visually recognizable, their connectivity to other relevant elements clearly understood, and the information includes non-geometric data such as material type, construction process data and construction method.

An embedded sensor planner deals with planning and sensing of embedded sensors to collect data from a construction element. For this, element geometry, its location and construction process information are required. Furthermore, the construction method is required in order to relate material type to a specific time of installation. The as-designed model does not contain such information, and additional information is needed in the living project model.

In order to optimize scanner use to attain the laser scanning goals in a dynamically changing environment, the laser scanning technician employs a scanner path planner. From the path planner point of view, elements in construction site are either obstacles or goals; the net objective is to produce the shortest path for collecting data. The elements include static elements in the building such as walls, columns, doors and so on, and temporary elements on site such as scaffolding, forms, temporary stacks of materials and so on. Depending on the specific range of the laser scanner, goal location and elevation are crucial. For example, the Z+F scanner is able to scan 360° horizontally and 70° vertically with a maximum range of 25 meters (Gordon, 2003). Goals should be within that region to capture data of sufficient quality to be able to produce a three-dimensional as-built model.

Table 1 summarizes the information required for the different views (participants). For geometric aspects of the as-designed model, it is necessary to be able to generate information appropriate to the individual needs, for example, a full model view for the construction inspector, and a two-dimensional plan view for laser scanner path planning.

TABLE 1. Information required by different views

View	*Requirements*
Construction Inspector	• Design specification • Construction specification • As-designed model • Construction process
Embedded sensor planner	• Geometric information of target element • Location • Material type • Construction methods
Laser scanning technician	• Two-dimensional geometric information of the region around the target element • Geometric information of target element • Location

2.3. APPROACH TO A FLEXIBILE REPRESENTATION

2.3.1. Background Research; Defining Sorts

From the case study, it is clear that each view derived from a different domain arrived at an understanding of the current problem solution technique through a different view of the same model. Moreover, each view was augmented by its domain knowledge in order to provide a visualization of the problem. Sometimes, even within the same task, different representations of the same information to afford different solutions to different problems prove helpful, an example with respect to slabs is considered later in this paper (see figures 2 and 3).

Currently, modeling approaches to integrate building information extend to different disciplines and views. These allow for various representations in support of the different disciplines or methodologies, enable information exchange between representations and collaborations across disciplines. Current product modeling tools, such as ISO STEP (ISO: 1994), Industry Foundation Classes (IFC), and aexXML, an object-oriented data model for product information sharing (Bazjanac, 1998), can be characterized as an a priori and top-down, are mainly the target of software developers to ensure compatibility of their representation (Stouffs and Krishnamurti, 2004).

On the other hand, there are modeling approaches that consider a bottom-up, constructive approach. These approaches provide more flexibility that allows for developing the information model that is context and project specific, furthermore, enabling incremental changes to existing representations. For example, the SPROUT modeling language used in the SEED project is a schema-definition language that supports shared schemas from which other representations can be generated (Snyder et al, 1995; Synder and Flemming, 1999).

For our purpose, a representational schema is a relationship between representations as concrete descriptions and models as the abstract entities described (Requicha, 1980). We consider an abstraction of representational schema to model *sorts* that allows us to explore the mathematical properties of a constructive approach (Stouffs and Krishnamurti, 2002). In order to compare representational structures with respect to scope and coverage, we use compositions of primitive data types in a constructive approach to model the representational schema.

A *sort* is defined as a complex structure that consists of compositions of other *sorts*. At a basic level, a *sort* may be defined as a set of similar data elements, e.g., a class of objects or the set of tuples solving a system of equations. Accordingly, a comparison with other *sorts* addresses a comparison of respective data types, their reciprocal relationship, and overall structure. The elementary data type of *sort* is defined as a *primitive sort*, and the *primitive sorts* construct a *composite sort* under compositional operation.

TABLE 2. Some of predefined compositional operations

Operation	*Symbol*	*Behavior*
attribute	^	specifies a subordinate composition of *sorts*
semantic identification	:	assigning name to a *sorts*
sum	+	disjunctively co-ordinate composition of *sorts*

Sorts can be compared and matched, for example as *equivalent*, *similar*, or *convertible* (see TABLE 3).

TABLE 3 . Comparing sorts

Comparing	*Definition*
equivalent	both are semantically derived from the same *sort*
similar	similarly constructed from the same primitive components
strongly	constructed over equivalent *sorts*
weakly	derivations from primitive *sorts*
convertible	two *sorts* are not similar, two primitive *sorts* are differ only in their arguments and constraints

2.3.2. Example Approach To Case Study

As we can observe from Table 1, the requirements of three different views on the design model represent multiple ways to serve as domain specific view points. When the construction inspector decides upon the object to be inspected, detailed information of the target is provided to the other two actors, embedded sensor planner and laser scanning technician. The detailed information includes what, when, and where information should be collected in order to accomplish the inspection purpose. Two actors see the same object from their perspective. The embedded sensor planner needs the geometric information, location, material type, and construction method of the target object. On the other hand, the laser scanning technician needs two-dimensional geometric information of the target region, geometric information, and location of the target object. This is illustrated in Figure 2.

Here we define the geometric information of target object as the shape of the object, and the material type as a composite of the material types of the compound object. Figure 3 illustrates same target object view in the two *sorts* built from the same components using attribute relationship, but considers the components in a different order.

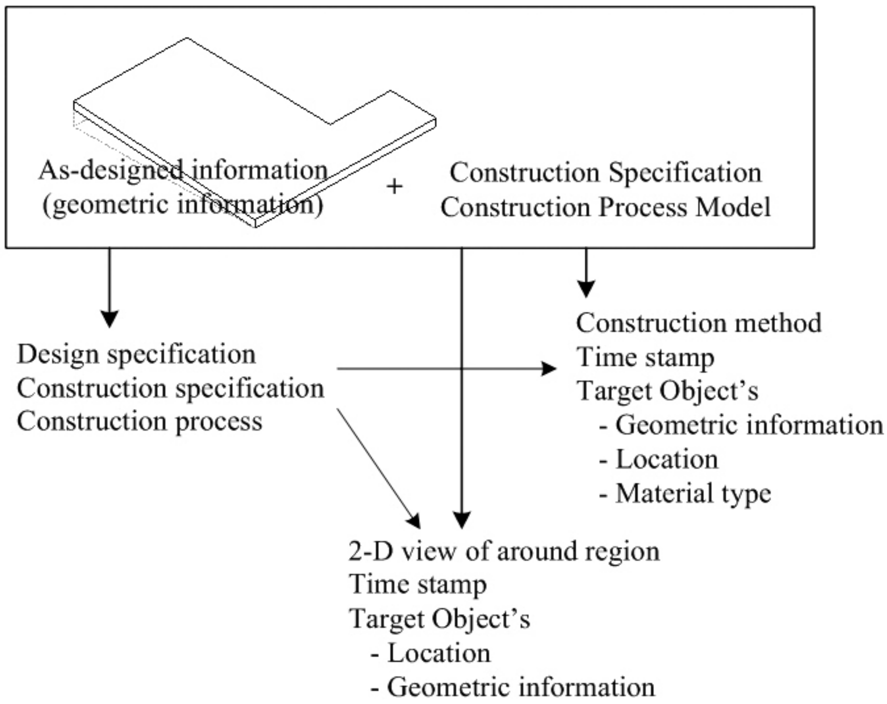

Figure 2. Different representational needs on a slab

In the first information view, embedded sensor view, the *materialtypes* sort is considered as an attribute to the *shape* sort, each ha an attribute having a collection of *location* sorts and each has a numeric array value of locations.

slab1_embeddedSensor_target1: slab ^ shape ^ materialtypes ^ location (1)

In the second data view, the *location* sort is instead considered as an attribute to the *materialtypes* sort, which itself is an attribute of a *slab* sort.

slab1_laserScan_target1: slab ^ location ^ shape^ materialtypes (2)

In this case, the laser scanning technician's view provides the location of the target slab instead of multiple material locations for the embedded sensor planner.

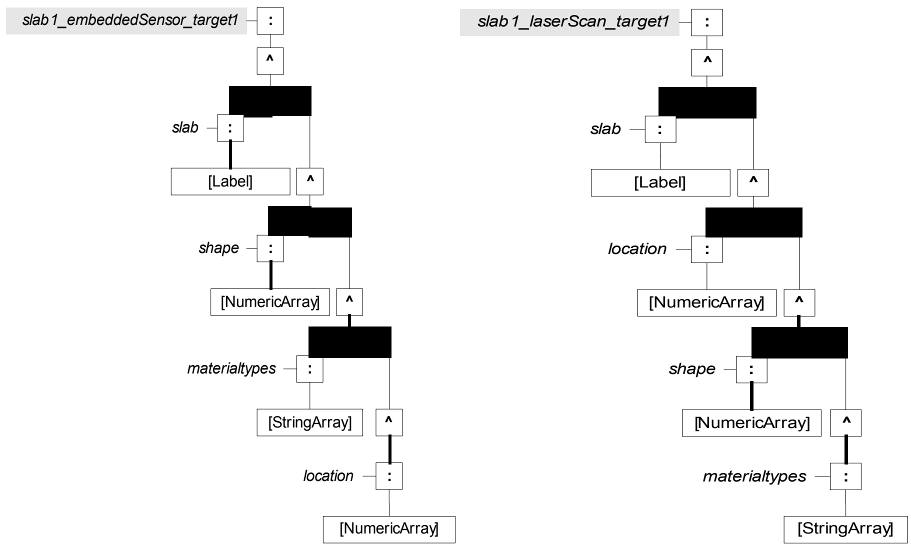

Figure 3. Example, diagrammatic description of two sorts

(The two sorts are considered convertible)

Exploring the representation for construction requires the ability to alter the representational structure by update, addition, and removal of compositional sortal relationships. In order to understand the scope and coverage of individuals, data recognition and design rules can be employed to facilitate building and manipulating sorts and corresponding data forms (Stouffs and Krishnamurti, 2004).

3. Conclusions

Through the case study, an integrated living project model (and its representation) is seen as a critical part of the project success. Especially important is being able to capture the dynamic changes of construction, including update, addition, and removal of data from the project model, and presenting an effective representation for the specific needs by the numerous experts. The idea of individual needs, a complex project model and its representation emphasizes the importance of user interaction.

We foresee that our further research into flexible design representation for construction will focus on database form, queries, and user interaction. These efforts will include how to integrate and maximize the use of collected data sets from the embedded sensors and laser scanning.

Acknowledgements

The project is funded by a grant from the National Science Foundation, CMS #0121549. NSF's support is gratefully acknowledged. Any opinions, findings, conclusions or recommendations presented in this paper are those of authors and do not necessarily reflect the views of the National Science Foundation.

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