OUTLINE OF A SYSTEM FOR SENSOR-DRIVEN, HIGH-RESOLUTION BUILDING MODELS

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SUMMARY

The continuous monitoring and evaluation of the performance of buildings and products, in particular during construction, operation, and de-commissioning phases is not well established and currently limited to a few safety- and mission-critical systems. We introduce sensor-driven, high-resolution building models (SDBM) that could provide more comprehensive and detailed information on the structure and state of a facility over space and time from pre-construction to demolition. Enabled by sensor technologies that permit the location and identification of building components in 3D space, SDBM would be capable to detect certain changes occurring in a building and automatically construct and update a detailed, structured building model. Such a model could provide services to applications in domains such as building automation and facility management. We outline a general system architecture for SDBM. Furthermore, we describe the features of a system for the simulation-assisted lighting control domain that will serve as a testbed for SDBM.

INTRODUCTION

There is common agreement that the quality and cost effectiveness of services in the building industry can and should be improved significantly. Realizing only a fraction of this potential could lead to significant savings because of the size of the construction industry. In industrialized countries, construction, and operation of built infrastructure represents approximately 8-12% of the economy. About 35% of the primary energy is consumed in the building sector, and buildings affect health and the productivity of the workforce, as over 90% of the average person's life is spent indoors. Other industries and service sectors have implemented strategies that have led to improved products and services. However, in the design, construction, and operation of buildings, performance assessment and evaluation for products and services has not been well established. One barrier for improved assessments of buildings is a lack of performance data and feedback/forward of such data to designers and engineers, facility operators, manufacturers, occupants, and owners.

Work in continuous data collection and monitoring exists in building automation and preventative maintenance. Although solutions are available for preventative maintenance of safety- or mission-critical systems such as elevator and office equipment (Otis 2002, Pitney-Bowes 2002), these cover only a small fraction of the information that could be potentially useful. What is lacking is a systematic and comprehensive approach to facility state information that would make the data accessible throughout the life cycle. If overall facility performance is to be tracked and analyzed, it is necessary to also consider 'inert' or 'grey' matter in buildings such as surfaces, furniture, manually operable windows and doors, which, although traditionally thought of as static, also change over time. For example, studies on churn rates and churn cost in office buildings suggest that significant physical changes can occur in workplace configurations over relatively short time periods (IFMA 1997, Ryburg 1996). Through appropriate sensing infrastructures, components affected by such changes could be made available for detailed performance analysis as well.

While this seemed like an unrealistic proposition just a few years ago, we believe that the enabling technology is increasingly available. Sensors and wireless communication devices are rapidly becoming smaller and cheaper, thus allowing for use on a wide scale. It is technologically feasible for manufacturers to embed small tags into products. Tags can carry an identification number, and can be interrogated by remote readers. The use of such sensing technology in the building context could have several implications: *i)* as-built and as-maintained digital building models become feasible that are derived automatically rather than manually; *ii)* The human bottleneck, which currently limits the size and resolution of computer-aided facility management and building automation models, can be overcome or at least significantly reduced; *iii)* with small, inexpensive tags and two-way communication devices embedded in products by manufacturers and in other components, building models can be constructed with far greater detail than current models; *iv)* quasi-real-time snapshots of a facility's state become possible; *v)* modifications to a facility's configuration over time can be tracked.

DEFINITION

Since little work exists in this specific area, it is useful to begin with a working definition for sensor-driven, high-resolution building models (SDBM):

Sensor-driven, high-resolution building models provide comprehensive and detailed information on the structure and state of a facility over space and time from pre-construction to demolition. This involves the description of individual systems and components, their spatial arrangement, and behavioral aspects at the facility, systems, and component levels. A model is constructed largely automatically, updated in real-time, and supplied with information through sensors and communication infrastructures placed across a facility.

The concept of SDBM's raises the following issues.

Model resolution: Desired space-time resolutions for building models are dependent on the information needs of particular users and applications, that is, the consumers or clients of the information captured by a building model. Building models can be highly structured and include spatial as well as semantic information.
Model derivation: Mapping algorithms need to be developed that are suited for the automated derivation of such structured building models from sensor data. This is a non-trivial problem since certain client applications implement abstract concepts such as 'space', which may not necessarily have a direct correspondence to physical building components. Some form of processing and inference is therefore required.
Sensor configuration: Depending on the required model resolution, the kind, quantity and placement of sensors need to be determined for a particular building component. Sensor readings should permit the unambiguous and automated generation of continuously updated building models. A communication infrastructure needs to be configured and installed that facilitates sensor readings and transmission of sensor data. Sensor configuration factors include desired model resolution, data read/write capability of sensors, desired accuracy, frequency and reliability of sensor readings.
Event handling: Buildings are exposed to various agents of change, including humans, weather, depreciation, and aging of materials. Building models need to be notified of these changes and adjust themselves accordingly. Events might be explicitly invoked by human operators or controllers, or detected during routine sensor readings. Schedules for sensor readings need to reflect the diverse dynamics in a facility.
System performance: With the implementation of a prototype system for the lighting control domain, we will be able to evaluate performance with respect to accuracy, responsiveness, robustness, and scalability.

RELATED WORK

Developments in related research areas are summarized and their relevance discussed in the context of SDBM's introduced above. The research areas are: building automation systems, self-aware buildings, computerized maintenance management systems, machine vision, and sensor-driven computing.

Building automation systems

The rationale behind building automation systems is to improve occupant comfort and to operate buildings more efficiently (Kelly 1998). Building automation systems utilize sensors to measure, for instance, illuminance, air quality, or temperature in a room. Several communication protocols exist or are under development in order to facilitate the integration of sub-systems such as lighting and heating, ventilation, and air-conditioning (see, for instance, EIB 2002, LON 2002). The LUXMATE system is an example for a commercial product aimed at balancing natural lighting and artificial lighting in office buildings (Zumtobel 2002). Conventional lighting control systems are limited at least in two respects. First, related factors such as glare, thermal performance and comfort implications are not considered. Second, certain changes in space layout require a manual recalibration of the system. Thus, the effectiveness of lighting controllers could be improved through access to automatically generated, real-time building models.

Self-aware buildings, self-organizing building models, simulation-based control strategies

A main intellectual root of the present work stems from representational and methodological advances in the area of building control. Of specific relevance is in this context the idea of self-aware buildings (Mahdavi 2001a, 2001b) that rely on self-organizing models with the built-in potency of real-time and predominantly autonomous evolvement and adaptation with regard to changes in building context, structure, systems, status, processes, and occupancy. A self-aware building possesses thus an internal (dynamic) representation of its own systems and can use it toward self-regulatory determination of its status. As such, the functionality of a self-aware building requires the realization of a self-organizing building model. Self-organization is supported by sensor-based real-time monitoring of indoor and outdoor environmental variables as well as building status monitoring in view of components, systems, processes and occupancy. The process control functionality (e.g. for indoor environmental systems) in a self-aware building can be supported through a simulation-based strategy (Mahdavi 2001c, 1997, Mahdavi et al. 2000). It can be argued, that the central impetus for envisioning self-organizing models was the emergence of proactive building control strategies that rely on the predictive capacity of embedded knowledge sources (particularly simulation applications). Behavioral models could be thus integrated within the building automation system of a self-aware building, and thus facilitate the virtual exploration of the control state space of the building's environmental systems (e.g. for heating, cooling, ventilation, lighting).

Computerized Maintenance Management Systems (CMMS)

Computer-aided Facility Management (CAFM). Computer-aided facility management (CAFM) systems were originally introduced as derivatives of computer-aided design (CAD) systems. As CAFM evolved and increasingly diverse tasks and data formats needed to be accommodated, CAD-centered applications were replaced by systems organized around databases. Most of the data maintenance tasks performed in CAFM are manual, which, in particular for large buildings or groups of buildings, is labor intensive and often lacks the necessary accuracy, consistency, and timeliness (Clayton et al. 1998). Anecdotal evidence suggests that, for large organizations, it is too costly to build even simple models of the building stock (Gauchel 2000). Thus, techniques are desirable to automate these routine data maintenance tasks to the greatest extent possible and to give FM personnel more time for value-added tasks such as diagnostics, planning, and priority response.

Remote building monitoring systems

Remote monitoring systems have become increasingly common for infrastructure with high safety and reliability requirements (Deb et al. 2000). The motivation for these systems lies in the minimization of down-time and streamlined maintenance operations. Otis, for instance, offers monitoring systems for elevators based on sensors capable of tracking more than 300 elevator system functions (Otis 2002). Real-time data is transmitted to remote diagnostics centers and analyzed with computational tools such as statistical analysis, data mining or rule-based algorithms. At present, these kinds of systems tend to be standalone in a sense that they are aimed at monitoring specific systems rather than whole buildings.

Machine Vision

Efforts are underway in the robotics and artificial intelligence community to devise systems capable of automatically computing digital models from a range of images taken from a scene without explicit location information. Mobile robots have been developed for decommissioning and decontaminating nuclear plants which are also capable of semantic interpretation of the environment. In this case, a geometry is matched against geometries stored in a library (Broz et al. 1999). The use of machine vision in building operation services, for example, is appealing as it would not rely on identification tags that is often attached to equipment. However, there are at least two barriers with regard to using machine vision in the building operation services context. First, hidden building components such as air ducts and structural components cannot be tracked (line-of-sight problem). Second, the recognition of building component classes might be feasible in principle, but discerning instances of the same class would be next to impossible. Non-physical information such as purchase date or cost thus could not be derived by a machine vision system alone.

Sensor-driven computing

Computing paradigms such as ubiquitous computing, context-aware computing, sentient computing or augmented reality systems rely extensively on sensors to create models of the real world (Weiser 1991, Feiner et al. 1993, Schilit et al. 1995). In augmented reality systems, views of the real world are enriched and superimposed with a virtual world. Applications include augmented reality for construction, inspection, and renovation (Webster et al. 1996). Webster et al. describe a scenario where technicians equipped with see-through head mount displays detect hidden structural columns in a space. The system uses static building models that are derived manually from construction drawings.

Sensor-driven, high-resolution building models would perhaps be most closely related to the field of context-aware or, more specifically, location-aware computing (Want et al. 1992, Harter and Hopper 1994, Ward 1998). Context-aware applications in general are capable of adapting their behavior to changes in the environment (Harter et al. 1999). Location-aware applications use sensor-based positioning systems to gather information about objects of interest, which include personnel, computer monitors, and printers. We believe that location-aware applications and SDBM's could complement each other. In location-aware applications, most building infrastructure is assumed to be static. Rather than relying on construction drawings that are costly to maintain and might lack accuracy, information in automatically updated building models could be reused by these systems. On the other hand, an advanced lighting controller, for example, might access data collected by a personnel tracking system. Positioning systems developed for tracking people in indoor environments could play a crucial role as enablers of sensor-driven, high-resolution building models.

SYSTEM OUTLINE

A general architecture for an SDBM system is outlined for an example application domain. Usage scenarios for that domain are presented, and the system layers and subsystems explained. Requirements and candidate technologies for one key subsystem, the building component locator, are described.

Selection of an application domain

SDBM's could be useful in a range of settings and life-cycle phases, including construction (e.g. monitoring of construction process) facility management (e.g. inventory management, space layout management) and building automation (e.g. remote user control of light fixtures or air conditioning systems via a graphical interface representing facility state). Ideally, a model would be set up to serve multiple applications simultaneously. Simulation-assisted lighting control is used as an application domain to illustrate how a system for sensor-driven, high-resolution building models might operate (Mahdavi et al. 2000). Simulation-assisted lighting control is chosen because it relies on detailed, three-dimensional building information and could benefit significantly from timely, automatically updated information about a facility's state. Current implementations implicitly assume that the internal models are updated manually by facility operators when a space configuration changes. This task could be automated by SDBM.

Scenarios

The following scenarios described provide a high-level view of system usage. The scenarios involve the installation and operation an office space.

Space set-up. Prior to the space set-up phase, sensors are embedded into components, equipment, and products by manufacturers, construction contractors, and installers. Networked sensor readers are installed and linked to data storage devices. Readings of the sensors during the set-up phase and corresponding updates of the emerging building model are performed. A supervisor can track work progress remotely on a 3D display.
Events detected during normal operation. The lighting control system is utilized during normal operation. The following events occur: *i)* facility personnel adds a new partition to the space; *ii)* facility personnel moves a partition; *iii)* facility personnel removes a workplace from the space; *iv)* an occupant enters/leaves the space. The changes caused by these events are detected by the system during scheduled or routine sensor readings, and the model is adjusted. The lighting controller accesses the updated model and resets light fixture ballasts and/or window blinds accordingly in order to ensure a target illuminance level on the work surface.
Events invoked during normal operation. Changes in the environment invoked through actuators of the lighting control system are directly propagated within the model. Events include: i) the lighting controller adjusts ballasts; ii) a supervisor modifies the assignment of light fixtures to control groups; iii) an occupant adjusts window blinds, iv) an occupant adjusts the target illuminance. Sensor readings are performed to verify that an action had its desired effect.

System architecture

The lighting control system is organized into functional layers and subsystems (Figure 1).

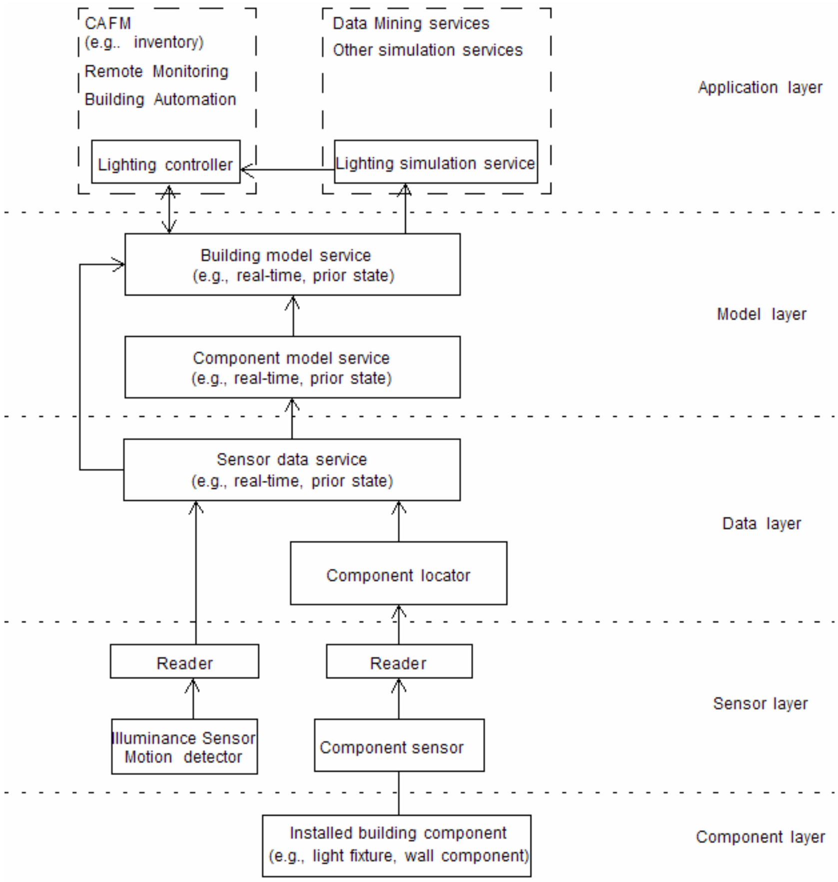

Figure 1 Functional layers of the lighting control system. - Note: for simplicity, the communication link between the lighting controller and ballasts is not shown. Arrows indicate information flow between subsystems.

Component layer (bottom layer). The component layer includes all physical building components installed in the space. For the lighting control system, the product layer would comprise visible, space-defining components such as wall partitions, openings (doors and windows), ceiling and floor

surfaces, tables, and light fixtures.
Sensor layer. Three types of sensors would be required in the lighting control system. Illuminance sensors measure indoor and outdoor lighting conditions. Motion detectors sense the presence of occupants in the space. Component sensors are used to measure distances between building components and readers.
Data layer. Sensor readings are coordinated by a sensor data service, which is further responsible for organizing and storing sensor data. Lighting measurements and motion detection signals are passed directly from readers to sensor data services. A component locator manages distance readers and sensors. It processes component sensor readings and uses multilateration techniques to determine the actual position of a building component. This information is passed on to the sensor data service.
Model layer. A component model service requests sensor data from a sensor data service, processes and matches that data with component models. Component information reflects the state of relevant properties of individual, physical building components. It does not consider relations to other components. The building model service processes that component information, requests data from occupancy sensors, and generates structured building models through mapping procedures. Both component and model services maintain historical records which can be accessed by other applications and services.
Application layer (top layer). In case of the lighting control domain, the application layer could consist of a lighting controller application and lighting simulation service. At the controller's request, the lighting simulation service would retrieve updated building information from the building model, run a simulation and return the results to the controller. Through actuators, the lighting controller would adjust the ballasts (or, if applicable, window shades). The controller would further pass the new state of the controlled entity back to the building model service. Sensor readings might be performed after the model update to verify that an action had its desired effect. Besides other applications, this layer could further include utility services (e.g. data mining) accessed by multiple applications.

Requirements for the building component locator subsystem

Wireless sensor technology. Due to the potentially large number of component sensors involved, transmission of sensor data should occur via a wireless link. Furthermore, sensors should be interrogated remotely, that is, readers should be stationary rather than portable.
Size. Sensors need to be small enough to be embedded in products without affecting visual appearance.
Cost. Sensors need to be inexpensive as a large quantity is required.
Maintenance. Due to large quantities, potential lack of accessibility, and multi-year observation time frames, sensors should not be battery-powered. Furthermore, sensors need to be resistant against typical indoor/outdoor conditions as well as various forms of pollution such as dust, paint, and grease.
Spatial information. Three-dimensional location and orientation information is required for most building components. In existing location systems, location can be determined by a generic procedure which typically involves some form of multilateration of distances between an object and known reader locations (Ward 1998). The computation of an object's orientation is more involved as it is dependent on object-specific parameters such as shape, sensor placement and quantity. However, due to constraints and redundancies that characterize many buildings, orientation might not need to be tracked explicitly for every component.
Position/orientation tolerance. For the proposed scenarios, we consider a tolerance of 30 cm in position and 30 degrees in orientation (95% confidence level) to be acceptable. Existing positioning technologies achieve a tolerance as good as a few millimeters in position and one degree in orientation (Ward 1998).
Reading frequency. Tracking building infrastructure appears different from tracking people in several ways. For building components, acceptable time intervals between readings may vary between minutes, hours, and days rather than milliseconds, seconds and minutes, as is the case in people location systems. High-frequency, parallel tracking of multiple moving objects will typically not be necessary. Thus, synchronized location measurements, which are performed to track moving objects, are not required. Altogether, these less demanding sensor reading requirements will probably give building component location system developers more design flexibility as speed may not be as critical for system performance.
Scalability. It can be assumed that complete multi-storey buildings involving thousands of sensors should be trackable.

Candidate technologies for the building component locator subsystem

Wireless sensor technologies have matured to a point where they are used on a large scale in the manufacturing (e.g. in the car industry), wholesale and retail sector (e.g. in sales), and personnel location in facilities (see, for instance, TI 2002, ATT 2002). Active Badges are an example for wireless, ultrasound location sensing technology used to track individuals in buildings (Want et al. 1992). Furthermore, radio frequency identification (RFID) technology appears to be well suited because of its significant potential as a scalable, relatively inexpensive sensor technology (Finkenzeller 1999). "Passive" RFID tags do not require a battery and can thus last almost perpetually with minimal or no service required. Compared to battery-powered active tags, passive tags have a relatively short reading range between several inches to several meters. The use of RFID technology in indoor environments is currently limited in several respects. Reflections, deflections due to metallic objects, the number of people in a building, and air humidity are among the environmental factors that can have a negative impact on the performance of an RFID system, especially on the accuracy of location readings.

IMPLEMENTATION PLAN FOR A SYSTEM PROTOTYPE

We plan to implement a prototype system according to the scenarios and specifications described above to test the feasibility of SDBM's. For that purpose, an office space with moveable partitions and flexible layout will be installed in the Building Physics laboratory at Vienna University of Technology. A simulation-assisted lighting control will be deployed in the test space. In order to provide a certain level of illuminance in an office, daylight, electrical light, or a combination thereof can be used. Instead of a direct mapping attempt from the desirable value of an objective function to a control systems state, the simulation-based control adopts an 'if-then' query approach (Mahdavi 1997). The simulation results are organized in a table and ordered (ranked) according to the objective function. In the test scenario, we will initially use workplace illuminance levels with minimal artificial lighting as the objective function and plan to add other objective functions such as glare factors and impact on energy use.

We will use the program LUMINA (Pal and Mahdavi 1999) for the prediction of light levels in the physical space. LUMINA utilizes the three component procedure (i.e. the direct, the externally reflected, and the internally reflected component) to obtain the resultant illuminance distribution in buildings. The model is based on the notion of 3D spaces consisting of a space enclosure, windows, and artificial light sources. We expect that if a model can be populated with such structured, three-dimensional information derived from sensor readings, this should also be feasible for other, informationally less demanding domains. Component sensor placement will be determined by the lighting simulation requirements. Alternative component sensor configuration schemes will be explored in order to achieve desired accuracy, robustness, responsiveness, and scalability of the generated model with a minimum amount of sensors.

The approach with respect to the building component locator subsystem is twofold. An off-the-shelf ultrasound-based system will be used to determine the location of building components. It has a relatively high location accuracy of 0.3 m or less compared to 10 feet of a similar commercial RFID-based system. We believe that the ultrasound-based system is otherwise not well-suited as a building component locator system. For example, tags are relatively large and battery-powered. Nevertheless, we consider the system sufficient for the purposes of the system prototype, where location accuracy is crucial to derive accurate building models.

The system will be tested according to the scenarios for space set-up and normal operation described earlier. The performance of the lighting controller with respect to the various events that can occur in the test space will be measured and assessed. All data will be saved in a database and made available for visualization and chronological analysis, for instance, of the space assembly process.

CONCLUDING REMARKS

We introduced the concept of sensor-driven, high-resolution building models (SDBM). We believe that such models could benefit several domains in construction, facility management, and building automation. With models that automatically update themselves to reflect changes in the built environment, the human bottleneck, which currently severely limits the size, accuracy and resolution of most models, could be overcome or at least significantly reduced. Dynamic changes in a facility, if collected systematically and, ideally, in real-time, could provide valuable information and feedback to a number of building professionals and companies, not least to building designers, who currently know very little about the long-term behavior of their products.

Sensing technologies, in particular positioning technologies, are maturing rapidly to make their deployment in buildings increasingly feasible. Clearly, the availability of enabling sensing technologies at low cost is crucial for the practicality of SDBM. As sensor technologies are expected to continue to evolve, we plan to design and implement the prototype system as independent as possible from the characteristics and constraints of specific sensor products. With such a decoupling, the system can be adapted and extended more easily.

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