Development of a Remote Building Monitoring System

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ABSTRACT

We describe the design, development and initial operation of a prototype system which permits remote monitoring of multiple heterogeneous commercial buildings across the Internet from a single control center. Our system is distinguished by its ability to interface to multiple heterogeneous legacy building Energy Management Control Systems (EMCSs), its use of the Common Object Request Broker Architecture (CORBA) standard communication protocols, development of a standardized naming system for monitoring points, the use of a relational DBMS to store time series data, automatic unit conversion, and a scripted time series visualization system.

We discuss design decisions related to the selection of CORBA and a relational DBMS implementation. We also discuss related standards efforts such as BACnet and the International Alliance for Interoperability.

We conclude with discussions of the HVAC system data and future work.

Introduction

This paper updates the discussion of our Remote Building Monitoring and Operations (RBMO) Project previously described in (Olken, 1996). Our motivation, discussed at length in our first paper, is to reduce energy usage of buildings.

Our system is based on utilizing the capabilities of a legacy (pre-existing) Energy Management Control Systems (EMCSs) which controls the HVAC (heating ventilating and air conditioning equipment) in commercial buildings. EMCSs are commonplace in large commercial buildings (see references in (Olken 1996).

This project is developing software systems to support remote monitoring and control of multiple buildings, i.e., HVAC, lighting, etc., across the Internet, using CORBA - Common Object Request Broker Architecture protocols. It is intended to work with heterogeneous EMCS and HVAC systems

We are also developing a remote building monitoring and control center which provides data visualization, database management, building energy simulation, and energy usage analysis tools. The ultimate users of the system will be owner/operators of multiple buildings e.g., U.S. GSA (federal buildings), school districts, universities, retail chains, banks, property management firms, ESCOs, utilities, et al.

The research project has two primary goals: demonstration of technical feasibility of the proposed design, and demonstration of the utility of the system. Close attention and careful analysis of the data from building EMCS's typically affords many opportunities to improve building operations, resulting in improvements to occupant comfort and reductions in energy use.

However, for most buildings, such close attention and analysis are not undertaken due to lack of appropriate software, operator training, staff, or inaccurate/malfunctioning sensors. Remote building monitoring offers the possibility to reduce the labor costs involved in monitoring/analyzing EMCS's by spreading such labor costs over a large number of buildings. This will also make it economically feasible to employ expert HVAC engineers.

An overview of the RBMO system is shown in **Figure 1**.

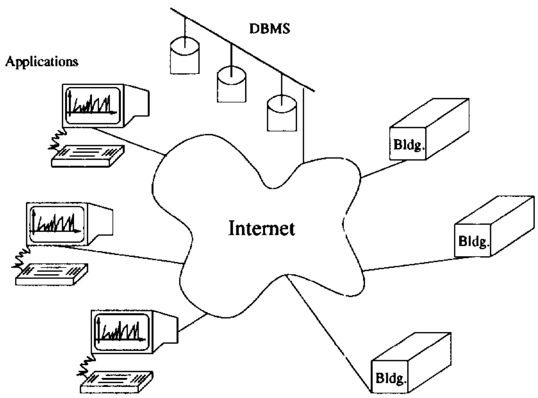

Figure 1: The RBMO system setup.

Use of the Internet, as underlying communication infrastructure, has two aspects: use of the Internet communications protocols, and use of the actual Internet network.

Use of Internet *networking protocols* permits access to a wide variety of affordable interoperable hardware and software from many different vendors over many different media. Internet markets are huge, in the millions of users, hence vendors can readily amortize development costs.

Use of the Internet *network* permits users to share the costs of a common communications infrastructure. The downside of using the public Internet is the necessity of more stringent security precautions, discussed further below.

Background

Building Data Model Standards

ASHRAE in 1995 approved a new communications standard, for building automation systems – The Building Automation and Control Network (BACnet) Standard (ASHRAE, 1995) (Butler, 1996). This standard views the HVAC (Heating, Ventilating and Air Conditioning) system as a collection of objects. However, the standard does not (yet) include standard applications–level objects such as chillers or cooling towers. We expect that BACnet will shortly be used to connect building gateways to EMCSs.

The International Alliance for Interoperability (IAI 1996) is a consortium of architectural/ engineering/ construction software vendors (e.g., Autodesk and Bentley Systems) who are working on developing a standard data model for description of buildings. The data model is intended to be used by architectural and engineering design tools, construction cost estimation software, construction scheduling software, etc. We are tracking these efforts for use in our naming conventions for monitoring points. Unfortunately, the portion of the standard concerned with HVAC specification and control has yet to be completed.

The Common Object Request Broker Architecture

The Common Object Request Broker Architecture (CORBA) is a standard for distributed computing which has been developed by the Object Management Group (OMG) (OMG, 1996), a consortium of independent companies. CORBA aims at providing a uniform communication infrastructure for building distributed applications. It supplies unifying mechanisms for interoperating software components, operating on various hardware platforms, and running under different operating systems implemented in different programming languages.

Interoperability is gained by specifying all component interfaces in a universal interface definition language (IDL). IDL is a declarative 'lingua–franca' for specifying interfaces, following a C++–like syntax, (Mowbray 1995).

RBMO System Design

In this section we describe the architecture of the RBMO system in further detail, motivate our primary design decisions, and describe the following components of the system:

- Gateway systems in each building
- Data acquisition sub–system
- Applications–level object specifications and unit conversion
- Time series database

System Architecture

The RBMO system architecture is shown in **Figure 2.** It constitutes a three tier architecture with the individual components being: the applications, the database management system, and the building gateway system. The individual tiers are entire sub–systems inter–connected through the Internet via CORBA adaptors.

The system has been designed in a modular manner to ease the evaluation of alternative technologies for database, user interfaces and visualization components (cf. Section). The following subsection will describe the individual components and their design in further detail.

The RBMO system constitutes a highly heterogeneous system incorporating several different hardware platforms and operating systems, ranging from extremely proprietary systems (building EMCSs) to common platforms (Sun workstations/UNIX and PC/NT). This large heterogeneity was the primary motivation for using CORBA instead of alternate proprietary protocols, such as OLE/Active X/DCOM. Other candidates were SNMP, MMS, and netDDE. For a fuller exposition of protocol issues

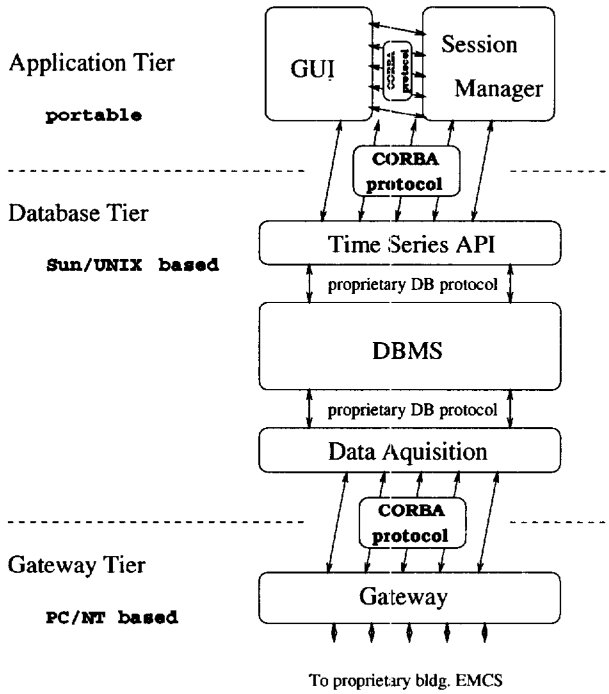

Figure 2: RBMO System Design

see either our earlier paper (Olken et al. 1996) or web site (Olken, et al. 1997). For additional information on MMS see (Castori 1997) (including a bibliography). For information on SNMP see (Cohen 1995), (SNMP Research 1997), (IETF SNMVPv3 Working Group 1997), (SimpleGroup 1997). For netDDE see (Wonderware 1996).

Gateway

The system architecture requires that each participating building have an internet point-of-presence, also referred to as a building "gateway". These building gateways are addressed in the usual internet fashion (e.g. northTowerBuilding.myCompany.com). Within the gateway itself, further addressing of building-specific objects (more below) is accomplished by a CORBA-compliant object request broker (ORB). The gateway ORB acts as a mediator between incoming CORBA object references and the actual objects resident in the gateway process. Currently, building gateways are Pentium-class PCs running the Windows NT operating system.

One of our goals was to present a network view of a building's monitoring and control data that was consistent across multiple buildings - regardless of EMCS system differences.

The building data point database portion of the gateway contains entries for all building monitoring and control data points accessible through the building's EMCS. Each entry contains attributes for units, point name, and description, as well as methods for reading and modifying values. Since this database has to mirror that of the EMCS itself, methods have been developed for deciphering and re-creating data point lists for each vendor-specific EMCS encountered. Specific attention has been given to mapping data point units information from vendor or installation-specific descriptions to standard representations. Standard units representations are required for automatic unit system transformation facilities located further downstream.

The EMCS adaptation layer is responsible for interacting with the building EMCS via the specific communications formats and protocols required by the EMCS vendor. In some cases, e.g., interfacing to the EMCS in Soda Hall, this involves use of proprietary message protocols using standard serial communications media. In others, e.g., interfacing to the EMCS in the Oakland Federal Building, the netDDE protocol over LAN-based media is used. In all cases, specific message formatting and handling algorithms are encapsulated in methods associated with each element of the internal data points database (see above) and vendor-specific differences are not visible above the EMCS adaptation layer.

The external CORBA interface layer provides a common layer of C++ objects that are accessible to the gateway's ORB. These objects have full access to the internal data points database and are able, through appropriate overloaded methods, to query the EMCS system for current monitor and set point values.

Data Acquisition System

Our telemetry data on the building state are initially available as cross–sectional data, i.e., we sample the entire building state periodically, typically at 1–5 minute intervals. However, typical analyses use only a few state variables, but will typically want to look at long time series of each such state variable. Thus it is expedient for analysis purposes to have the stored data in a separate time series for each state variable, a database design known as transposed files..

The question then arises as to when and where the data are to be transposed from cross–sectional to time series storage formats. Transposition at collection time slows the collection process, but speeds the analysis phase. Transposition at analysis time permits very fast data collection, but slows the analysis phase. We have chosen to transpose the data at the database server as it is collected. For a more detailed discussion see (Olken 1996).

The data acquisition system (DAQ) presently is a polling system residing on the central server together with the time series DBMS. Placing the DAQ on the TS DB server is useful for performance reasons as the DAQ does a lot of I/O to the DB server.

Measurement Units and Time Zones

In dealing with multiple buildings we were forced to confront the diversity of the measurement units employed for various monitoring points and EMCSs. There are 3 approaches to dealing with this issue: (1) record all measurements as pairs (value, units), (2) record the units for each monitoring point as part of the metadata for the monitoring point, (3) record all measurements in canonical set of units.

Conventional practice in EMCS systems is method 2. The IAI data model adopts method 1. However, the variation in measurement units across monitoring points and EMCSs render comparisons and computations in the DBMS awkward. We have adopted the convention of storing all measurements in standard SI (metric) units in the DBMS (the conversion is done by the data acquisition system). This expedites the construction of indices and comparisons or computations in query processing. We plan to permit users to specify a preferred systems of units for display of query results.

Similar difficulties arise with time zones. There are two problems - a collection of monitored buildings may span multiple time zones (e.g., a large retail chain), and the use of daylight savings time introduces anomalies. We address both problems by converting all timestamps to UTC (Universal Coordinated Time (a.k.a. Greenwich Mean Time (GMT)). This is done in the data acquisition system prior to storing data.

Naming

One of the most vexing problems in developing the system has been the heterogeneity of names across building EMCSs. It seems that every building has its own naming conventions, and these may actually vary between building drawings and the control system documentation. In addition to naming variation, EMCSs often employ cryptic abbreviations of these names.

In order to support centralized monitoring, inter-building comparisons, aggregation of energy use across buildings, etc. one needs consistent naming of comparable measurements.

Names are comprised of two components: a generic designation (reflecting the data model) and an instance designator (reflecting a particular object - a proper name). Thus the generic name component might be chiller cooling water inlet temperature, and the instance designator would be Chiller 3.

In our system, name conversion from local (building EMCS names) to application names is done in the data acquisition system prior to storage in the database.

Time Series Database

The bulk of the data we are collecting will be time series, e.g., of temperatures, power usage, etc. Although the raw data may be slightly irregular time series, we will transform these to regular time series for analysis. Regular time series assume periodic temporal sampling. Hence, our most important criterion for selection of the database management system (DBMS) is its suitability for time series data and queries.

Irregular time series are employed in some EMCS systems. Repeated measurements which fall within a dead band are suppressed. Such systems are referred as change of variable (COV) monitoring systems. COV systems consume less communication bandwidth and storage. Multiple irregular time series are more difficult to deal with in a DBMS or analysis setting and require the software to perform temporal joins.

It is possible to support regular time series data on any of several DBMS: relational, object-oriented (OO), or hybrid object-relational. Use of relational DBMS for regular time-series data typically offers mediocre performance, weak support for operations such as smoothing and calendars. Object-oriented DBMSs permit the implementation of time-series data collections with better support for calendars, smoothing, etc. However, no commercial object-oriented DBMS yet provides off-the-shelf support for time series data, so the user must code his own. In contrast, one of the hybrid object-relational DBMSs, Illustra (Illustra 1996), offers built-in time-series support. Also, Oracle has recently released a similar time series package.

Most of the data which are not time series are building description data - i.e., CAD (Computer Aided Design) data describing the physical configuration of the building, HVAC system, and the EMCS system. Object-oriented DBMSs (OODBMSs) are generally much better suited to CAD data than relational DBMSs (RDBMSs), both because the object data model is more closely matched to CAD data modeling requirements, and because OODBMSs typically offer much better performance for CAD applications. Indeed, CAD applications were the primary drivers for the development of OODBMSs.

CORBA interfaces, for at least some of the commercial CORBA implementations, are available for several object-oriented DBMSs, but not yet for most of the relational or hybrid DBMSs. However, Oracle has announced it intends to support CORBA interfaces. Third party CORBA interfaces are available for relational DBMSs (I-Kinetics 1997).

Support for client-server DBMS configurations is typically available for all of the DBMSs. This will allow us to move the analysis and visualization codes to the PC-workstations while maintaining the database on a robust database server.

The RBMO applications software

The RBMO applications are designed around providing the following three capabilities:

- Archiving historical time series data in a database
- Providing visualization means for building energy performance analysis
- Performing a series of regressions and statistical analysis techniques to (1) define "baseline" conditions and (2) evaluate energy performance after a retrofit, operations and maintenance changes, occupancy changes, or for historical tracking.

The archiving and visualization applications presently run on Sun workstations. We envision, however, that a future deployment of the visualization and statistical analysis applications will primarily be PC-based, running Windows NT.

We are developing a standard set of performance tracking plots to allow users to view archived data with a user–friendly menu. This includes daily (24-hour) load shapes of 5-minute operating data for all values; weekday, weekend, and weekly load shapes (hourly data); and monthly average load shapes. The chiller and cooling plant analysis will consist of plots such as power versus cooling load (kW versus tons) and efficiency versus load (kW/ton versus tons).

The applications are intended for use by a remote expert. Most of the focus on the graphics is on energy use. However, the capability exists for the user to look at detailed data such as time series of cooling plant water temperatures or cooling tower fan start–stop intervals. The concept is to provide a tool for a remote user who might be responsible for tracking the performance of building systems at multiple locations. The menu of standard graphs are designed to allow the user to easily view the most critical, macro–level performance data, while providing additional means for more detailed analysis of micro–level data. In other words, the scripted graphs should allow the user to answer the question, "is the building and cooling plant operating well?"

To enhance the application extensibility we have developed a scripting language which drives the visualization and GUI software. See **Figure 3**. Most of the common plots already exist as scripts which need simply be run by the user. Certain extensions and additions may, however, either be performed online or by preparing a script. Below we show several extracts of such scripts to illustrate their capability.

We plan to integrate some control capabilities into the system. This will require the availability of a secure version of CORBA, not yet readily available.

```
// Example 1, defining a plot

NAME = "Chiller Elec. Power Use";
SESSION = { DISPLAY = { GRAPH = {
    X = Cooling.Chiller.1.Elec_Power;
    Y = Cooling.Chiller.1.Chilled_Water_Return_Temp
    AGGREGATION =  MINIMUM; FREQUENCY = 10;
    NAME = "return vs power";
} } ... }

// Example 2, defining a table of plots

NAME = "Whole Building Energy";
SESSION = {
  TABLE(4,3) = {
     CELL(1,1) = { START = 1/14/1996:0:0:0; STOP = 1/15/1996:0:0:0;  }
     CELL(1,2) = { START = 2/14/1996:0:0:0; STOP = 2/15/1996:0:0:0; }
     ...
  }
  SITE     = "UCB"; BUILDING = "Soda";
}

// Example 3, defining the UI interaction panel

SUBSESSIONS =
{ LABEL = "Building Energy:";
  BUTTON = { name = "Cooling Power";
  file = "Scripts/cooling_power.ses"; }
  BUTTON = ...
}
```

Figure 3: Examples of scripting language for plots, UI, and session management.

Building Data, Analysis

The research project has emphasized the RBMO architecture, with relatively minimal analysis of the data collected. In this section we provide a brief description of the buildings and the data collected to date. In general the RBMO system was extremely reliable and well suited for real-time data collection. Most of the complications came from the lack of applications to examine the data, which again, were considered a lower priority because of the research sponsor's interests. In addition to collecting data in real time, the database was populated with several months of historical data collected manually from the EMCS at Soda Hall. This allowed historical and real-time data to be integrated into the original Illustra database.

Soda Hall Building Data

Soda Hall, a 109,000 ft^2 Computer Science building was selected as our case-study site for several reasons. The building was equipped with an Energy Management Control System that the research team had worked with before. Second, the building was located near LBNL, permitting easy access. Finally, the building has two, 220 ton screw chillers, for a total of 440 tons of cooling plant capacity (or 248 sqft/ton). Early in the project we decided to focus on chillers, which are the largest single energy-using component in buildings with central cooling plants. The building has served as the subject of several research tasks that involved commissioning and performance. The eight tasks were as follows:

1. Compiled HVAC specifications, control sequences, and as-built documents.
2. Conducted short-term measurements to characterize flows, temperatures, and pressures.
3. Conducted additional power measurements on cooling towers for use in estimating energy savings from set-point optimization.

Table 1: Number and Type of Data Points Collected at Soda Hall

	Power	Temperature and Humidity	Flow	Status Counters	Misc	Total
Whole-Building	3	2		2		7
Cooling System		1	1	2		4
Chillers	2	8	2	2		14
Cooling Towers	2	1	1	4		8
Pumps	4			8		12
Calculated Fields					5	5
Total	11	12	4	18	5	50

4. Installed long-term, permanent metering equipment for as-operated model calibration and diagnostics using the EMCS as the data acquisition system.

5. Conducted false load tests of chillers to evaluate kW/ton at partial and full loads.

6. Evaluated model calibration methodologies and developed calibrated models of the chillers and cooling towers.

7. Identified and implemented improved control sequences.

8. Extrapolated from six months of measurements and modeling analysis to evaluate annual energy impacts of various operating strategies and retrofit scenarios.

Results from this work are reported in (Piette et al. 1997), and (Meyers 1996). The data collected at Soda Hall are summarized in **Table 1**. A total of 46 points were monitored for about two years, starting in September, 1995 during the first few months of inital occupancy. We compiled one-minute data for each point and have recently reviewed the completeness of the data set. There are many periods of incomplete data because the data collection was hampered by software and hardware changes that took place both at our end and at the building site. At our end, we lost data during periods when the system was down because of modifications to the system itself. In some cases this resulted in errors in the data logging procedures that resulted in the loss of a calculated data point. We were also influenced by some minor changes on campus when the EMCS was modified.

Oakland Federal Building Data

A total of 107 points were monitored at the Oakland Federal Building. This building is a 1.1 M sqft twin-tower, 18-story office building complex. The building was constructed in 1989 and houses Federal agencies such as the IRS, US District Courts, the US DOE, and Department of Veteran Affairs. The building is served by a central plant with five chillers, three at 1000 tons and two at 450 tons totaling 3900 tons of capacity. This is 280 sqft/ton. One of the interesting questions we are examining at both sites is chiller capacities and over sizing. The operators report that the last 1000 tons of cooling is not needed, even in the warmest weather.

The 107 points cover systems similar to those at Soda Hall, including whole-building power, chiller power and tons, plus cooling tower, and pump data. Additional points include heating loop flow, a series of outside temperatures from 5 air handlers, and several internal zone temperatures. Only two months of data were collected (August 1997 through October 1997).

Experience with System

Time Series DBMS

Our first implementation used the early release of the Illustra DBMS product, chosen because it offered facilities for storing and querying time series data, including calendars. We encountered reliability problems with the DB server. We therefore switched to storing our time series data in a more mature conventional relational DBMS, i.e., Oracle Version 7.3 (at present). This solved our server reliability problems. Whereas Illustra provided direct support for storing and querying time series data, in Oracle we have had to construct these facilities atop a relational system. For each time series value, Oracle 7.3 requires substantially more space, 25 bytes vs. 4-bytes for Illustra. Also, Oracle has proven quite complex to administer.

CORBA

We have used Expersoft ORBs on both the gateway machines (PC clones running Windows NT) and the server (Sun Solaris 2.5 Unix box). The ORBs have performed satisfactorily across these heterogeneous platforms. These ORBs support CORBA 2.0 specification and use IIOP inter-ORB communication protocol.

Gateways

Problems with gateway systems concerning unit conversion and time zone issues are discussed above. We have modified the gateways to store a backup log of the monitored data, which can be used to recover from central server failures.

We have also experienced gateway failure induced by system configuration changes at the building EMCSs.

Graphics Application

Our initial development of the graphics application (on PCs) revealed several problems. The graphics application proved to be too monolithic and difficult to modify. This motivated us to develop scripting facilities for both the plots and session management. We have since decided to introduce a CORBA interface between the graphics application and the Time Series API. The initial implementation assumed a "fat client", and did much of the aggregation computations in the client. In our second implementation (on X-windows Motif) assumes a "thin client" and performs the aggregation computations in the DB server.

Operations

We have collected approximately one year of data from Soda Hall (plus one year of historical data). We have at present approximately 2 months of data from Oakland Federal Building. We have been collecting several dozen monitoring points for both Soda Hall and Oakland Federal Building. Sampling rates for both buildings are once per minute. Basic data rate is presently approximately 1 KB per minute. This requires approximately ten times as much storage in the DBMS.

Some operational problems seem to be primarily due to inadvertent operator problems with EMCS. We have experienced downtime due to a disk crash and associated recovery problems - due to inadequate backups.

Related Work

An extensive discussion of related work can be found in our earlier paper, (Olken 1996).

Honeywell recently announced a new building monitoring system, Atrium, (Honeywell 1998) quite similar in design to our project. Atrium employs a different operating system and window system (Windows NT), different relational database management system (SQLserver). However, it has a very similar overall architecture. They have also chosen to use a (popular) proprietary distributed object management system, Active X/DCOM, in contrast to our use of the standard CORBA distributed object system.

Other major differences between RBMO and Atrium lie in the time series database. We use a (simpler) regular time series, while Honeywell uses a COV (change of variable) irregular time series database. Honeywell discards repeated measures within dead bands. This results in irregular time series. Honeywell has also implemented a simple time series query language and temporal join operator to query and extract align multiple (irregular) time series. Their approach is more efficient w.r.t. to storage (and perhaps communications bandwidth) at the expense of more complex software.

The Enflex System from CTI Ltd. (CTI 1998) employs proprietary applications protocols atop TCP/IP.

Future Work

We are currently investigating the use of the CORBA Security Service and Secure IIOP for remotely controlling the HVAC operations of the buildings from the application component of the RBMO system. This is for authenticating the building operator and to ensure the uncorrupted and safe arrival of building control messages at the target sites. We aim at operating buildings remotely using a secure CORBA implementation. So far, such implementations are not stably available. Moreover their interoperability with different object request brokers is yet not given.

Conclusion

We have described the design and development of the remote building monitoring and operation system, which employs the CORBA protocol across the Internet for communications between remote buildings and a time series database, as well as to distribute individual 'application' components across different machines.

We have firmly argued for the use of CORBA aside other distributed computing platforms and protocols within our project context. We discuss methods for coping with heterogeniety among buildings, e.g, measurement units, time zones, naming conventions and schemas. An object model has been developed to alleviate these problems and present a uniform interface to the user. The development of the time series data base atop different commercial data bases incorporating these issues has been described.

We have discussed related work, tradeoffs between alternative networking/distributed object protocols, tradeoffs among various CORBA and DBMS systems, and a number of design issues in constructing such systems.

A stable secure CORBA implementation is needed to support remote control functionality Retrofitting concurrency control mechanisms into legacy EMCS systems will also be required.

The attraction of our approach lies in the extensive availability of commercial software products which support distributed heterogeneous computing applications based on the CORBA model and underlying Internet communications protocols.

While our (experimental) implementation required an additional PC in each building, commercial implementations could run on the same processor as the EMCS.

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For further information see the web page: http://www.lbl.gov/~olken/RBO/rbo.html

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